Implementation of LNG as marine fuel in current vessels. Perspectives and improvements on their environmental efficiency.

Master's Thesis

Facultat de Nàutica de Barcelona
Universitat Politècnica de Catalunya

Candidate:
Llorenç Sastre Buades

Supervised by:
Dr. Francesc Xavier Martínez de Osés

Master's Degree in Nautical Engineering and Maritime Transport

Barcelona, February 2017

Department of Nautical Sciences and Engineering

UNIVERSITAT POLITÈCNICA DE CATALUNYA
BARCELONATECH
Facultat de Nàutica de Barcelona

Acknowledgments

First of all, I would like to express my most sincere thanks to my supervisor Dr. Francesc Xavier Martínez de Osés for his accessibility and continuous support of my master’s thesis, for his wise advice and suggestions, which guided me throughout the development of this paper, and also for sharing with me his immense knowledge about marine pollution and maritime activities.

Second, I would like to make special mention to my grandparents, Llorenç Sastre and Jeroni Sampol, with whom I will forever be grateful for bringing me up in my infancy, instilling their outlook on life and essential values on me and their undying love for me.

Third, I would like to thank my parents for providing me with all the things that a child can ever deserve and for their attention and support in the good times and most important in the bad ones. To my father for his unceasing encouragement to achieve my academic and career goals, and my mother for her dedication and patience during my adolescence.

Then, I would like to thank my university colleague, Eduardo Sáenz, for his feedback, understanding about maritime subjects related to my study and of course long-life friendship. Moreover, I would like to mention Josep Riera, who has been like a brother to me since I stared my university education in Barcelona.

Last but no least, I would like to thanks Transportes Marítimos Brisa for placing total confidence in me from the first moment I started to work for them and specially mention Anacaona II crewmembers, Lluís Dominguez, Alex Villar and Miquel Ventayol, who not only helped me to improve my nautical knowledge and skills but also taught me real-life lessons and experiences.

Abstract

The necessity of a sustainable and environmentally friendly maritime transport and the introduction of International Maritime Organization (IMO) regulations regarding ship emissions have driven to a new type of marine fuel. Nowadays, Liquefied Natural Gas (LNG) as marine fuel appears to be an attractive, potential and technically feasible option for new building vessels to comply with air pollution regulations. Consequently, the implementation of LNG on board vessels has been conducted together with the development of LNG-fuelled engines, LNG fuel tanks, gas supply systems and LNG infrastructure. LNG-fuelled vessels are equipped principally with lean-burn gas engines or dual-fuel (DF) engines, vacuum insulated C-type tanks and compact fuel gas supply systems. Over the next decade, the number of LNG-fuelled vessels is forecasted to increase fast, even tough, certain LNG-fuelled vessel segments will experience a bigger expansion. Furthermore, potential for LNG-fuelled vessels depends on several features and car/passenger ferries seem to be the LNG-fuelled vessel segment with a higher potential. To date, air pollution regulations significantly reduce nitrous oxides (NO_X) emissions and almost eliminate sulphur oxides (SO_X) and particulate matter (PM) emissions, although, carbon dioxide (CO_2) emissions are reduced only 20-30%. Owing to the foreseen rise of global seaborne trade, CO_2 emissions are expected to grow even more emphasising the necessity to adopt highly restrictive measures. International legislative bodies have started to propose upcoming regulations and manufactures have developed technical improvements to improve energy efficiency of vessels and thereby decrease CO_2 emissions. Nevertheless, these solutions merely provide small benefits on vessels' environmental efficiency. As a result of the study, LNG-fuelled vessels present a bright future, as an alternative option to meet short-term air pollution regulations due to they do not sufficiently minimise CO_2 emissions.

Keywords: LNG, air pollution, CO_2, NO_X, SO_X, ECA, marine fuel, LNG-fuelled engines, DF engines, LNG fuel tanks, gas supply systems, LNG bunkering infrastructure, LNG-fuelled vessel segments, forthcoming air pollution regulations, technical improvements, energy efficiency, GHG.

Table of Contents

List of Figures

List of Tables

List of Abbreviations

ABS	*American Bureau of Shipping*
ASD	*Azimuth Stern Drive*
BV	*Bureau Veritas*
CAPEX	*Capital Expenditures*
CCS	*China Classification Society*
CO_2	*Carbon Dioxide*
CPP	*Controllable Pitch Propeller*
DF	*Dual-Fuel*
DP	*Dynamic Positioning*
DNV-GL	*Det Norske Veritas- Germanischer Lloyd*
DWT	*Dead Weight Tonnage*
ECA(s)	*Emission Control Area(s)*
EEDI	*Energy Efficiency Design Index*
EGR	*Exhaust Gas Recirculation*
EGS	*Exhaust Gas Scrubbers*
EIAPP Certificate	*Engine International Air Pollution Prevention Certificate*
ESD	*Emergency Shutdown*
EU	*Europe*
Fi-Fi	*Fire Fighting*
FWE	*Fuel Water Emulsion*
GHG	*Greenhouse Gas*
GIA	*Global Industry Alliance*
GL	*Germanischer Lloyd*

GloMEEP	*Global Maritime Energy Efficiency Partnership*
GT	*Gross Tonnage*
GVU	*Gas Valve Unit*
HAM	*Humid Air Motors*
HFO	*Heavy Fuel Oil*
IEEC	*International Energy Efficiency Certificate*
IFO	*Intermediate Fuel Oil*
IGC Code	*International Code for the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk*
IGF Code	*International Code of Safety for Ships Using Gases or Other Low-Flashpoint fuels*
IMO	*International Maritime Organization*
KR	*Korean Register of Shipping*
LDC(s)	*Least Developed Countries*
LEG	*Liquefied Ethylene Gas*
LNG	*Liquefied Natural Gas*
LOA	*Length Over All*
LPC(s)	*Lead Pilot Countries*
LR	*Lloyd's Register*
MARPOL	*International Convention for the Prevention of Pollution from Ships*
MCR	*Maximum Continuous Rating*
MDO	*Marine Diesel Oil*
MEPC	*Marine Environment Protection Committee*
MGO	*Marine Gas Oil*
MSC	*Maritime Safety Committee*
MTCC(s)	*Maritime Technological Cooperation Centre(s)*
NECA(s)	NO_X *Emission Control Area(s)*

NK	*Nippon Kaiji Kyokai*
NO	*Nitrogen Oxide*
NO_X	*Nitrous Oxides*
NO_2	*Nitrogen Dioxide*
NT	*Net Tonnage*
ODS	*Ozone Depleting Substances*
OSV	*Offshore Service Vessels*
PBU	*Pressure Build-up Unit*
PID(s)	*Propulsion Improving Device(s)*
PM	*Particulate Matter*
PSC	*Port State Control*
PSV	*Platform Supply Vessels*
RINA	*Registro Italiano Navale*
ROI	*Return On Investment*
RoPax	*Roll On-Roll Off Passenger*
Ro-Ro	*Roll On-Roll Off*
ROV	*Remotely Operated Vehicle*
RPM	*Revolutions Per Minute*
SCR	*Selective Catalytic Reduction*
SECA(s)	*SO_X Emission Control Area(s)*
SEEMP	*Ship Energy Efficiency Management Plan*
SIDS	*Small Island Developing States*
SO_X	*Sulphur Oxides*
SO_2	*Sulphur Dioxide*
SO_3	*Sulphur Trioxide*
SSS	*Short Sea Shipping*
TEU(s)	*Twenty Feet Equivalent Unit(s)*

UK	*United Kingdom*
US	*United States*
USD	*United State Dollar*
VOC(s)	*Volatile Organic Compound(s)*

Chapter 0. Introduction

Background

Shipping is the principal mean of transport used worldwide and has been essential for the global economic development. Consequently, emissions from vessels are a major environmental concern because of their impact on the deterioration of the environment, especially global warming of the atmosphere. Moreover, it is estimated a growth in the world seaborne trade in the near future on account of world's growing population, which exacerbates air pollution forecasts from maritime transport. As a result, the IMO has developed and adopted more stringent regulations aimed to significantly decrease emissions from vessels. These air pollution regulations focus on reduction of CO_2, NO_X, SO_X and PM, since they are the main emissions of vessel engines. Due to the necessity of vessels to comply with tight restrictions on their emissions, new options and solutions have emerged in the shipping industry. Manufacturers have started to design and develop a wide variety of abatement technologies addressed to decrease levels of CO_2, NO_X, SO_X and PM emissions (Semolinos, Olsen, & Giacosa, 2013; Wan et al., 2015).

Utilization of LNG as marine fuel is an attractive and potential option because of its low sulphur content, it is a mature technology and its relative low price. LNG as ship fuel removes SO_X and PM emissions and reduces NO_X and CO_2 emissions. Then, LNG has already been proved in the maritime sector, as LNG carriers have been using it for several decades. LNG carriers use the natural boil-off of the LNG stored in their cargo tanks to supply their engines. Nevertheless, LNG-fuelled vessels require technological developments so as to overcome challenges in combustion, handling and storage of LNG, which have empowered it to become a feasible alternative considered among ship owners (Adamchak & Adede, 2013; Semolinos et al., 2013).

Finally, economic attractiveness of LNG as marine fuel is driven by its low price. Records of marine fuel prices show that natural gas, and therefore LNG, is relatively lower than low sulphur distillates, marine diesel oil (MDO) and marine gas oil (MGO), and high sulphur marine fuel oils, heavy fuel oil (HFO) and intermediate fuel oil (IFO), during the last years. Besides, LNG reserves capable of covering LNG demand from shipping sector in the years ahead also contribute to the implementation of LNG in vessel engines.

However, prices of marine fuels depend on several external factors, which lead on fluctuating prices and make difficult to reach trustworthy price forecasts and assessments. Furthermore, the scarce availability of LNG bunkering infrastructures is the main disadvantage of LNG as ship fuel, since only there are few LNG facilities in the Baltic Sea and North Sea area, and therefore, a consolidated LNG supply chain along international trade routes has been established yet (IMO, 2011b; Wan et al., 2015).

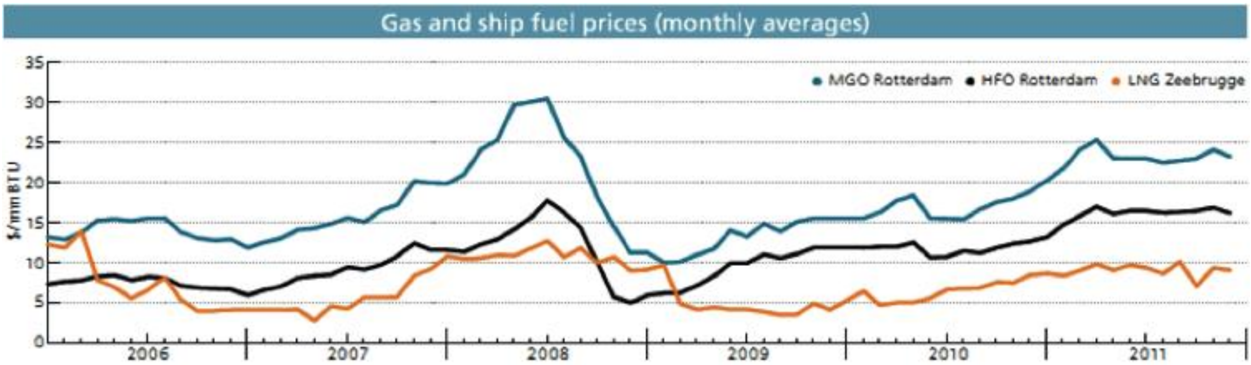


Figure 0.1: Record of gas and ship fuel prices from 2006 to 2011 (Source: IMO, 2011b).

Purpose and Objectives

The purpose of this paper is to provide knowledge about the implementation of LNG as marine fuel on board vessels from a technical and environmental point of view. Moreover, this paper aims to thoroughly explain the main drivers that triggered the utilization of LNG to supply vessel engines, how it has been achieved and further developments to improve the environmental efficiency of LNG-fuelled vessels.

The principal objectives, which outline the development and structure of this paper, are mentioned as follows:

a) Examine the impact of shipping emissions on the environment.
b) Explain air pollution regulations and future amendments to reduce emissions from vessels.
c) Detail and explain the challenges overcome to implement LNG as marine fuel in current vessels.
d) Describe dominant LNG-fuelled vessel segments and analyse LNG-fuelled vessels feasibility.
e) Propose technical improvements to enhance energy efficiency of vessels and assess their potential.

This paper comes as a result of my curiosity and interest in the liquid bulk cargo shipping sector along with the growing concern generated by the high contribution of vessels to the global warming of the atmosphere. First, during my bachelor's degree, and later throughout my master's degree in Nautical

Engineering Maritime Transport, I have acquired a firm grasp about navigation, ship theory, stowage, maritime safety and protection, marine pollution prevention, logistics and ship operation, among other subjects. However, I started to be keen on the hydrocarbon and liquid bulk cargo business when I took the chance to study abroad in Norway, and since that moment, I have not stopped learning more about it. Likewise, I am worried about high air pollution levels generated by the human activity during lasts decades, which exacerbate climate change and cause harmful effects on the environment and society. That is why, I decided to focus my master's thesis on the implementation of LNG as marine fuel on board vessels.

Scope and Limitations of the Study

This paper about the implementation of LNG on board vessels has been conducted from a technical and environmental point of view, since its extension could have been huge if I would have also included the economical aspects of the introduction of LNG as marine fuel. Moreover, this paper is based on updated information published during the lasts years, although, LNG-fuelled vessels are an emerging market and technological advances can be expected in the near future.

The analysis and description of the LNG-fuelled vessel segments focuses on the dominant segments, as they represent a large percentage of the global LNG-fuelled fleet. In addition, despite there is lots of information about general arrangement, equipment, propulsion systems and operational procedures of conventional vessels, very limited information is available of the latest LNG-fuelled vessels built, restricting the degree of detail of their description.

Methodology

This paper on implementation of LNG as marine fuel in current vessels, perspectives and improvements on their environmental efficiency is the result of a literature research. I started my literature research looking up and collecting information regarding LNG as marine fuel through sources such as Science Direct, Bibliotècnica and Google Scholar. The majority of the collected information was reports and guidelines from different classification societies and maritime organizations and also I found articles, books and websites. Once I acquired a theoretical background about LNG as ship fuel through reading the different reports, guidelines, articles, books and websites, I decided to focus my project on the implementation of LNG as marine fuel in vessels.

Then, I looked up and collected more focused information about the implementation of LNG on board vessels in order to define the objectives of this paper. Afterwards, I elaborated a structure that included all the objectives set for the project and complied with the basic parts of a literature research. Once the structure was defined, I started conducting a deep explanation of the theoretical framework, secondly, I developed an analysis and discussion based on the collected information, and finally, I proposed the conclusions obtained throughout the whole paper. From the beginning to the end, I have had the support of my supervisor, who has guided me to elaborate my project and has made comments and suggestions in order to improve it.

Structure of the Paper

For the purpose and objectives detailed previously, this paper is structured into seven differentiated chapters. Chapter one briefly describes the environmental situation in which maritime transport lives from an air pollution point of view and includes an overview of the regulation framework currently in force regarding air emissions from vessels adopted by the international and European legislative bodies. Chapter two mentions the wide variety of technologies addressed to meet air pollution regulations and describes to larger or lesser extent the technological challenges for the implementation of LNG in current vessels. Chapter three details the principal rules and standards for the construction and equipment of LNG-fuelled vessels. These three chapters comprise the theoretical framework of the paper. Chapter four analyses and describes the main LNG-fuelled vessel segments. Chapter five discusses the potential for LNG-fuelled vessels. Chapter six assesses future air pollution measures and proposes technical improvements to comply with them. These three chapters comprehend the practical analysis and discussion of the paper. Finally, chapter seven summarises the key points of each chapter and presents the conclusions obtained throughout the development of the paper.

Chapter 1. Shipping Emissions

Maritime transport is an international industry, since more than 80 per cent of world trade is carried by vessels (IMO, n.d.-f). Although shipping is the most efficient and reliable mean of international transport, it emits several gases and particles to the atmosphere, being the most important CO_2, NO_X and SO_X. According to the Third Greenhouse Gas (GHG) Study 2014 (IMO, 2014b), in 2012 international shipping emitted 796 million tonnes of CO_2, 18.6 million tonnes of NO_X and 10.6 million tonnes of SO_X. International shipping CO_2, NO_X and SO_X emissions represent approximately 2.2%, 13% and 12% of global CO_2, NO_X and SO_X emissions, respectively (CE Delft, Germanischer Lloyd, Marintek, & Det Norske Veritas, 2006; IMO, n.d.-c, n.d.-k, 2014b).

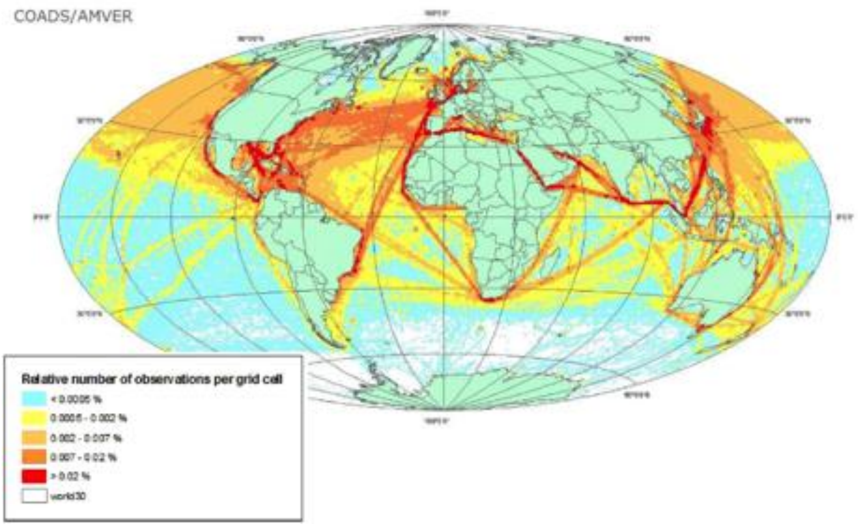


Figure 1.1: Geographical distribution of shipping emissions (Source: Dalsøren et al., 2009).

Carbon Dioxide (CO_2)

Carbon dioxide is the principal GHG and is unnaturally produced when fossil fuels are combusted in engines. GHG are the main mechanism for global warming of the atmosphere (Baumgart & Bolsrad, 2010; CE Delft et al., 2006; Rodrigo de Larrucea, 2015).

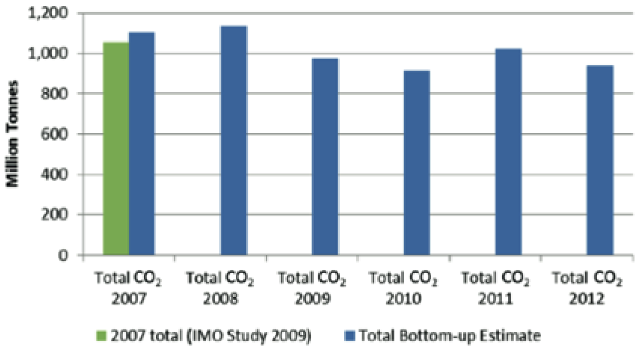


Figure 1.2: Total shipping CO_2 emissions for the period 2007-2012 (Source: IMO Third GHG Study 2014).

Nitrous Oxides (NO_X)

Nitrous oxides include all types of NO_X, e.g. nitrogen oxide (NO) or nitrogen dioxide (NO_2), although NO_2 is the most predominant. NO_X emissions cause the generation of ozone, which contributes to global warming of the atmosphere and decomposition of methane. In addition, NO_X also contributes to the generation of acid rain. NO_X emissions from vessel are generated when burning marine fuels (Baumgart & Bolsrad, 2010; CE Delft et al., 2006; Rodrigo de Larrucea, 2015).

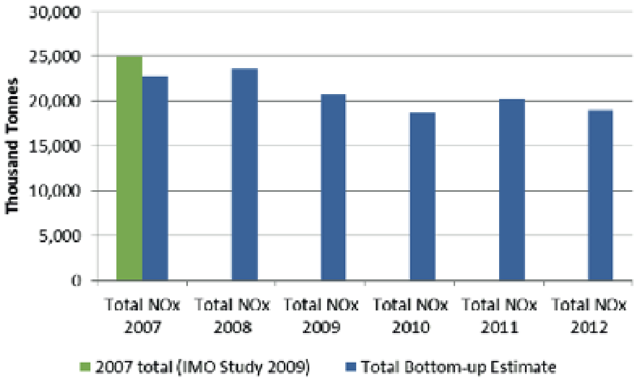


Figure 1.3: Total shipping NO_X emissions for the period 2007-2012 (Source: IMO Third GHG Study 2014).

Sulphur Oxides (SO_X)

Sulphur oxides include all types of SO_X, e.g. sulphur dioxide (SO_2) or sulphur trioxide (SO_3), even though SO_2 is the most common. SO_2 is an irritating and toxic gas. Most SO_X emissions are generated by human activities because of carbon and fuel combustion. Moreover, SO_X effects worsen when reacting with volatile organic compounds (VOCs), and as a consequence, it generates acid rain. International shipping contribute to 12% of global SO_X emissions due to HFO is the main fuel used in the maritime industry, which contains a high amount of sulphur (Baumgart & Bolsrad, 2010; CE Delft et al., 2006; Rodrigo de Larrucea, 2015).

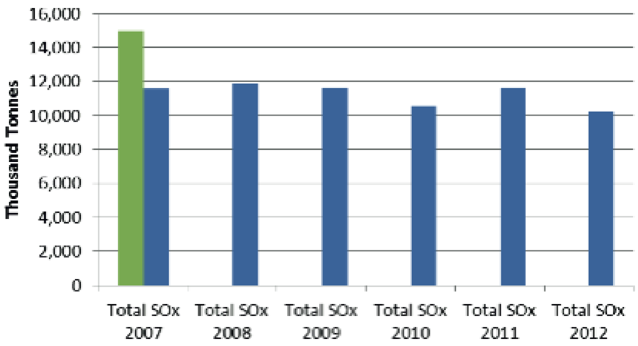


Figure 1.4: Total shipping SO_X emissions for the period 2007-2012 (Source: IMO Third GHG Study 2014).

1.1 Air Pollution Regulations

Air pollution from vessels is an increasing environmental concern due to world trade is estimated to grow significantly in the near future, and consequently, shipping emissions are expected to increase too (DNV-GL, 2012). For this reason, more stringent air pollution regulations intended to reduce emissions from vessels are expected to come into force in the years ahead. The IMO through the International Convention for the Prevention of Pollution from Ships (MARPOL convention) Annex VI pretends to reduce emissions from vessels. The MARPOL convention sets operational energy efficiency measures intended to minimise CO_2 emissions from vessels, which are regulated in Chapter 4 of MARPOL Annex VI and entered in force on January 1, 2013. In addition, it establishes limits on the NO_X and SO_X emissions from vessels, which are ruled in Regulation 13 and Regulation 14 of MARPOL Annex VI, respectively, and came into force on July 1, 2010. Moreover, the MARPOL Annex VI establishes other strict regulations about ozone depleting substances (ODS), VOCs, shipboard incinerator, reception facilities and fuel oil availability and quality (DNV-GL, 2012; IMO, n.d.-c, n.d.-k, 2011a, 2014b). Besides, the European Parliament and the Council of the European Union through the directive 2012/33/EU also pretends to reduce emissions from vessels. It establishes limits on the SO_X emissions from vessels and entered in force twenty days after its publication in the Official Journal of the European Union (The European Parliament & The Council of the European Union, 2012).

1.1.1 International Convention for the Prevention of Pollution from Ships (MARPOL) Annex VI Prevention of Air Pollution from Ships

Chapter 4: Regulations on Energy Efficiency for Ships

MARPOL Annex VI Chapter 4 sets both technical and operational energy efficiency measures so as to minimise CO_2 emissions from international maritime transport. These measures are an Energy Efficiency Design Index (EEDI) whose purpose is to promote the development of more energy efficient engines and a Ship Energy Efficiency Management Plan (SEEMP), which pretends to enhance the vessels operational energy efficiency. MARPOL Annex VI Chapter 4 is mandatory for vessels with a gross tonnage (GT) equal or greater than 400 GT (IMO, n.d.-b, 2011a; Krüger, 2011).

The EEDI indicates vessel CO_2 emissions per tonne mile of goods transported. New vessels shall calculate their own EEDI, which specifies an expected vessel performance in relation to energy efficiency, according to their design specifications and include a technical file with the procedure and information required for calculating the EEDI (Attained EEDI). The Attained EEDI shall be equal or smaller than a Required EEDI, which varies depending on the corresponding ship type and reference line value. Furthermore, an International Energy Efficiency Certificate (IEEC) will be issued to complaint vessels (IMO, n.d.-b, 2011a; Krüger, 2011).

The SEEMP provides a mechanism for controlling and monitoring energy efficiency performance of vessels, and consequently, companies take into account new technologies and procedures to improve vessels' operational energy efficiency. The principal aim of a SEEMP is to manage environmental performance of vessel and assist companies in the development of energy efficient procedures. The SEEMP details the operational mechanisms to enhance energy efficiency and is a specific document for each vessel of the shipping company. In addition, the SEEMP is divided in four stages: planning, implementation, monitoring, and self-evaluation and improvement. Finally, the SEEMP is mandatory for both new and existing vessels, and companies are responsible for the development and implementation of it (IMO, n.d.-b, 2011a; Krüger, 2011).

With these regulations, the IMO expects to minimise significantly CO_2 emissions from vessels and estimates that vessels will be 30% more efficient by 2025 (Krüger, 2011; Rodrigo de Larrucea, 2015).

Regulation 13: Nitrogen Oxides (NO_X)

According to MARPOL Annex VI Regulation 13 (IMO, 2011a), vessels equipped with a diesel engine with a power output of more than 130 kW, applicable from July 1, 2010, or diesel engine that has been subject to a major conversion on or after January 1, 2000 with a power output of more than 130 kW shall comply with this regulation (DNV-GL, 2015a, 2016b; IMO, n.d.-j).

Regulation 13 establishes three different tiers, (Tier I, II and III) which limit NO_X emissions from diesel engines depending on their rated operating speed (n^1, rpm). Tier I affects vessels constructed between January 1, 2000 and January 1, 2011; Tier II affects vessels constructed on or after January 1, 2011; and Tier III affects vessels constructed on or after January 1, 2016. Moreover, Tier I and Tier II apply to vessels operating in global waters, whereas, Tier III applies to vessels operating in NO_X Emission Control Areas (NECAs) (DNV-GL, 2015a, 2016b, IMO, n.d.-j, 2011a).

Tier	**NO_X Limit, g/kWh**		
	n < 130 rpm	130 rpm ≤ n < 2000 rpm	n ≥ rpm
Tier I	17.0	$45 \cdot n^{(-0.2)}$	9.8
Tier II	14.4	$44 \cdot n^{(-0.23)}$	7.7
Tier III	3.4	$9 \cdot n^{(-0.2)}$	2.0

Table 1.1: NO_X emissions limit for Tier I, II and III (Source: IMO, 2011a).

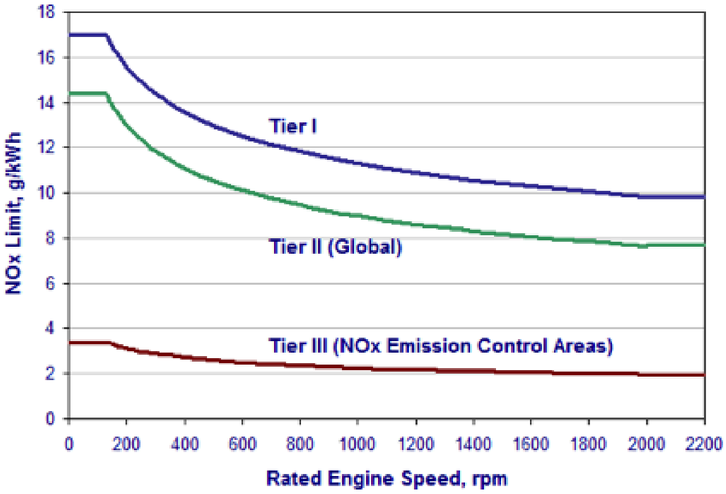


Figure 1.5: Chart of NO_X emissions limit for Tier I, II and III (Source: DNV-GL, 2015a).

NO_X Tier III requirements apply to Emission Control Areas (ECAs) designated for Tier III NO_X control, which are North American area and United States Caribbean Sea area. Although, if new NECAs are

---

[1] n = rated engine speed (crankshaft revolutions per minute).

established, Tier III requirements apply to vessels constructed on or after the date the new NECA is implemented (DNV-GL, 2015a, 2016b, IMO, n.d.-j, 2011a).

Diesel engines that shall comply with this regulation require an Engine International Air Pollution Prevention Certificate (EIAPP certificate) in order to prove that the engine is compliant with it. The NO_X Technical Code 2008 specifies the certification, testing and procedure for determining NO_X emissions from engines. The EIAPP certificate and technical documents regarding engine testing and changeover procedures in case of DF engines shall be stored on board (DNV-GL, 2015a, 2016b, IMO, n.d.-j, 2011a).

The MARPOL Annex VI Regulation 13 determines specific requirements for those vessels and diesel engines that differ from the main regulation criteria explained above. With this regulation, the IMO expects to reduce about 15-20% vessels NO_X emissions in global waters and 80% in NECAs (IMO, n.d.-j, 2011a; Rodrigo de Larrucea, 2015).

Regulation 14: Sulphur Oxides (SO_X) and Particulate Matter (PM)

According to MARPOL Annex VI Regulation 14 (IMO, 2011a), the sulphur content of any marine fuel oil used by vessels operating in global waters shall not exceed the following limits:

- 4.5% m/m (mass to mass per cent) before January 1, 2012
- 3.5% m/m on or after January 1, 2012
- 0.5% m/m on or after January 1, 2020

However, 0.5% m/m limit could be delayed to January 1, 2025 depending on the result obtained from a review conducted in 2018 concerning the availability of the required fuel oil (IMO, n.d.-l, 2011a).

Moreover, Regulation 14 establishes ECAs where the sulphur content of marine fuel oil used by vessels operating in them shall not exceed the following limits:

- 1.5% m/m before January 1, 2010
- 1.0% m/m on or after January 1, 2010
- 0.1% m/m on or after January 1, 2015

The SO_X Emission Control Areas (SECAs) are Baltic Sea area, North Sea area, North American area and United States Caribbean Sea area. With this regulation, the IMO pretends to reduce about 80% vessels SO_X emissions in global waters and 96% in SECAs (IMO, n.d.-l, 2011a; Rodrigo de Larrucea, 2015).

Figure 1.6: ECAs (Source: DNV-GL, 2015a).

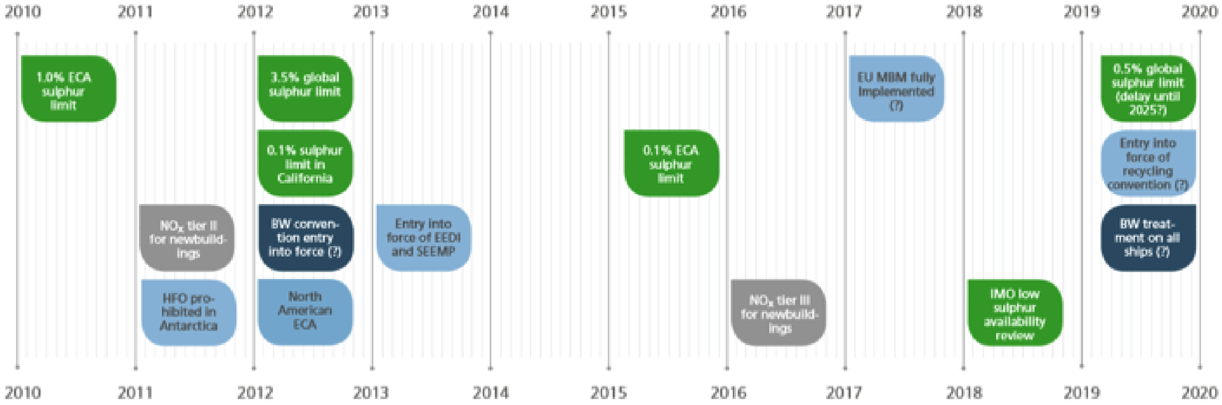


Figure 1.7: Chronology of IMO environmental regulations from 2010 to 2020 (Source: DNV-GL, 2012).

1.1.2 Directive 2012/33/EU as regards the Sulphur Content of Marine Fuels

The principal aim of the directive 2012/33/EU is to decrease SO_2 emissions from the combustion of marine fuels and therefore minimise harmful effects of SO_X emissions on human health and the environment. It sets limits on the sulphur content of marine fuel used within the territory of the Member States. According to Directive 2012/33/EU (The European Parliament & The Council of the European Union, 2012), the sulphur content of marine fuels used by vessels operating in territorial seas, exclusive economic zones and pollution control zones of Member States shall not exceed the following limits:

- 3.5% m/m as from June 18, 2014
- 0.5% m/m as from January 1, 2020

Furthermore, Directive 2012/33/EU establishes that the sulphur content of marine fuels used by vessels operating in territorial seas, exclusive economic zones and pollution control zones falling within SECAs of Member States shall not exceed the following limits:

- 1.0% m/m until December 31, 2014
- 0.1% m/m as from January 1, 2015

In addition, Directive 2012/33/EU sets that the sulphur content of marine fuels used by passenger vessels operating on regular services to or from any Union port in territorial seas, exclusive economic zones and pollution control zones falling outside SECAs of Member States shall no exceed 1.5% m/m until January 1, 2020 (The European Parliament & The Council of the European Union, 2012).

According to Directive 2012/33/EU, the sulphur content of marine fuels used by vessels at berth in Union ports shall not exceed 0.1% m/m. However, Member States have to allow sufficient time for the crew to complete fuel-changeover operations as soon as possible after arrival at berth and as late as possible before departure. On the other hand, vessels that switch off all engines and use onshore electricity while at berth, or those that spend less than two hours at berth shall not apply this limit (The European Parliament & The Council of the European Union, 2012).

Finally, Directive 2012/33/EU allows vessels of any flag operating in ports, territorial seas, exclusive economic zones and pollution control zones of Member States to install emission abatement methods as an alternative to using compliant marine fuels (The European Parliament & The Council of the European Union, 2012).

Chapter 2. Technological Solutions to Comply with Air Pollution Regulations

The principal aim of air pollution regulations is to significantly reduce emission of gases and particles from vessels. Consequently, manufacturers have started to develop new technologies capable of complying with these restringing regulations. Shipping companies will be forced to retrofit their vessels in the near future adopting technological solutions due to upcoming air pollution regulations. Technology suppliers have developed a wide range of technical options so as to meet forthcoming international regulations, which can de divided into CO_2, NO_X and SO_X reduction technologies. Because of the wide range of complying solutions, ship owners have to take into account many factors in order to make a difficult decision. For this reason, it is essential an assessment of the different technological measures bearing in mind rate of emissions reduction, capital cost, installation cost, operating cost, lifespan, required space, side effects, operational implications, among others (Brynolf, Magnusson, Fridell, & Andersson, 2014; DNV-GL, 2012; Yang et al., 2012).

CO_2 Reduction Technologies

Air pollution regulations, such as EEDI and SEEMP, pretend to minimise CO_2 emissions. According to the previous chapter, the EEDI pretends to make new building vessels more energy efficient, whereas, the SEEMP manages operational procedures on board vessels in an energy efficient manner. These requirements have two benefits, on one hand, they reduce fuel consumption and as a result minimise emissions, and on the other hand, they are cost effective. In the near future, more vessels will be built in accordance with energy efficiency restrictions due to their enforcement and the increase on energy prices. With the aim of reducing GHG emissions and improve energy efficiency, manufacturers have developed several measures which cover different areas, e.g. reduction of vessel resistance, increase in propulsive efficiency and reduction in auxiliary consumption (DNV-GL, 2012).

The development of vessel resistance reduction measures depends on the adoption of fuel efficiency options, and they include a wide range of possibilities. Designing vessel hulls with advanced software, building vessels with lighter materials or reducing operational vessel speed are some of the solutions currently used in vessels in order to minimise vessel resistance once sailing (DNV-GL, 2012).

The principal reason of using measures designed to increase propulsive efficiency is to enhance efficiency of propellers that work on poor or high loaded conditions. However, these measures can also be used in any type of vessel so as to reduce their fuel consumption. In the shipping industry, systems such as shaft generators or hybrid propulsive designs are widely used among ship operators with the aim of enhancing propulsive efficiency (DNV-GL, 2012).

Finally, systems to reduce power consumption are used in the maritime transport, for example transmission systems or renewable power technologies. The main benefits are enhancement of power management and reduction of fuel consumption. In spite of these advantages, vessels equipped with this type of technologies are rather unusual because of the level of sophistication of these systems (DNV-GL, 2012).

NO_X Reduction Technologies

Air pollution regulations, such as Tier I, II and III, are intended to reduce NO_X emissions. According to the previous chapter, the different tiers limit NO_X emissions of vessel engines depending on their rated operating speed (rpm) in global waters, except of Tier III which apply to vessels operating in NECAs. The degree of stringency of tiers vary between them, since Tier I and II restrictions can be met retrofitting vessels engines, whereas, Tier III restrictions require the development of new technologies in order to comply with them (DNV-GL, 2012). Due to the necessity to obey this requirements, technological solutions, such as exhaust gas recirculation (EGR), selective catalytic reduction (SCR), water injection systems and LNG as marine fuel have stated to be developed and installed on board vessels (DNV-GL, 2012).

One potential option to comply with NO_X Tier III requirements is the installation of EGR systems on vessels engines. An EGR consists of recirculating exhaust gases from engines into their combustion stage. As a result, it is obtained a higher heat capacity and a lower content of oxygen of the recirculated exhaust gas, which considerably reduce the combustion temperature. A decrease of temperature into the combustion chamber leads into a reduction of NO_X emissions. Although the number of vessels currently equipped with this sort of technology remains low, the installation of EGR systems in the maritime industry has a promising potential in the years ahead, and consequently, industries have started to develop EGR for marine engines (DNV-GL, 2012).

Another technological alternative to meet IMO requirements is to fit vessels engines with SCR. The NO_X reduction process involves spraying a solution of urea, which is a reducing agent, into the exhaust. Urea turns into ammonia, which decomposes NO_X into N_2 and water into a metal catalyst installed in the engine. Although SCR systems have been used on land in factories and vehicles for many years, several ship owners have started to introduce this reduction technique on board their vessels. Furthermore, SCR systems designed for on land applications differ in terms of operational conditions from those intended for marine utilization, e.g. engine type and fuel sulphur content. That is why, SCR makers have focused on the application of SCR systems in the shipping industry. However, the application of SCR on merchant vessels presents three concerns regarding its optimum NO_X reduction capacity and continuous operability. First, SCR systems require high operation temperatures to reach their maximum NO_X reduction capacity, and it can not be achieved while engines operate at low loads. Second, ammonia might form sulphates, which deposit on the catalyst reducing its NO_X reduction capacity when exhaust gas temperature is low. Third, sulphur content of fuel damages catalyst materials and reduces its efficiency. For this reason, SCR should only be used with engines supplied with low sulphur content fuel or engines fitted with a SO_X reducing device so as to enhance its lifespan. NO_X reduction capacity of SCR systems is about 95% when operational temperature is high despite low exhaust gas temperature and fuel sulphur content (Brynolf et al., 2014; DNV-GL, 2012; Yang et al., 2012).

NO_X emissions could also be reduced through water injection. Nowadays, there are two methods of water injection: humid air motors (HAM) and fuel water emulsions (FWE). NO_X reduction is obtained due to the saturation of the scavenging air, in HAM, scavenge air is saturated through direct water injection, whereas in FWE, it is saturated through adding water into the fuel. The NO_X reduction capacity depends on the amount of injected water and it ranges from 70% to 50% (DNV-GL, 2012; Yang et al., 2012).

LNG as marine fuel is currently being used in certain vessels, usually in LNG carriers, which use natural boil-off of LNG to supply their engines. However, this tendency has started to spread over other type of vessels, such as ferries, containership and offshore vessels, and the number of shipping companies ordering new buildings with LNG as marine fuel is increasing. LNG can be burnt either into gas engines or DF engines, although, most new buildings are equipped with DF engines. In gas engines, LNG is ignited by a spark plug, whereas in DF engines working in their gas mode, ignition is made by the injection of small amounts of diesel. DF engines working in their diesel mode are based on the normal diesel cycle. In spite of the experience with LNG as marine fuel gained from LNG carriers, new buildings face some technical challenges, such as handling and storage of LNG on board and bunkering. Traditional tanks, pipes and systems used to contain LNG have to be retrofitted with insulation alloys capable of maintaining LNG at a very low temperature (-162°C). LNG as marine fuel presents several benefits: it reduces NO_X emissions about 90% because of lower temperatures during combustion, eliminates SO_X emissions and PM and reduces CO_2 emissions around 20% due to low carbon content of LNG. In contrast, gas and DF engines release unburned methane, which has a great impact on the global warming potential. In addition, GHG effect of methane is around 25 times higher than for CO_2 and methane emissions from DF engines are higher than those from gas engines. However, unburned methane release could be reduced more than 90% with an oxidation catalyst (Brynolf et al., 2014; DNV-GL, 2012; Yang et al., 2012).

SO_X Reduction Technologies

SO_X regulations limit the content of sulphur in marine fuels with the aim of reducing SO_X emissions and PM from vessels. According to the previous chapter, Regulation 14 of MARPOL Annex VI establishes SO_X emission limits depending on whether vessels operate in global waters or in SECAs, being more stringent in SECAs. As a result of this regulation, manufacturers have to develop technological solutions in order to allow vessels to operate in ECAs. Nowadays, exhaust gas scrubbers (EGS) and low sulphur fuels are the main alternatives to meet SO_X pollution regulations for shipping companies (DNV-GL, 2012).

One option to reduce SO_X emissions is the installation of EGS on board vessels. EGS are used to eliminate sulphur of engine exhaust gases through a dry or wet process depending on the type of EGS used. Dry scrubbers are filled with lime or other minerals containing calcium, whereas, wet scrubbers are filled with seawater, freshwater or chemicals, usually alkaline liquids. In dry scrubbers, hot exhaust gases pass through a scrubber absorber containing lime, which reacts with the SO_X and generates gypsum, a soft sulphate mineral. Alternatively in wet scrubbers, seawater is pumped through the scrubber, which reacts with the SO_X and makes seawater acidic (wash water). Wash water has to be neutralised either on board through adding more seawater or overboard through reacting with seawater substances. Furthermore, after SO_X removal, scrubbers produce a sludge, which is regarded as a special waste and consequently has to be stored on board until discharging it at dedicated port facilities. Not only marine scrubbers are capable of reducing SO_X emissions around 95% but also reduce large amounts of PM and soot, and consequently, vessels can be supplied with high sulphur fuels. However, retrofitting vessels with scrubbers becomes a challenge in relation to their design and installation, since they affect vessel stability because of their weight and required space. Consequently, scrubbers increase power consumption approximately 2% leading into an increase of CO_2 emissions (Brynolf et al., 2014; DNV-GL, 2012; Yang et al., 2012).

Finally, vessel engines can be supplied with low sulphur fuels so as to minimise SO_X emissions. Low sulphur fuel options are expensive distillates whose sulphur content has been reduced in refineries through several processes, such as MDO and MGO, or LNG. On one hand, low sulphur distillates (MDO and MGO) reduce SO_X emissions and they do not require any treatment on board, although, they have a high price and their long-term availability is a concerning issue. On the other hand, LNG as marine fuel complies with SO_X and NO_X regulations and presents several benefits, as it has already been explained above (Adamchak & Adede, 2013; DNV-GL, 2012; Levander, 2011).

2.1 LNG as Marine Fuel

Nowadays, LNG as marine fuel is an available and potential solution for complying with upcoming air pollution requirements. Moreover, using LNG to supply vessel engines is an attractive commercial solution for both, new building LNG-fuelled vessels and existing vessels. There are three main drivers that make LNG a feasible alternative. First and foremost, LNG as ship fuel removes completely SO_X emissions and PM, reduces NO_X emissions up to 90% and also minimise CO_2 emissions around 20%. Second, in the shipping industry there is an important number of vessels using LNG as fuel, since LNG carriers have been using it for several years. LNG carriers use the natural boil-off of the LNG stored in their cargo tanks so as to supply their engines. Finally, LNG as marine fuel is commercially attractive because of its worldwide availability, since LNG reserves will be able to fulfil LNG demand from the maritime industry in the coming years, and its low price compered to the main marine fuel oils used on board vessels. Although, it is the low price of natural gas and LNG compared to high sulphur marine fuel oils, including HFO or IFO, and low sulphur distillates (MDO and MGO) in some markets that makes LNG attractive as a marine fuel. To date in United States (US) and Europe (EU), natural gas price is considerably lower than high sulphur fuel oils and low sulphur distillates, whereas in Asia, LNG price is higher than high sulphur fuel oils, but lower than low sulphur distillates. However, it has to be taken into account that natural gas requires an infrastructure, as it must be liquefied, stored and supplied to vessels. For this reason, low natural gas price may not turn into low LNG price (Adamchak & Adede, 2013; DNV-GL, 2014a, 2015b).

However, LNG as marine fuel faces several challenges: development of LNG-fuelled engines, handling and storage equipment of LNG on board and LNG bunkering infrastructure. LNG-fuelled engines have already been used on LNG carriers but not on other types of vessels, e.g. ferries, containership and offshore vessels. As a result, engine manufacturers have started to develop DF engines capable to burn both diesel and LNG. Secondly, LNG has to be stored at very low temperature during voyages, for this reason fuel tanks, pipes and handling systems must be fitted with insulation alloys able to keep LNG at the right temperature (-162°C). Finally, port facilities to produce, store and fuel bunkering installations or vessels are required to reliably and operationally supply LNG-fuelled vessels (DNV-GL, 2012, 2014a, 2015b).

2.1.1 LNG-Fuelled Engines

Today, LNG-fuelled vessels in operation are equipped basically with two types of engines: lean-burn gas engines and DF engines. Lean-burn gas engines comply with IMO Tier III regulations, whereas, DF engines comply with IMO Tier II regulations when operating in their liquid fuel oil mode and IMO Tier III regulations when operating in their gas mode. Nowadays, the principal manufacturers of LNG-fuelled engines are Wärtsilä, Rolls Royce and MAN, which offer a wide variety of engine designs in all power ranges (Brynolf et al., 2014; DNV-GL, 2015b; LNG Fuelled Vessels Working Group, n.d.-a).

Lean-Burn Gas Engines

Lean-burn gas engines are designed for being supplied only with LNG and work according to the lean-burn Otto principle. Lean-burn gas engines are supplied with natural gas through a gas valve unit (GVU) that filters and controls natural gas pressure. Gas engine cylinders are fed by individual pipes, which are connected to a main double wall pipe running along the engine. Gas engines are fuelled with a lean premixed air-gas mixture, which is ignited in the pre-combustion chamber by a spark plug. The mixture of air and gas contains more air than is needed leading to a lower combustion temperature, and therefore, NO_X emissions are reduced and efficiency increases due to a higher compression ratio and an optimized injection timing (DNV-GL, 2015b; LNG Fuelled Vessels Working Group, n.d.-a; Rolls-Royce, 2012; Woodyard, 2004).

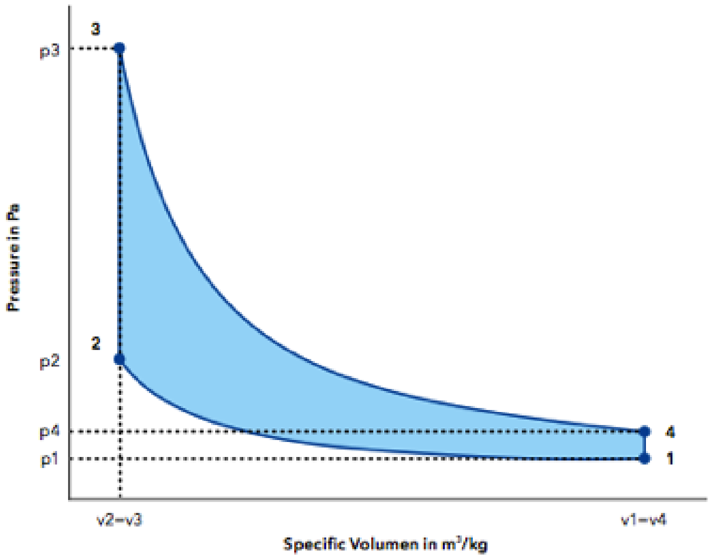


Figure 2.1: Volume-pressure diagram of Otto principle (Source: DNV-GL, 2015b).

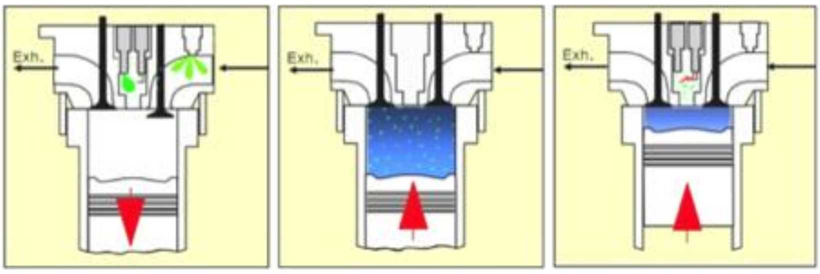


Figure 2.2: Lean-burn gas engine operating system (Source: Stenersen, 2011).

The air-gas mixture is injected at low pressure (4-5 bars) and is generated outside the cylinder behind the turbocharger. The gas can be provided directly from the pressurised LNG fuel tanks because of lean-burn gas engines are low-pressure engines. In addition, gas engines have high-energy efficiency at high load, generate low NO_X emissions and reduce GHG approximately 20% (DNV-GL, 2015b; LNG Fuelled Vessels Working Group, n.d.-a; Rolls-Royce, 2012; Woodyard, 2004).

Furthermore, propulsion systems using lean-burn gas engines present two applications, gas-mechanical application and gas-electrical application. In a gas-mechanical layout, the lean-burn gas engine provides propulsion power to the propellers through reduction gears and shaft lines, whereas, in a gas-electrical layout the generators sets, which are driven by a lean-burn gas engine, supply electric motors with electric power to propel the propellers (Baumgart & Bolsrad, 2010; Rolls-Royce, n.d.-e, n.d.-f).

Rolls Royce is the main producer of lean-burn gas engines and has developed a wide variety of LNG powered propulsion systems with a power range from 1,400 to 9,400 kW. Rolls Royce lean-burn gas engines operate at medium speed and are characterised by their high efficiency, low operating costs and improved environmental performance resulting in very low emission levels. In addition, Rolls Royce gas engines present a high gas quality tolerance and reduce noise, lube oil composition and maintenance costs. Rolls Royce has developed two series of lean-burn gas engines, Bergen B and C. Bergen B series are engines designed for large ferries and Roll On-Roll Off (Ro-Ro) vessels, and provide a power output from 3,500 to 7,700 kW. Alternatively, Bergen C series are addressed to tugs and small ferries and cargo vessels, and provide a power output from 1,460 to 2,430 kW. Both engines series are available in gas-mechanical layout and gas-electric layout (generator sets) (Rolls-Royce, n.d.-a, n.d.-b, n.d.-c, n.d.-d, n.d.-g).

Engine Series	Engine Type	Cylinder Configuration	Max. Continuous Rating (MCR)
Bergen B35:40L	B35:40L8PG	8 cylinders in line	3,500 kW at 750 rpm
	B35:40L9PG	9 cylinders in line	3,940 kW at 750 rpm

Bergen B35:40V	B35:40V12PG	12 cylinders in V	5,700 kW at 750 rpm
	B35:40V16PG	16 cylinders in V	7,700 kW at 750 rpm
Bergen C26:33L	C26:33L6PG	6 cylinders in line	1,620 kW at 750 rpm
	C26:33L8PG	8 cylinders in line	2,160 kW at 750 rpm
	C26:33L9PG	9 cylinders in line	2,430 kW at 750 rpm

Table 2.1: Types of Rolls Royce lean-burn gas engines (Source: Rolls-Royce, n.d.-f).

Dual-Fuel (DF) Engines

DF engines are designed for being supplied with LNG and liquid fuels, e.g. MDO or HFO. DF engines work according to the lean-burn Otto principle in gas mode and according to the normal diesel cycle in diesel mode. DF engines working in gas mode are supplied with natural gas through a GVU that filters and controls natural gas pressure. Engine cylinders are fed by individual pipes, which are connected to a main double wall pipe running along the engine. When working in gas mode, DF engines are fuelled with a lean premixed air-gas mixture, which reduces peak combustion temperatures and NO_X emissions owing to the air-gas mixture contains more air than is needed. The air-gas mixture is fed into the cylinder during the intake stroke and is ignited by a small amount of diesel injected into the combustion chamber at the end of the compression stroke, since the self-ignition temperature of air-gas mixture is too high to be achieved with the compression of the cylinder. In four-stroke engines, the air-gas mixture is injected at low pressure (4-5 bars) and is generated outside the cylinder behind the turbocharger. As four-stroke engines are low-pressure engines, natural gas can be provided directly from the pressurised LNG fuel tanks (DNV-GL, 2015b; LNG Fuelled Vessels Working Group, n.d.-a; Stenersen, 2011; Wärtsilä, 2015; Woodyard, 2004).

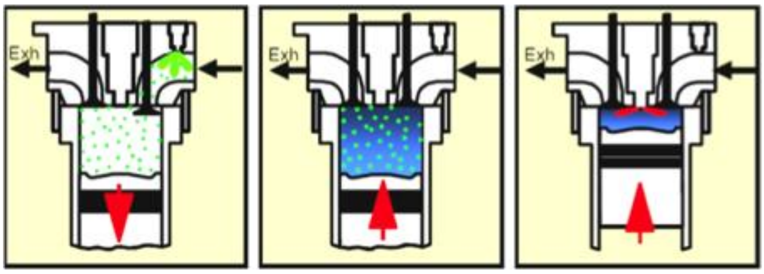


Figure 2.3: DF engine operating system when working in gas mode (Source: Stenersen, 2011).

To ensure minimum NO_X emissions the amount of diesel injected at the end of the compression stroke is very small, usually less than 1% of the total fuel consumption. DF engines use a micro-pilot injection and an engine speed and load control and monitoring system so as to optimize combustion (DNV-GL, 2015b; LNG Fuelled Vessels Working Group, n.d.-a; Wärtsilä, 2015; Woodyard, 2004).

When DF engines work in diesel mode, diesel is injected into the combustion chamber at high pressure just before the top dead centre. Gas admission is deactivated, even though, the micro-pilot is activated so that ensure reliable pilot ignition when the engine changes from diesel mode to gas mode (DNV-GL, 2015b; LNG Fuelled Vessels Working Group, n.d.-a; Wärtsilä, 2015; Woodyard, 2004).

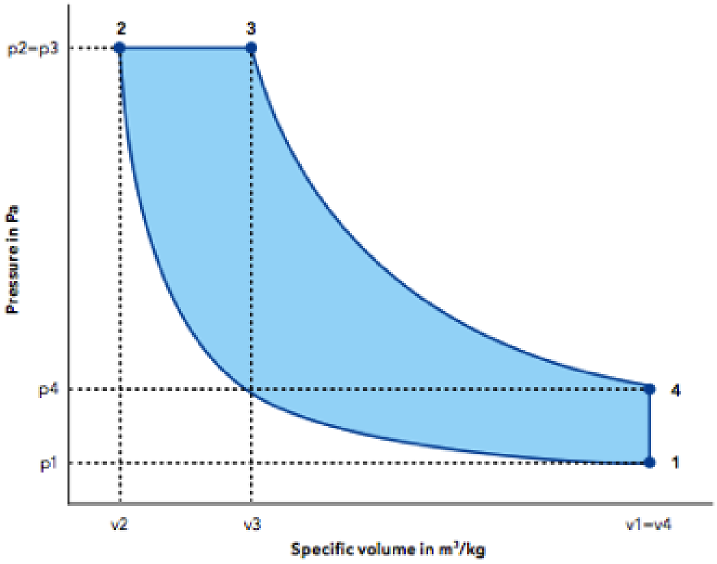


Figure 2.4: Volume-pressure diagram of diesel cycle (Source: DNV-GL, 2015b).

DF engines are able to change easily from one mode to another one when operating. Switchover from gas mode to diesel mode lasts less than one second and does not affect the engine load and speed. In case of natural gas supply interruption or engine component failure, gas mode to diesel mode transfer is instantaneous and automatic. Switchover from diesel mode to gas mode is a gradual process, diesel supply is slowly reduced meanwhile the amount of natural gas provided is increased. However, transferring from diesel mode to gas mode has a minimal effect on the engine load and speed. Although switching from LNG to MDO or vice versa does not require engine modifications, switching from LNG to HFO requires minor engine modifications (DNV-GL, 2015b; LNG Fuelled Vessels Working Group, n.d.-a; Wärtsilä, 2015; Woodyard, 2004).

MAN is one of the main manufacturers of DF engines, although, it has developed two-stroke DF engines, which lightly differ from four-stroke DF engines. MAN DF engines operate at high pressure, and consequently, they compress the air, start the combustion stroke injecting fuel oil and inject the natural gas in the air-fuel oil mixture. For this reason, natural gas pressure must be high (300 bars) and two-stroke DF MAN engines use pumps to increase LNG pressure. DF MAN engines can operate in three different fuel modes: fuel oil only mode, minimum fuel mode and specified gas mode. DF engines working in fuel oil only mode are supplied only with fuel oil. When working in minimum fuel mode, DF engines require the injection of pilot fuel and natural gas into the combustion chamber. The minimum amount of pilot fuel ranges from 5-8% of the total fuel consumption when the engine operates at a load between 30% and 100%, and it can be used as pilot fuel either HFO or MDO. When the engine load is lower than 30%, the stable combustion of natural gas and pilot fuel is not guaranteed. As a result, the engine switches from minimum fuel mode to fuel oil only mode. Finally, DF engines working in specified gas mode allow operators to inject a certain amount of natural gas (DNV-GL, 2015b; MAN Diesel, 2013).

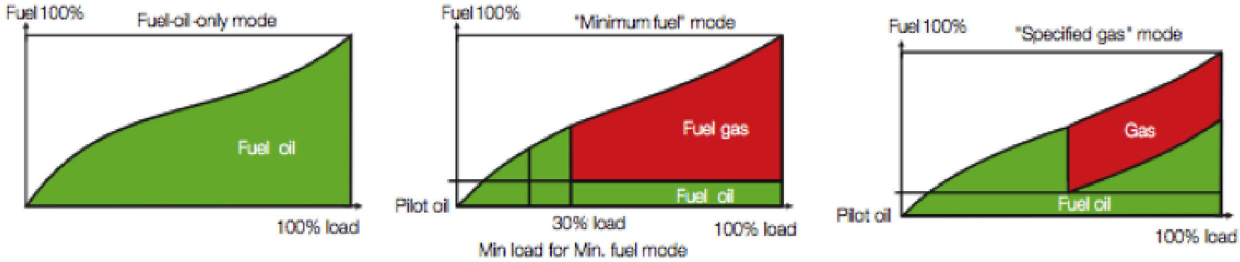


Figure 2.5: DF MAN engine modes (Source: MAN Diesel, 2013).

Furthermore, DF engines mainly present two propulsion system layouts, DF-mechanic engines and DF-electric engines. On one hand, DF-mechanic engines provide propulsion power to the propellers through reduction gears and shaft lines. On the other hand, DF-electric engines supply electric motors with electric power to propel the propellers (Baumgart & Bolsrad, 2010; Wärtsilä, 2015).

Wärtsilä is the main producer of DF engines and has developed a wide variety of LNG powered propulsion systems with a power range from 0.9 to 18.3 MW. Wärtsilä DF engines operate at a speed that oscillates between 500 and 1,200 rpm and are characterised by their fuel flexibility, low exhaust gas emissions and application flexibility, since DF engines are able to operate either at constant speed as generator sets or variable speed as mechanical drives. In addition, Wärtsilä DF engines use proven and reliable DF technology, an integrated automation system for switching modes and has a fuel economy at any engine load. Wärtsilä has developed four series of DF engines, Wärtsilä 20DF, Wärtsilä 34DF, Wärtsilä 46DF and Wärtsilä 50DF. Wärtsilä 20DF is addressed for tugs and small cargo vessels and ferries when operating as drive prime mover, although, it is also suitable for a wide range of vessels when working as generator set. It provides a power output from 0.9 to 1.6 MW. Secondly, Wärtsilä 34DF is appropriate for a wide range of vessels either as a prime mover or generator set. It provides a power output from 2.8 to 8.0 MW. Thirdly, Wärtsilä 46DF is designed for operating as DF-mechanic or DF-electric engine and provides a power output from 6.2 to 18.3 MW. Finally, Wärtsilä 50DF is intended for large LNG carriers and ferries when working as a prime mover. It provides a power output from 5.7 to 17.5 MW (Wärtsilä, 2015).

Engine Series	Engine Type	Cylinder Configuration	Rated Power
Wärtsilä 20DF	6L20DF	6 cylinders in line	1,110 kW at 1,200 rpm
	8L20DF	8 cylinders in line	1,480 kW at 1,200 rpm
	9L20DF	9 cylinders in line	1,665 kW at 1,200 rpm
Wärtsilä 34DF	6L34DF	6 cylinders in line	3,000 kW at 750 rpm
	8L34DF	8 cylinders in line	4,000 kW at 750 rpm
	9L34DF	9 cylinders in line	4,500 kW at 750 rpm
	12V34DF	12 cylinders in V	6,000 kW at 750 rpm
	16V34DF	16 cylinders in V	8,000 kW at 750 rpm
Wärtsilä 46DF	6L46DF	6 cylinders in line	6,870 kW at 600 rpm
	7L46DF	7 cylinders in line	8,150 kW at 600 rpm
	8L46DF	8 cylinders in line	9,160 kW at 600 rpm
	9L46DF	9 cylinders in line	10,305 kW at 600 rpm
	12V46DF	12 cylinders in V	13,740 kW at 600 rpm
	14V46DF	14 cylinders in V	16,030 kW at 600 rpm
	16V46DF	16 cylinders in V	18,320 kW at 600 rpm
Wärtsilä 50DF	6L50DF	6 cylinders in line	5,850 kW at 514 rpm
	8L50DF	8 cylinders in line	7,800 kW at 514 rpm
	9L50DF	9 cylinders in line	8,775 kW at 514 rpm
	12V50DF	12 cylinders in V	11,700 kW at 514 rpm
	16V50DF	16 cylinders in V	15,600 kW at 514 rpm
	18V50DF	18 cylinders in V	17,550 kW at 514 rpm

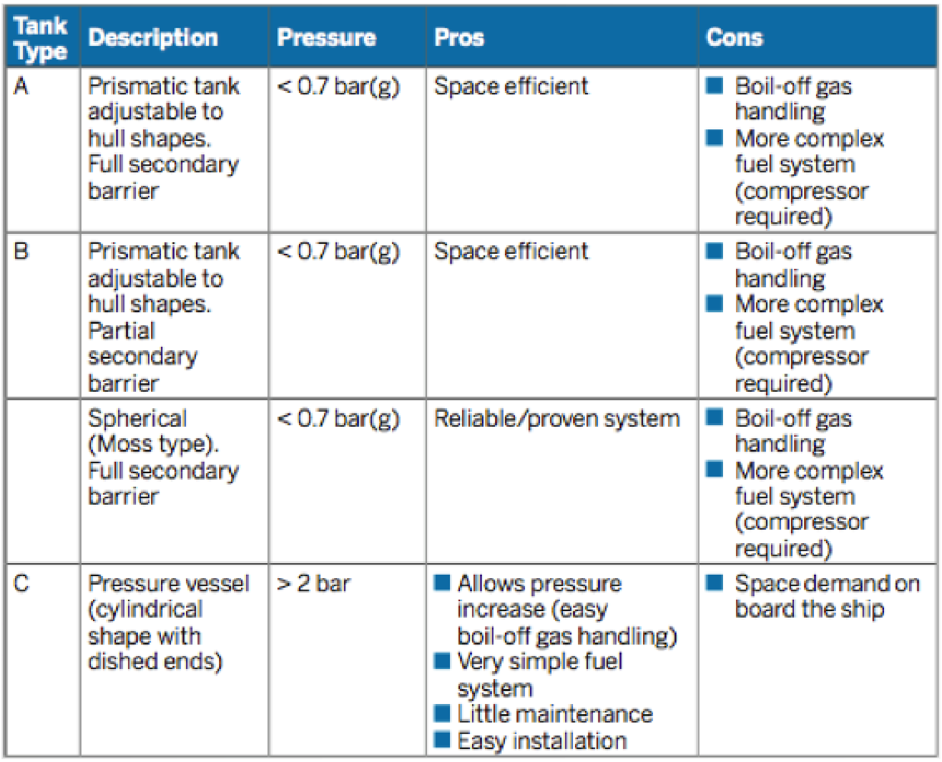
Table 2.2: Types of Wärtsilä DF engines (Source: Wärtsilä, 2015).

2.1.2 LNG Fuel Tanks and Gas Supply Systems

Due to the increased stringency of air pollution regulations, ship owners have started to order new building vessels and retrofit their current fleet with LNG-fuelled engines, since LNG as marine fuel is regarded as an available and feasible solution so that meet international limits on emissions of vessels. LNG-fuelled engines require a fuel gas supply system and LNG fuel tanks, which store the LNG required to feed them during the whole voyage. However, LNG fuel tanks present some challenges. First and foremost, LNG fuel tanks demand more space in comparison with tanks used to store HFO, specifically, they are around 2.5 times bigger than HFO tanks. Furthermore, LNG fuel tanks have to keep LNG at a very low temperature (-162°C) and minimise natural boil-off in order to avoid an increase of pressure, and as a consequence, they are fitted with insulation measures, which also increase tank size (DNV-GL, 2015b; MAN Diesel, 2013).

LNG-fuelled engine manufacturers have also started to develop LNG storage and handling systems on board vessels able to supply their engines. Several options of LNG fuel tanks and fuel gas supply systems are available depending on the vessel size and type of engine, respectively. According to the vessel size, large ships can be equipped with three different types of tanks, although, the different tank options on board large vessels require a further development. On the other hand, small vessels are equipped with vacuum insulated C-type tanks. Furthermore, fuel gas supply systems vary depending on the operational pressure of the engines, low-pressure engines and high-pressure engines (LNG Fuelled Vessels Working Group, n.d.-d; MAN Diesel, 2013; Rolls-Royce, n.d.-d).

LNG fuel tanks are designed in accordance with the International Code for the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk (IGC code). Moreover, IMO guidelines determine the types of tanks allowed to store LNG, which are Type A, B and C (Karlsson & Sonzio, 2008).



Tank Type	Description	Pressure	Pros	Cons
A	Prismatic tank adjustable to hull shapes. Full secondary barrier	< 0.7 bar(g)	Space efficient	■ Boil-off gas handling ■ More complex fuel system (compressor required)
B	Prismatic tank adjustable to hull shapes. Partial secondary barrier	< 0.7 bar(g)	Space efficient	■ Boil-off gas handling ■ More complex fuel system (compressor required)
	Spherical (Moss type). Full secondary barrier	< 0.7 bar(g)	Reliable/proven system	■ Boil-off gas handling ■ More complex fuel system (compressor required)
C	Pressure vessel (cylindrical shape with dished ends)	> 2 bar	■ Allows pressure increase (easy boil-off gas handling) ■ Very simple fuel system ■ Little maintenance ■ Easy installation	■ Space demand on board the ship

Figure 2.6: Types of IMO IGC code independent tanks (Source: Karlsson & Sonzio, 2008).

Prismatic B-type tanks and C-type tanks seem to be the most feasible option for large vessels, since both of them can be partially filled and allow vessel operation. The main advantages of prismatic B-type tanks are that tank design can be adjusted to hull shapes and tanks can have any size. Talking about C-type tanks, tank design can only be partially adjusted to the hull shape and tank maximum capacity is around 20,000 m^3, even tough, a working pressure of up to 5-6 bars allow them to easily manage boil-off during operation (MAN Diesel, 2013; Munko, 2013).

Figure 2.7: Prismatic B-type tank and C-type tank (Source: Munko, 2013).

On the other hand, small LNG-fuelled vessels are equipped with prefabricated vacuum insulated cryogenic C-type tanks. This type of tank has a design pressure of just below 10 bars, is available in several sizes, from 50 to 500 m^3, and can be arranged either horizontally or vertically and inside or outside the vessel. The cryogenic C-type tanks are cylindrical with dished ends, use vacuum insulation and have an inner vessel made of stainless steel and an outer vessel made of stainless steel or carbon steel, which acts as a secondary barrier. In addition, boil-off can be easily managed because of the tank is able to resist a significant pressure (Haraldson, 2011; Karlsson & Sonzio, 2008; LNG Fuelled Vessels Working Group, n.d.-d).

Figure 2.8: Prefabricated vacuum insulated cryogenic C-type tank (Source: Wärtsilä, 2014).

The principal aim of fuel gas supply systems is to handle LNG and natural gas on board vessels in a safe manner. That is why, the whole LNG supply chain, from bunkering stations at shore to the engine gas valves, has to be properly integrated. Design of fuel gas supply systems varies depending on the operational pressure of engines. LNG-fuelled engine producers have designed two layouts for fuel gas supply systems, one for low-pressure engines and another for high-pressure engines. Nevertheless, both fuel gas supply system layouts are fairly similar in terms of operation (Karlsson & Sonzio, 2008).

On one hand, fuel gas supply systems for low-pressure engines consist of a pressure build-up unit (PBU), a product evaporator, a GVU and a control and monitoring system. Low-pressure engines have to be fuelled with natural gas at 4-5 bars, and consequently, LNG has to be stored at the right pressure and evaporated. First of all, LNG from the shore terminal or LNG-bunkering vessel is supplied through an on board bunkering station which contains one bunkering line, one return line and one nitrogen purging line, all of them fitted with their respective pressure safety valves. LNG circulates along vacuum insulated lines from the bunkering station to the cryogenic LNG fuel tank, where it is stored at around 5 bars. Then, the LNG goes into the PBU whose objective is to raise storage tank pressure after bunkering and maintain the right pressure in the tank. Low-pressure engines can reach their maximum power when tank pressure is maintained at the right level (5 bars). Furthermore, engine gas inlet pressure requirements are achieved maintaining the appropriate pressure into the LNG fuel tank, as the fuel gas supply system is not equipped with cryogenic pumps or compressors. Moreover, the LNG flows from the bottom of the tank to the PBU thanks to the difference in pressure between the top and the bottom of the tank, and then, returns to the tank through its top. The natural circulation of LNG between the storage tank and PBU stops when the right pressure into the tank is reached. Afterwards, the LNG is fed into the product evaporator, where it is turned into natural gas and heated at least at 0°C depending on the engines requirements. Both, the PBU and product evaporator use hot water of the engine cooling system as heat source so that increase tank pressure and vaporise LNG, respectively. Finally, the natural gas flows towards the GVU, which regulates natural gas pressure according the engine load and ensure safe disconnection of the fuel gas supply system. The GVU is located between the LNG handling system and the LNG-fuelled engine and is placed inside an enclosure in order to be installed in the same engine room, and therefore, reduce complexity and installation costs (Haraldson, 2011; Karlsson & Sonzio, 2008; Wärtsilä, 2014).

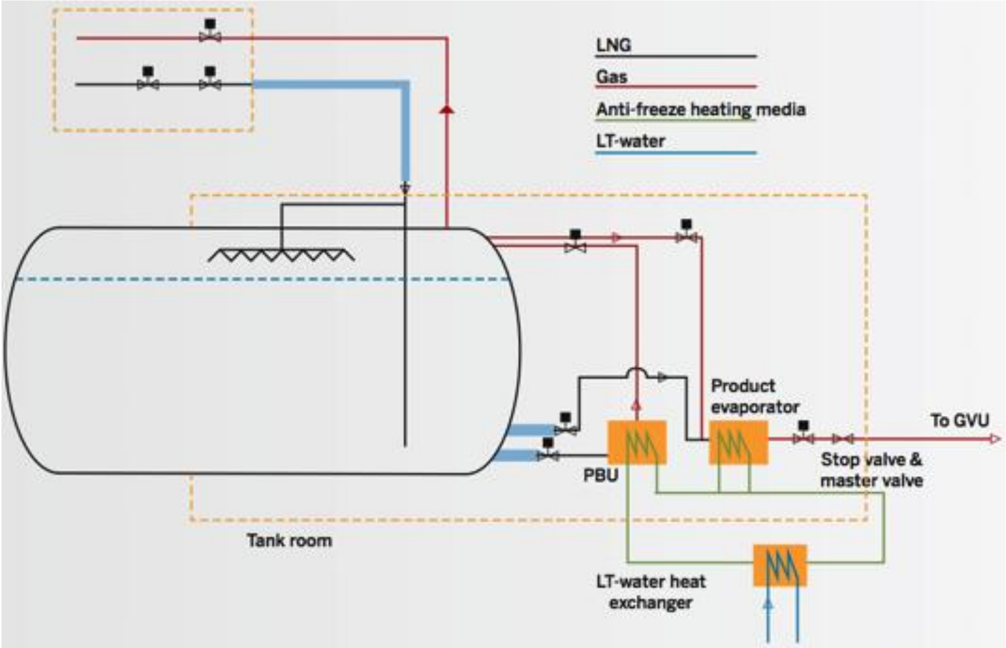


Figure 2.9: Low-pressure fuel gas supply system (Source: Karlsson & Sonzio, 2008).

On the other hand, fuel gas supply systems for high-pressure engines consist of a high-pressure LNG pump, a pump management system, a heat exchanger and a buffer capacity system. High-pressure engines have to be fuelled with natural gas at 250-300 bars, and consequently, LNG has to be pressurised and evaporated. The high-pressure pump is supplied with LNG stored in the cryogenic LNG fuel tank by a pump located in the tank, and is used to rise LNG pressure at 200-300 bars and circulate the pressurized LNG through the heat exchanger (LNG vaporizer). The heat exchanger uses the hot water of the engine cooling system as heat source in order to vaporise the LNG. Then, the pressurised natural gas is transferred into the buffer capacity system (natural gas accumulator), where it is stored in order to feed the engine with a constant flow rate of pressurised natural gas (MAN Diesel, 2013).

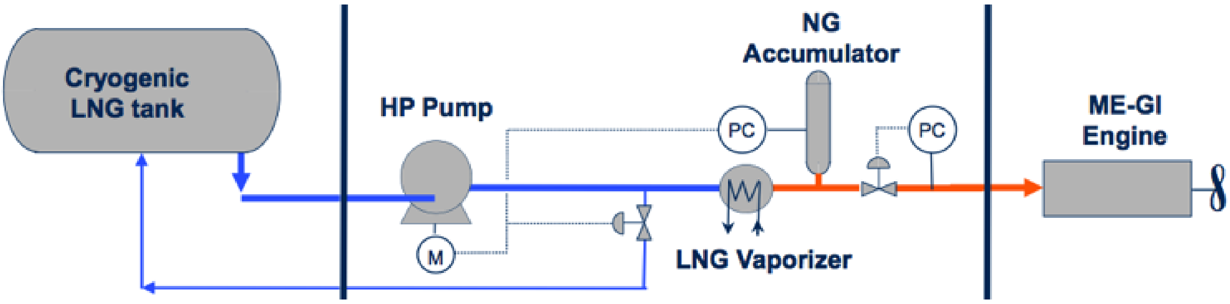


Figure 2.10: High-pressure fuel gas supply system (Source: MAN Diesel, 2013).

Basically, a fuel gas supply system stores LNG, converts LNG into natural gas and supplies engines with natural gas under perfect and stable conditions, and it is characterised by their enhanced safety and reliability. The principal benefits of a compact fuel gas supply system are efficient space utilization, less interfaces, reduced capital and operational costs and maximised LNG storage room. In addition, fuel gas supply system designs offer various configurations that allow the installation of multiple tanks and GVUs depending on the requirements of the vessel (Karlsson & Sonzio, 2008; Wärtsilä, 2014, 2016).

2.1.3 LNG Infrastructure

LNG maritime trade represents an important segment in the global maritime trade, since LNG has been carried as cargo for many years and large amounts of LNG are being transported nowadays by LNG carriers. The exportation of LNG from production and liquefaction plants to import terminals, which supply the local LNG pipeline grid, by LNG carriers is a deep-rooted industry with pricing mechanisms, fixed contractual models and proven technology and operations. Moreover, it is regarded as one of the safest segment in the shipping industry. Alternatively, the re-exportation of small amounts of LNG intended to supply LNG-fuelled vessels from large export or import terminals is not currently a well-established industry, although, thanks to the latest air pollution regulations, which toughen emission limits of vessels, it seems to be an emerging industry (DNV-GL, 2015b).

To date, the LNG infrastructure faces two major concerns that prevent it from becoming a consolidated market. First, LNG infrastructures require a huge investment because of their high level of sophistication and necessity to meet safety standards. The return on investment (ROI) for this kind of infrastructures ranges from years to decades, whereas, charter parties between ship owners and charterers cover a time period of months or in some cases years. As a result, this uncertainty in amortisation impacts infrastructure developments. Second, prices of HFO used for conventional bunkering in most relevant ports are available on internet, whilst, only prices of LNG at export and import terminals are available online and not prices of LNG as marine fuel. For these reasons, a well-established small-scale LNG industry will be developed once these concerns are overcome (DNV-GL, 2015b).

LNG bunker facilities are all those installations required to supply vessels with fuel, in this case LNG, in a port and include all elements of the LNG value chain. Furthermore, the key drivers to develop a LNG bunkering infrastructure are the following:

- LNG availability
- Reliable and safe logistical concepts
- Established legislation and regulatory framework
- Favourable investment climate and taxation regime
- Necessary competences, knowledge and skills
- Public acceptance

Moreover, LNG bunker installations have to ensure safety at any time through: planning, design and operation; safety management; and risk assessment (DNV-GL, 2015b).

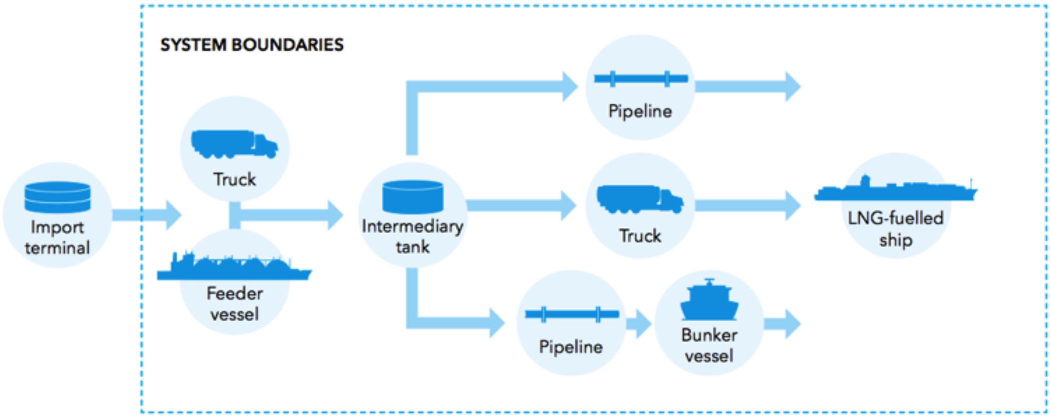


Figure 2.11: Small scale LNG value chain (Source: DNV-GL, 2015b).

When talking about global LNG infrastructure, five areas can be identified: Canada, US, EU, Middle East and Far East. Canada and US are the major exporters of LNG, although, they also have an increasing demand for LNG as marine fuel. Middle east is a LNG producer and supplier of LNG as marine fuel. Far East is the major consumer of LNG and could also become a supplier of LNG as marine fuel. Finally, EU is divided into three geographic areas: Northern Europe, Central Europe and Southern Europe. Northern Europe corresponds to the European ECA, where SO_X emissions are limited to 0.1%, and consequently, it is the main driver of using LNG as marine fuel. In Central Europe, the main driver of using LNG as marine fuel is the reduction of NO_X emissions from inland waterway vessels. In Southern Europe, LNG bunker facilities are potentially feasible so as to supply vessels sailing through the Mediterranean, since LNG is available at multiple import terminals (DNV-GL, 2015b).

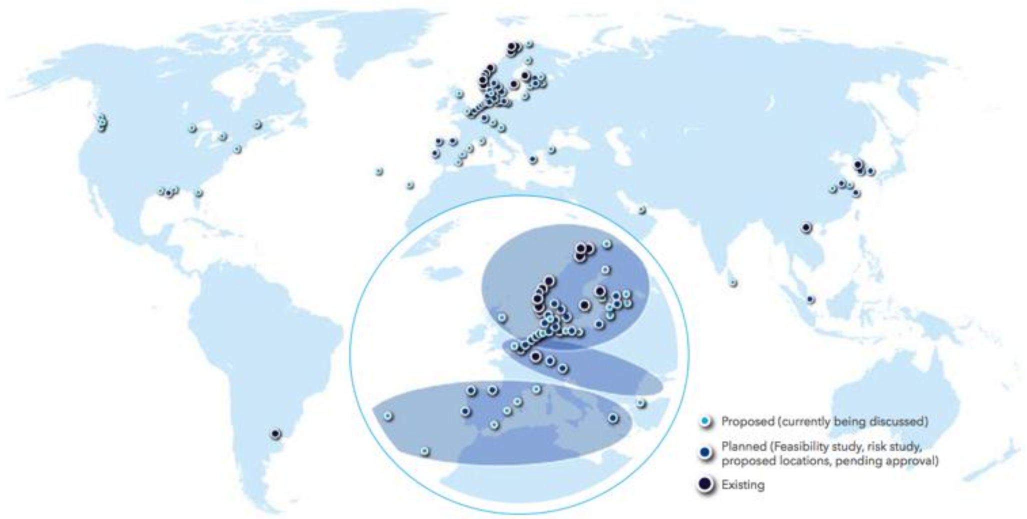


Figure 2.12: Global LNG infrastructure (Source: DNV-GL, 2015b).

Chapter 3. Rules for Gas-Fuelled Vessels

The introduction of LNG as marine fuel in the shipping industry seems to have a bright future because of its compliance with air pollution regulations, lower price compared to the main marine fuel oils and uptake of already proven technology on board vessels (Semolinos et al., 2013). LNG carriers have been using LNG in order to fuel their engines for many decades, and consequently, rules, guidelines and standards for gas carriers aimed to ensure high safety levels on board have already been used and implemented. As a result, LNG carriers have achieved a high safety record. Despite the fact that LNG-fuelled vessels share many principles with gas carriers, new systems have been installed on board vessel, such as LNG fuel tanks or gas supply systems. The implementation of these systems involves the investigation of their associated risks so as to design, build and operate LNG-fuelled vessels in a safe and sustainable manner. For this reason, it is important to consider important risk-related items for LNG-fuelled vessels (DNV-GL, n.d.-b; Semolinos et al., 2013). According to DNV-GL (DNV-GL, n.d.-b), main safety challenges include:

- Fire/explosion hazard in case of leakage: LNG ignites in mixture with air (5-15%) and has a high auto ignition temperature (600°C).
- Extremely low temperatures: LNG has a temperature of -163°C and can lead to cryogenic spills and frost burns in case of human exposure.
- High energy content of the LNG fuel tank: it requires protection from shipside and bottom, external fire and mechanical impact.
- Inexperienced crew: LNG is a new type of marine fuel.

Consequently, suitable LNG safety measures have to be implemented to minimise inherent risks. LNG is stored in fuel tanks at a temperature between -163°C and -155°C and a pressure between 1 and 4 bars. Furthermore, its energy density is 600 times higher than natural gas at atmospheric conditions. That is why, LNG systems have to be made of materials that are capable to stand cryogenic temperatures. Location and arrangements of systems, e.g. LNG fuel tanks or gas supply systems, have to be carefully decided during vessels design and safety issues have to be taken into account from the beginning of the design. Moreover, safety issues have to be in accordance with vessel design and operability. Therefore, the IMO and classification societies have developed different standards and rules aimed to minimise risks related with building gas-fuelled vessels (DNV-GL, n.d.-c).

3.1 International Code of Safety for Ship Using Gases or Other Low-flashpoint Fuels (IGF Code)

In 2004, the Marine Safety Committee (MSC) of IMO proposed the development of the IGF code owing to the lack of international regulations for gas-fuelled vessels other than gas carriers. The principal aim of the IGF code is to provide an international standard for vessels with natural gas-fuelled engines. In 2009, the MSC published the Interim Guidelines MSC.285(86), which provides a criteria for the arrangement and installation of auxiliary and main LNG-fuelled engines so that reach integrity levels in terms of safety, reliability and dependability comparable to conventional auxiliary and main engines. The IGF code follows the goal of the MSC.285(86) guideline and addresses all areas that require special attention for the usage of natural gas or other low-flashpoint fuels, such as gas fuel storage tanks or machinery spaces. It provides compulsory standards for the arrangement and installation of engines, equipment and systems for gas or low-flashpoint fuelled vessels with the aim to reduce risks for the vessel, its crew and environment (DNV-GL, 2015b; IMO, n.d.-e).

In addition, several classification societies have also developed a framework and rules for minimising risks of gas-fuelled vessels. These rules offer a clear guidance for building LNG-fuelled vessels and new components of their storage and handling systems (DNV-GL, 2015b). The most common rules and guidelines developed by classification societies are the following:

- DNV-GL Rules for Gas Fuelled Ship Installations
- American Bureau of Shipping (ABS) Guide for Propulsion And Auxiliary Systems For Gas Fuelled Ships
- Bureau Veritas Safety Rules for Gas-Fuelled Engine Installations in Ships
- Germanischer Lloyd (GL) Guidelines for Gas as Ship Fuel

These standards and rules specify arrangements for the installation of engines, equipment and systems for gas-fuelled vessels. However, the principal installations defined are the inherently gas safe machinery space, the emergency shutdown (ESD) protected machinery space and the gas fuel storage tanks (Osberg, 2008).

3.1.1 Inherently Gas Safe Machinery Space

An inherently gas safe machinery space is considered gas safe under all conditions (DNV-GL, 2014b). All natural gas supplying pipes in the engine room have to be enclosed in a double wall pipe/duct able to withstand pressure build-up in case of pipe break. Double wall pipes/ducts shall be either equipped with a ventilation system and a gas detector, or filled with inert gas and fitted with pressure monitoring. An inherently gas safe machinery space is compulsory for high-pressure piping (> 10 bars), although, it can also be used with low-pressure installations (Andersen, 2015; Osberg, 2008).

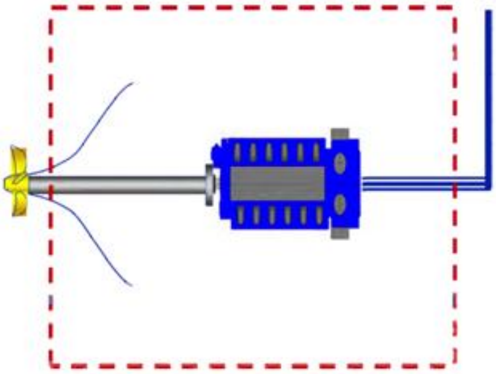


Figure 3.1: Arrangement of an inherently gas safe machinery space (Source: Andersen, 2015).

3.1.2 Emergency Shutdown (ESD) Protected Machinery Space

An ESD protected machinery space is considered non-hazardous under normal conditions, but under certain abnormal conditions may have the potential to become hazardous (DNV-GL, 2014b). Natural gas supplying pipes in the engine room can be enclosed in a single wall pipe/duct. Nevertheless, propulsion engines and electric power engines shall be placed in two or more machinery spaces, and in the event of shutdown, sufficient fuel supply could be maintained to any machinery space, gas supply pipes pressure shall be lower than 10 bars and machinery spaces shall be equipped with gas detection systems able to automatically shutdown fuel supply and electrically disconnect non-explosion protected systems in the machinery space (DNV-GL, 2014b).

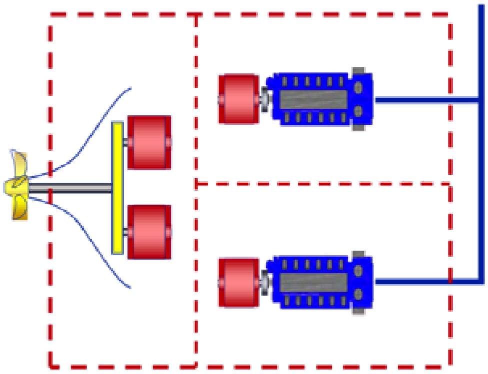


Figure 3.2: Arrangement of ESD protected machinery spaces (Source: Andersen, 2015).

3.1.3 Gas Fuel Storage Tanks

LNG fuel storage tanks shall be independent or membrane tanks designed in accordance with the IGC code and fitted with efficient insulation. LNG fuel storage tanks can be placed above or bellow deck. According to the IGF code (IMO, 2014a), LNG fuel tanks on open deck shall be placed to assure natural ventilation so as to avoid accumulation of gas in case of leakage. Whereas, LNG fuel tanks in enclosed space shall be protected from external damage and located as close as the centreline of the vessel: minimum, the lesser of B[2]/5 and 11.5 m from the shipside; minimum, the lesser of B/15 and 2 m from the bottom; and not less than 760 mm from the shell plating (IMO, 2014a).

---

[2] B = Breadth: means the maximum breadth of the ship measured in metres.

Chapter 4. Main LNG-Fuelled Vessel Segments

LNG as marine fuel has been proved to be an attractive alternative to meet MARPOL Annex VI air pollution regulations because of low gases emissions (NO_X, SO_X and PM emissions), the relative low price of LNG compared to traditional marine fuels in some markets and its worldwide availability (Adamchak & Adede, 2013; DNV-GL, 2015b). Moreover, engine manufacturers have already developed a vast variety of LNG-fuelled engines, such as lean-burn gas engines and DF engines, and have also designed and produced LNG storage and handling systems on board vessels. Furthermore, LNG bunkering facilities already exist in areas where strict air pollution restrictions are in force, such as Baltic Sea and North Sea areas, and new LNG infrastructure projects are proposed and developed along the main shipping areas. For these reasons, the number of vessels using LNG as fuel is increasing fast. As of March 2016, 77 LNG-fuelled vessels, excluding LNG carriers and inland waterway vessels, operate worldwide and another 85 LNG-fuelled new buildings are confirmed (DNV-GL, 2016a). According to DNV-GL (DNV-GL, 2015b), the LNG-fuelled fleet will grow even more rapidly over the next decade, initially in areas with existing bunkering facilities and LNG as marine fuel will continue to progress as we head towards 2020, reaching the number of 1,000 LNG-fuelled vessels at that time or shortly after. However, studies show that the demand for LNG-fuelled vessels depends on many factors, being rather difficult to determine a trustworthy growth rate. As a result, studies present different scenarios based on the global economic growth and air pollution regulations (LNG Fuelled Vessels Working Group, n.d.-b, n.d.-c).

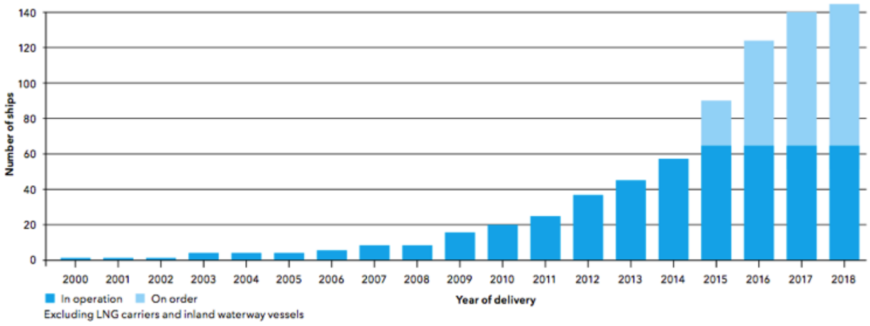


Figure 4.1: Development of LNG-fuelled fleet from 2000 to 2018 as of May 2015 (Source: DNV-GL, 2015b).

Nowadays, the main vessel segments that dominate the LNG-fuelled fleet are ferries, platform supply vessels (PSV), harbour tugs and gas carriers. Despite the fact that ferries and PSV are the predominant segments of the current LNG-fuelled fleet, trends in the LNG-fuelled fleet order book evidence that the number of large vessels, such as containerships and product tankers, will grow significantly. However, most LNG-fuelled vessels will operate in the north of EU and North America as a result of the ECAs (DNV-GL, 2015b; LNG Fuelled Vessels Working Group, n.d.-b).

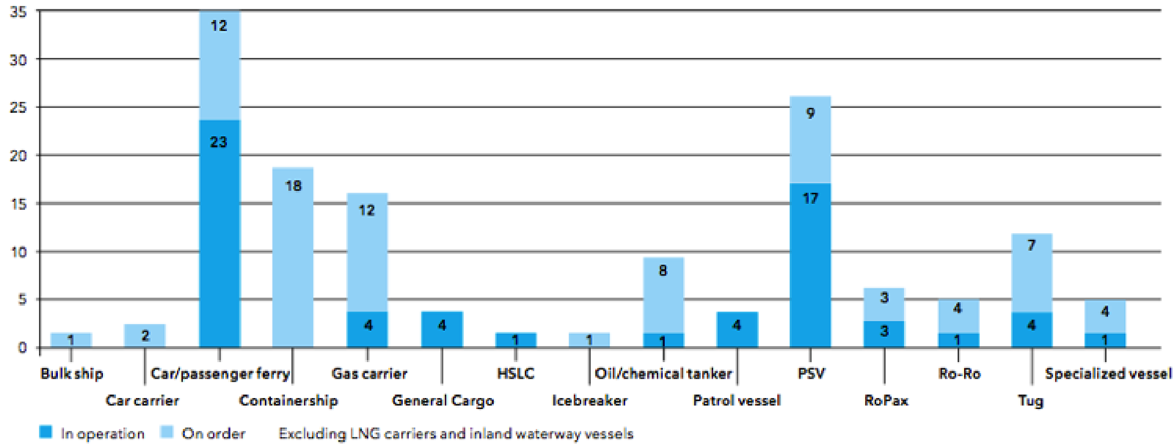


Figure 4.2: Development of LNG-fuelled fleet per segments as of May 2015 (Source: DNV-GL, 2015b).

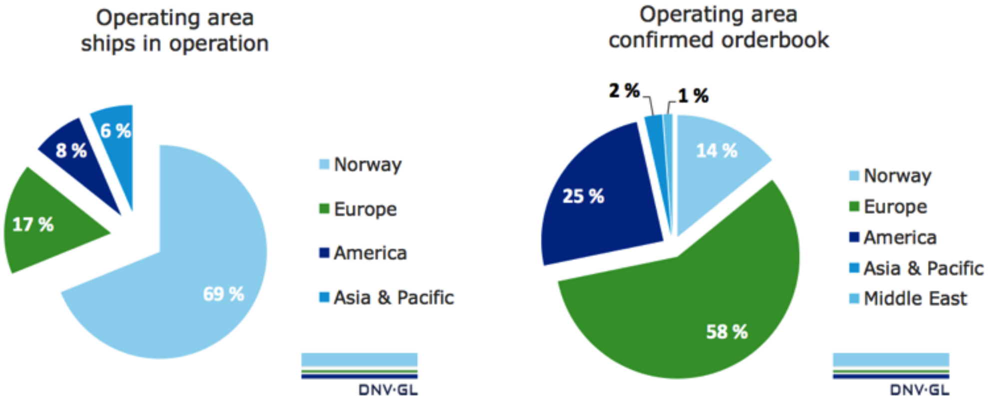


Figure 4.3: Operating areas of LNG-fuelled vessels as of March 2016 (Source: DNV-GL, 2016a).

Therefore, the most predominant segments of LNG-fuelled vessels, both in operation and on order, are car/passenger ferries, PSV, harbour tugs, gas carriers and containerships. For this reason, these types of vessels are going to be explained in more detail in the following points.

4.1 Car/Passenger Ferries

Ferries are designed to carry passengers and their vehicles usually on fixed routes through coastal waters, for example Baltic Sea, North Sea, North America and United States Caribbean Sea, which are ECAs (Kluijven, 2003). Supplying this type of vessels with LNG as marine fuel seems to be a feasible option because of operational, regulatory and economic reasons (IMO, 2016a). LNG-fuelled ferries represent the biggest segment in the LNG-fuelled fleet, since there are 26 LNG-fuelled ferries in operation and 12 LNG-fuelled ferries on order as of March 2016 according to DNV-GL (DNV-GL, 2016a). One of the most relevant LNG-fuelled ferries currently in operation is the Viking Grace, since she is the largest LNG-fuelled passenger vessel (Wärtsilä, n.d.-b).

4.1.1 Viking Grace

The Viking Grace is a combined Ro-Ro and passenger ferry powered with LNG. The ferry was built in STX Turku yard (Finland) and was delivered in January 2013. Viking Line operates the vessel, which covers the trans-Baltic route between the southwest Finish port of Turku and Stockholm (Sweden) (IMO, 2016a; Wärtsilä, n.d.-b).

Figure 4.4: Viking Grace (Source: Wärtsilä, n.d.-b).

Viking Grace	
Vessel Type	Passenger/Ro-Ro Ferry
IMO Number	9606900
Call Sign	OJPQ
MMSI	230629000

Shipyard	STX Turku (Finland)
Year of Build	2013
Owner	Viking Line Abp (Finland)
Length Over All (LOA)	218.60 m
Breadth	31.80 m
Draught	6.80 m
Depth to main deck	13.80 m
Gross Tonnage (GT)	57,565 GT
Net Tonnage (NT)	38,039 NT
Dead Weight Tonnage (DWT)	6,107 Tons
Flag	Finland
Classification Society	Lloyd's Register
Main Engine	4 x Wärtsilä 8L50DF
Total Installed Power	30,400 kW
Maximum Speed	25.6 Knots

Table 4.1: Viking Grace ship particulars (Source: Equasis, n.d.; Wärtsilä, n.d.-b).

The Viking Grace is operated by 200 crewmembers and has a capacity of 2,800 passengers, with a total of 880 cabins. She has a lane load capacity of 1,275 m, plus 500 m on deck 4 and 500 m on deck 5 for passenger cars. In addition, the hull has been strengthened and hydro-dynamically optimised based on 1A Super ice-class in order to be able to operate in ice waters during Baltic winter conditions (Equasis, n.d.; Wärtsilä, n.d.-b, n.d.-e).

The vessel is supplied with LNG every day due to limited supply of LNG at Port of Stockholm. LNG bunkering operations are performed when the vessel is loading or unloading passengers and cargoes, and take place at sea side through a LNG-bunkering barge without interfering operational activities. LNG bunkering lasts 45 minutes, whereas, loading an unloading operations last one hour. Therefore, LNG bunkering activities does not delay vessel schedule. The RoPax ferry operates 21.5 h per day during 300 days per year (6,450 h/year) (Faber et al., 2015).

Figure 4.5: Viking Grace undergoing LNG bunkering operations at Port of Stockholm (Source: Faber et al., 2015).

Propulsion System

Viking Grace propulsion system is designed based on a DF-electric concept. The ferry is equipped with four Wärtsilä 8L50DF engines with 8 cylinders in line and a power output of 7,600 kW each (Total power output 30,400 kW). Four Wärtsilä engines drive alternators, which supply two propulsion motors of 10,500 kW each (Total propulsion power 21,000 kW) and other services with electric power. The two propulsion motors drive two stainless steel fixed-pitch main propellers through two complete propeller shaft lines with shaft-line seal systems. The vessel has two independent engine rooms, which offer a high degree of redundancy (Wärtsilä, n.d.-b).

Figure 4.6: Wärtsilä 8L50DF engine on board Viking Grace (Source: Wärtsilä n.d.-b).

Furthermore, the Viking Grace is fitted with two bow thrusters of 2,300 kW each and one stern thruster of 1,5000 kW (Wärtsilä, n.d.-b). Vessel engines develop a service speed of 21.8 knots and their consumption of LNG per day is 126 m^3. Annually, the ferry is supplied with 38,200 m^3 of LNG and 340 tons of MGO (Faber et al., 2015).

LNG is stored in two stainless steel vacuum tanks with a fuel capacity of 200 m^3 each. Both, LNG fuel tanks and gas supply system compose the LNGPac system developed by Wärtsilä. LNG storage tanks are located at the aft of the ship in an open area above the stern ramp. Moreover, no loading space was lost due to the space used by the tanks (Wärtsilä, n.d.-b).

Environment Benefits

Wärtsilä DF engines allow the Viking grace to reduce significantly exhaust gas emissions. SO_X emissions are eliminated, PM emissions are minimised 90%, NO_X emissions are 80% lower than NO_X Tier III limits and CO_2 emissions are reduced 20-30%. In addition, engines do not emit exhaust odours and soot, and engine noise levels are fairly low. Wärtsilä DF engines enable the Viking Grace to operate in ECAs without restrictions (Faber et al., 2015).

4.2 Platform Supply Vessels (PSV)

PSV are designed to supply oilrigs with stores, goods for domestic use and spare parts (Kluijven, 2003). Depending on their operational areas, this type of vessel could navigate in ECAs. A significant number of PSV is currently operating in the North Sea, and as it is an ECA, they are supplied with LNG as marine fuel (IMO, 2016a). LNG-fuelled PSV represent an important segment in the LNG-fuelled fleet, since there are 18 LNG-fuelled PSV in operation and 8 LNG-fuelled PSV on order as of March 2016 according to DNV-GL (DNV-GL, 2016a). One of the most relevant LNG-fuelled PSV currently in operation is the Viking Energy, since she is the first LNG-fuelled PSV (Wärtsilä, n.d.-c).

4.2.1 Viking Energy

The Viking Energy is a PSV powered with LNG whose hull and superstructure were built in Maritim Shipyard (Poland), and then was outfitted in Kleven Verft AS Ulsteinvik (Norway). The vessel was delivered in April 2003 and is chartered by Statoil for delivering supplies to oil and gas platforms in the North Sea. The PSV has her homeport in Haugesund (Norway) (Wärtsilä, n.d.-c, n.d.-d).

Figure 4.7: Viking Energy (Source: Eidesvik, n.d.).

Viking Energy	
Vessel Type	PSV
IMO Number	9258442
Call Sign	LLVY
MMSI	258390000
Shipyard	Kleven Verft AS Ulsteinvik (Norway)
Year of Build	2003
Owner	Eidesvik Shipping AS
Length Over All (LOA)	94.90 m
Breadth	20.40 m
Draught	7.90 m
Depth to main deck	9.60 m
Gross Tonnage (GT)	5,073 GT
Net Tonnage (NT)	1,521 NT
Dead Weight Tonnage (DWT)	6,013 Tons
Flag	Norway
Classification Society	DNV-GL
Main Engine	4 x Wärtsilä 6L32DF

Total Installed Power	8,040 kW
Maximum Speed (Loaded)	16.0 Knots

Table 4.2: Viking Energy ship particulars (Source: Wärtsilä, n.d.-c).

The Viking Energy was designed by Vik-Sandvik according to demands for reducing GHG emissions and is operated by 24 crewmembers accommodated in 12 single cabins and 6 double cabins. She has a deck area of 1,030 m^2 with a maximum deck load of 3,700 tons. Regarding her deck equipment, the vessel is fitted with two capstans, two towing winches and two cranes. Moreover, she has loading and unloading stations for all types of liquid and dry bulk cargo on both sides aft and amidships, and is equipped with separate pumps and piping systems for all types of liquid cargo (Wärtsilä, n.d.-c).

Figure 4.8: Viking Energy (Source: Wärtsilä, n.d.-d).

The PSV has several cargo tanks for supplying Statoil North Sea platforms with a wide range of materials. She can carry 1,100 m^3 of fuel oil, 1,100 m^3 of potable water, 2,080 m^3 of drill/ballast water, 410 m^3 of methanol, 860 m^3 of liquid mud, 430 m^3 of dry bulk, 815 m^3 of brine, 220 m^3 of base oil and 208 m^3 of special products (Eidesvik, n.d.).

Propulsion System

Viking Energy propulsion system is designed based on a DF-electric concept. The PSV is equipped with four Wärtsilä 6L32DF engines with 6 cylinders in line and a power output of 2,010 kW each (Total power output 8,040 kW). Four Wärtsilä engines drive four main generator sets, which supply two contra-rotating stern thrusters of 3,000 kW each (Total propulsion power 6,000 kW) and other services with electric power (Wärtsilä, n.d.-c).

Furthermore, the Viking Energy is fitted with two bow thrusters of 1,000 kW each, one azimuthing retractable thruster of 880 kW and one emergency generator set of 116 kW. Vessel engines develop a service speed of 16 knots in loaded condition and this type of propulsion drives minimise noise and vibration (Wärtsilä, n.d.-c).

LNG is stored in a horizontal cylindrical tank with domed ends, it is made of stainless steel and consists of an inner and outer chamber that insulate LNG at -162°C. The storage tank is located in the middle of the vessel and has an effective fuel capacity of 220 m^3. In addition, the tank is placed in a compartment protected with fire insulation, and gas lines and valves are covered with ventilated sheaths (Wärtsilä, n.d.-c).

The gas supply system consists of a hot water vaporizer unit that vaporizes LNG and supplies engines with natural gas at 20°C and 5 bars, and another smaller unit that boils LNG to maintain the right pressure in the fuel tank (Wärtsilä, n.d.-c).

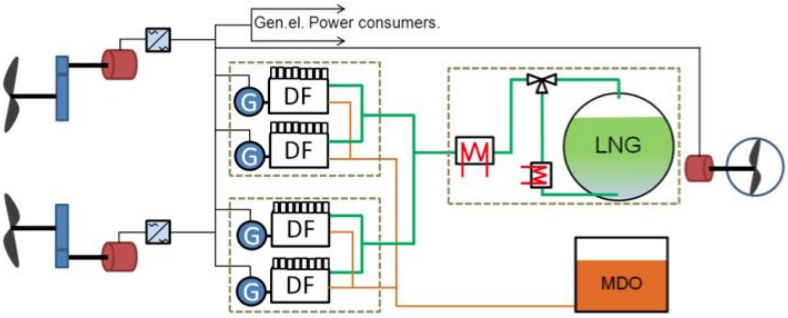


Figure 4.9: Diagram of Viking Energy propulsion system (Source: Stenersen, 2011).

Environmental Benefits

Wärtsilä DF engines allow the Viking Energy to operate on either gas mode or diesel mode. When working in gas mode, SO_X and PM emissions are eliminated, NO_X emissions are reduced 90% and CO_2 emissions are minimised 30%. Furthermore, engines in gas mode have a fuel economy rate of 30% better than that in diesel mode. Wärtsilä DF engines enable the Viking Energy to operate in ECAs without restrictions (Wärtsilä, n.d.-c).

4.3 Harbour Tugs

Harbour tugs are designed to assist other vessels in entering or leaving the port, especially berthing manoeuvres of large vessels with a limited manoeuvring capacity (Kluijven, 2003). Depending whether their harbour of operation is located in ECAs, this type of vessel could be subject to meet air pollution regulations. LNG-fuelled harbour tugs are a significant segment in the LNG-fuelled fleet, since there are

6 LNG-fuelled harbour tugs in operation and 5 LNG-fuelled harbour tugs on order as of March 2016 according to DNV-GL (DNV-GL, 2016a). One of the most relevant LNG-fuelled harbour tug currently in operation is the Borgøy, since she is the first LNG-fuelled tugboat (Sanmar A.S., n.d.).

4.3.1 Borgøy

The Borgøy is a harbour tug powered with LNG. The tugboat was built in Sanmar Denizcilik A.S. shipyard (Turkey) together with her sister vessel Bokn, and was delivered in 2014. Buksér og Berging AS operates the vessel, which is nowadays in service at Statoil's Kaarstoe terminal. The harbour tug has her homeport in Haugesund (Norway) (Buksér og Berging AS, n.d.; DNV-GL, n.d.-a).

Figure 4.10: Borgøy and her sister vessel Bokn (Source: Sanmar A.S., n.d.).

Borgøy	
Vessel Type	Tug
IMO Number	9662112
Call Sign	LDII
MMSI	259246000
Shipyard	Sanmar Denizcilik AS shipyard (Turkey)
Year of Build	2014
Owner	Buksér og Berging AS
Length Over All (LOA)	35.00 m

Breadth	15.40 m
Draught	5.50 m
Depth to main deck	7.50 m
Gross Tonnage (GT)	765 GT
Net Tonnage (NT)	229 NT
Dead Weight Tonnage (DWT)	150 Tons
Flag	Norway
Classification Society	DNV-GL
Main Engine	2 x Bergen C26:33L6PG
Total Propulsion Power	3,410 kW
Service Speed	13.5 Knots

Table 4.3: Borgøy ship particulars (Source: DNV-GL, n.d.-a; Sanmar A.S., n.d.).

The Borgøy was designed for escort, harbour, oil recovery and emergency towing operations, and is operated by 6 crewmembers accommodated in two single officer cabins and 2 double crew cabins. The tugboat has an optimised hull design, which together with the propulsion system offers a 20% higher thrust efficiency compared to standard designs. Talking about her towing features, the harbour tug has a steering force of 100 tons at 10 knots and a static bollard pull of approximately 70 tons. Regarding her deck equipment, the vessel is fitted with a main hydraulic towing winch developed by Karmoy with a brake load capacity of 250 tons. Moreover, the vessel is equipped with fire-fighting (Fi-Fi) and oil recovery systems and a deck crane (Sanmar A.S., n.d.).

Propulsion System

Borgøy propulsion system is designed based on a gas-mechanical concept. The tugboat is equipped with two Bergen C26:33L6PG engines with 6 cylinders in line and a power output of 1,705 kW at 1,000 rpm each (Total propulsion power 3,410kW). The two lean-burn gas engines drive two Rolls Royce azimuthing Z-drives mounted in an azimuth stern drive (ASD) configuration. The main engines offer high efficiency, low energy consumption, long intervals between overhaul, high degree of reliability and reduce exhaust emissions. Furthermore, the Borgøy is fitted with a bow thruster of 333 kW and a generator set of 240 kW. Vessel engines develop a service speed of 13.5 knots (Sanmar A.S., n.d.).

LNG is stored in a double walled tank with a fuel capacity of 80 m^3 and is located in the middle of the vessel. The LNG storage and handling system has been developed by AGA Cryo, comprises a bunkering station, gas supplying system and fuel tank; and does not require diesel back up (Sanmar A.S., n.d.).

Figure 4.11: Borgøy propulsion system (Source: Buksér og Berging AS, n.d.).

Environmental Benefits

Rolls Royce lean-burn gas engines allow the Borgøy to reduce significantly exhaust gas emissions. SO_X emissions are eliminated, PM emissions are reduced 98%, NO_X emissions are decreased 92% and CO_2 emissions are minimised 20%. In addition, engine sound levels have also been lowered. Rolls Royce lean-burn gas engines are compliant with Tier III regulations and enable the Borgøy to operate in ECAs without restriction (Sanmar A.S., n.d.).

4.4 Gas Carriers

Gas carriers are designed to carry liquefied gases, such as natural gas, petroleum gas, and ethylene, among others. LNG carriers use the natural boil-off of the LNG stored in their cargo tanks to supply their steam turbines. However, new gas carriers are fitted with DF engines, which allow them to operate either with LNG or other marine fuels, e.g. MDO (IMO, 2016a). LNG-fuelled gas carriers represent a considerable segment in the LNG-fuelled fleet, since there are 7 LNG-fuelled gas carriers in operation and 12 LNG-fuelled gas carriers on order as of March 2016 according to DNV-GL (DNV-GL, 2016a). Two of the most relevant LNG-fuelled gas carriers currently in operation are the Coral Energy, which is the first LNG-fuelled gas carrier powered with DF engines; and the Coral Star, which is the first LNG-fuelled liquefied ethylene gas (LEG) carrier powered with DF engines (SABIC, 2016; Wärtsilä, n.d.-a).

4.4.1 Coral Energy

The Coral Energy is a LNG carrier fitted with a DF-mechanic engine. The gas carrier was built in Meyer Werft GmbH & Co. KG (Germany) and was delivered in January 2013. Anthony Veder operates the vessel, which carries LNG from Rotterdam, Zeebrugge and Norway to Stockholm (Sweden), among other cities (Anthony Veder, n.d.).

Figure 4.12: Coral Energy (Source: Anthony Veder, n.d.).

Coral Energy	
Vessel Type	Gas carrier
IMO Number	9617698
Call Sign	PCQG
MMSI	246878000
Shipyard	Meyer Werft GmbH & Co. KG (Germany)
Year of Build	2013
Owner	Coral Energy Shipping BV
Length Over All (LOA)	155.64 m
Breadth	22.70 m
Draught	7.35 m
Depth to main deck	14.95 m
Gross Tonnage (GT)	13,501 GT
Net Tonnage (NT)	4,050 NT

Dead Weight Tonnage (DWT)	12,268 Tons
Flag	Netherlands
Classification Society	Bureau Veritas
Main Engine	1 x Wärtsilä 8L50DF
Total Propulsion Power	7,800 kW
Service Speed	15.8 Knots

Table 4.4: Coral Energy ship particulars (Source: Bureau Veritas, n.d.-a; Wärtsilä, n.d.-a).

The Coral Energy has three independent C-type horizontal bi-lobe tanks with a total cargo capacity of 15,600 m^3. The tanks have a design pressure of 4.2 bars and a design temperature of -163°C. The vessel is equipped with six cargo pumps with a feed rate of 270 m^3/h with LNG at -163°C and a maximal specific weight of 0.50 T/m^3, which enable a loading/unloading rate with vapour return line of 1,620 m^3/h. Furthermore, the vessel has been built according to ice-class 1A LNG carrier so as to be able to operate in tough winter conditions and has accommodation for 26 crewmembers divided into 25 cabins (Bureau Veritas, n.d.-a; Wärtsilä, n.d.-a).

Propulsion System

Coral Energy propulsion system is designed based on a DF-mechanic concept. The LNG carrier is equipped with one Wärtsilä 8L50DF engine with 8 cylinders in line and a power output of 7,800 kW at 514 rpm. The main propulsion engine drives a Wärtsilä controllable pitch propeller (CPP) via a gearbox. Moreover, the Coral Energy is fitted with a bow thruster of 850 kW, and two auxiliary engines Wärtsilä 6L20DF with 6 cylinders in line and a power output of 1,056 kW each, which drive the alternators. The vessel engine develops a service speed of 15.8 knots (Wärtsilä, n.d.-a).

LNG is stored in the cargo tanks, as she is a LNG carrier, and natural boil-off is used to fuel DF engines. However, the fuel gas supply system uses a vaporizer to heat up the gas (Wärtsilä, n.d.-a).

Environmental Benefits

Wärtsilä DF engine allows the Coral Energy to decrease CO_2 emissions more than 15% and reduce considerably NO_X, SO_X and PM emissions. Wärtsilä DF engine enables the Coral Energy to operate in ECAs without restrictions. In addition, DF-mechanic concept increases fuel efficiency making the Coral Energy one of the cleanest LNG carriers available nowadays (Anthony Veder, n.d.).

4.4.2 Coral Star

The Coral Star is a LEG carrier fitted with a DF-mechanic engine. The gas carrier was built in AVIC Dingheng Shipbuilding Co., Ltd. (China) and was delivered in July 2014. Anthony Veder operates the vessel, which carries LEG from SABIC's Wilton facility on Teesside (United Kingdom) to manufacturing plants in North-West Europe and Scandinavia (Bureau Veritas, n.d.-b; SABIC, 2016).

Figure 4.13: Coral Star (Source: SABIC, 2016).

Coral Star	
Vessel Type	Gas carrier
IMO Number	9685499
Call Sign	PCUP
MMSI	244790522
Shipyard	AVIC Dingheng Shipbuilding Co., Ltd. (China)
Year of Build	2014
Owner	Coral Star Shipping BV
Length Over All (LOA)	99.95 m
Breadth	17.20 m
Draught	6.85 m
Depth to main deck	9.80 m
Gross Tonnage (GT)	5,831 GT
Net Tonnage (NT)	1,749 NT

Dead Weight Tonnage (DWT)	3,604 Tons
Flag	Netherlands
Classification Society	Bureau Veritas
Main Engine	1 x Wärtsilä 6L34DF
Total Propulsion Power	2,700 kW
Service Speed	13.5 Knots

Table 4.5: Coral Star ship particulars (Source: Bureau Veritas, n.d.-b).

The Coral Star has two independent C-type horizontal tanks with a total cargo capacity of 4,700 m^3. The tanks have a design pressure of 6.0 bars and a design temperature of -104°C. The vessel is equipped with two cargo pumps with a feed rate of 300 m^3/h, which enable a loading/unloading rate of 600 m^3/h (AVIC Dingheng Shipbuilding Co., n.d.; SABIC, 2015).

Propulsion System

Coral Star propulsion system is designed based on a DF-mechanic concept. The LNG carrier is equipped with one Wärtsilä 6L34DF engine with 6 cylinders in line and a power output of 2,700 kW at 750 rpm. The main propulsion engine drives a CPP via a gearbox. Moreover, the Coral Energy is fitted with a bow thruster of 450 kW, and two auxiliary engines Wärtsilä 6L20DF with 6 cylinders in line and a power output of 1,056 kW each, which drive the alternators. The vessel engine develops an average speed of 13.5 knots (Bureau Veritas, n.d.-b; SABIC, 2015).

LNG is stored in two fuel tanks located above the deck with a LNG capacity of 100 m^3 each. The LEG carrier is supplied with LNG every two weeks by a truck (SABIC, 2016).

Environmental Benefits

Wärtsilä DF engine allows the Coral Star to reduce significantly exhaust gas emissions. SO_X and soot particles are almost eliminated, NO_X emissions are reduced 85% and CO_2 emissions are decreased 20%. Wärtsilä DF engine enables the Coral Star to operate in ECAs without restrictions (SABIC, 2015).

4.5 Containerships

Containerships are designed to carry goods packed in containers and are usually operated on a liner service. This type of vessels has a wide variety of sizes that ranges from small feeders to ultra large containerships and LNG-fuelled containership designs have started to grow in the LNG-fuelled vessel market. Nevertheless, LNG fuel tanks size seems to be the main concern for large containerships due to the lost of cargo space as a result of their bigger size (IMO, 2016a). LNG-fuelled containerships represent a potential segment in the LNG-fuelled fleet, since there are 2 LNG-fuelled containerships in operation and 13 LNG-fuelled containerships on order as of March 2016 according to DNV-GL (DNV-GL, 2016a). One of the most relevant LNG-fuelled containership currently in operation is the Isla Bella, since she is the first LNG-fuelled containership (TOTE Inc., 2012).

4.5.1 Isla Bella

The Isla Bella is containership powered with LNG and fitted with a DF engine. The containership was built in General Dynamics NASSCO (US) together with her sister vessel Perla del Caribe, and was delivered in October 2015. Sea Star Line operates the vessel, which covers the route from Jacksonville (Florida) to San Juan (Puerto Rico). Both vessels were built to cover this Puerto Rican trade route and replace company's vessels serving this route (TOTE Inc., 2012).

Figure 4.14: Isla Bella (Source: TOTE Inc., 2012).

Isla Bella	
Vessel Type	Containership
IMO Number	9680841
Call Sign	WTOI
MMSI	338760000
Shipyard	General Dynamics NASSCO (US)
Year of Build	2015

Owner	TOTE Shipholdings, Inc.
Length Over All (LOA)	233.00 m
Breadth	32.20 m
Draught	10.36 m
Depth to main deck	18.30 m
Gross Tonnage (GT)	36,751 GT
Net Tonnage (NT)	11,025 NT
Dead Weight Tonnage (DWT)	33,106.1 Tons
Flag	United States of America
Classification Society	American Bureau of Shipping
Main Engine	1 x MAN 8L70ME-C8.2-GI
Total Propulsion Power	25,191 kW
Speed	22.0 Knots

Table 4.6: Isla Bella ship particulars (Source: American Bureau of Shipping, n.d.; TOTE Inc., 2012).

The Isla Bella has a cargo capacity of 3,100 Twenty Feet Equivalent Units (TEUs) and her optimized design allow a higher cargo capacity in comparison to the previous vessels. Furthermore, the containership is able to carry a large volume of refrigerated containers (TOTE Inc., 2012).

Propulsion System

Isla Bella propulsion system is designed based on a DF-mechanic concept. The containership is equipped with one MAN 8L70ME-C8.2-GI engine with 8 cylinders in line and a power output of 25,191 kW at 104 rpm, which drives the propeller via a gearbox. Moreover, the Isla Bella is fitted with three auxiliary engines HFJ7 638-10P with a power output of 1,740 kW each. The vessel engine develops an average speed of 22.0 knots (American Bureau of Shipping, n.d.; TOTE Inc., 2012).

LNG is stored in two stainless steel cryogenic tanks with a total fuel capacity of 900 m^3 and are located at the aft of the ship. Bunkering operations are performed when the vessel is undergoing cargo operations and take at shore side through several LNG-bunkering trucks. Bunkering procedures allow simultaneous LNG transfer from four LNG-bunkering trucks at the same time in order to reduce bunkering time (Ship Technology, n.d.; TOTE Inc., 2016).

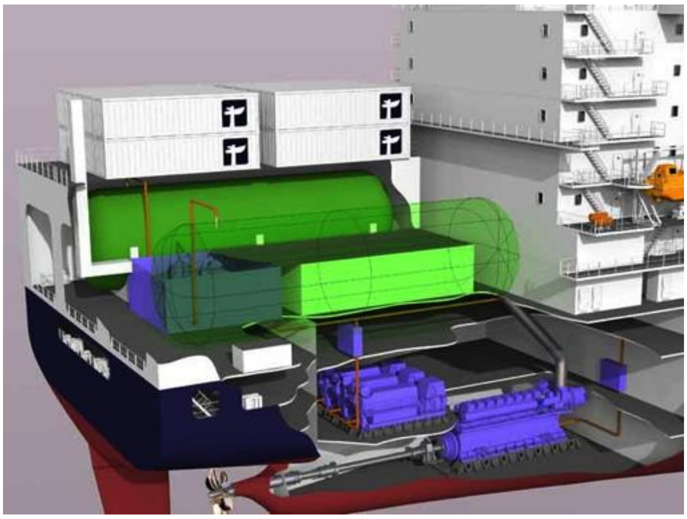


Figure 4.15: Isla Bella propulsion system (Source: Ship Technology, n.d.).

Environmental Benefits

MAN DF engines allow the Isla Bella to reduce drastically exhaust gas emissions. SO_X emissions are decreased 98%, PM emissions are almost eliminated (reduced 99%), NO_X emissions are lowered 91% and CO_2 emissions are minimised 71% compared with the previous vessels engaged in the route. MAN DF engines enable the Isla Bella to increase fuel efficiency and operate in ECAs without restrictions (TOTE Inc., 2012).

Chapter 5. Potential for LNG-Fuelled Vessels

LNG-fuelled vessels comply with latest air pollution regulations. However, utilization of LNG as marine fuel appears to be more attractive and advantageous for certain vessel segments. Moreover, supplying vessel engines with LNG presents both economic and environmental long-term benefits. Upcoming LNG-fuelled vessel projects expect high benefits and will trigger the development of LNG infrastructure in areas with high operation of LNG-fuelled vessels and safety standards. LNG as marine fuel is an attractive commercial solution for both, new building LNG-fuelled vessels and existing vessels, although, retrofitting of existing vessels require a high investment because of the installation of LNG fuel tanks and major modifications in the engine room. For this reason, most of LNG-fuelled vessels will be new building projects (IMO, 2016a).

All types of vessels are able to implement LNG, but certain vessel segments are more likely to do it due to their operational characteristics. The following features drive the introduction of LNG on board vessels:

- Operational time inside ECAs
- Coasters and local vessels
- Fuel cost sensitivity
- Capacity to accommodate LNG fuel equipment
- LNG cost and availability
- Retrofitting possibilities
- Fleet update perspectives
- Liner vessels
- Environmentally friendly profile

LNG-fuelled vessel potential depends on these features, vessels with operational characteristics matching these features will present a high potential for fuelling their engines with LNG (IMO, 2016a).

5.1 Operational Time Inside ECAs

Currently, vessels engaged in short sea shipping (SSS) routes are the ones that spend more time inside ECAs. Vessels operating in ECAs are subject to the most stringent air pollution regulations, though, they foresee meaningful economic benefits. As a result, vessels spending more than 30-40% of their operational time inside ECAs present a favourable ROI of their capital expenditures (CAPEX). Vessel segments that match this operational feature are tankers, general cargo ships, containerships, RoPax ferries and cruise vessels spending certain time in ECAs (IMO, 2016a).

5.2 Coasters and Local Vessels

These types of vessels are designed for working in a specific area or harbour, such as ferries, tugs and offshore service vessels (OSV). Depending whether their area or harbour of operation is located in ECAs, these types of vessels could work all the time under most stringent air pollution regulations. In addition, CAPEX on account of LNG implementation could be high due to their smaller size (IMO, 2016a).

5.3 Fuel Cost Sensitivity

For those vessels that operational costs and CAPEX are low in comparison to fuel costs, savings in fuel costs could rapidly balance the investment required to install LNG equipment. However, in some cases ship owners are not interested in building LNG-fuelled vessels because of fuel costs are chargeable to charterers (IMO, 2016a).

5.4 Capacity to Accommodate LNG Fuel Equipment

One of the most important challenges of using LNG as fuel is the bigger size of LNG fuel tanks, since they require more space (around 3-4 times) than the equivalent MDO tanks. The IGF code, together with classification societies rules, establishes the location and arrangements of fuel tanks, and as a result, vessels require enough space to install large LNG tanks and minimise the loss of cargo volume (IMO, 2016a).

5.5 LNG Cost and Availability

LNG as marine fuel is commercially attractive because of its low price compered to the main marine fuel oils used on board vessels, e.g. HFO, IFO, MDO and MGO. Nevertheless, LNG price varies between different ports and regions, as price in EU or Asia differs from the one in US. Furthermore, LNG availability varies among the different regions, since most of the LNG bunkering facilities is located in ECAs. LNG-fuelled vessels, such as tankers, containerships, car carriers and bulk carriers, have to take into account LNG availability at their operating harbours and bunkering regulations and methods (IMO, 2016a).

5.6 Retrofitting Possibilities

LNG as marine fuel is a feasible solution for both, new building LNG-fuelled vessels and existing vessels, although, retrofitting of existing vessels require a high investment. Nonetheless, several vessel segments have a significant potential for retrofitting to LNG, since new building costs in certain regions, e.g. US, are quite high (IMO, 2016a).

5.7 Fleet Update Perspectives

Certain types of vessels foresee to have a relevant increase and demand for using LNG as marine fuel. Owing to their operational characteristics, the number of OSV, containerships and oil/product tankers supplied with LNG is expected to increase significantly (IMO, 2016a).

5.8 Liner Vessels

Merchant vessels operate in accordance with their trading patterns and charter parties, and they can be classified as liner or tramps. Liner vessels carry cargoes between fixed ports on a prearranged sailing schedule, whereas, tramp vessels carry cargoes from one port to another without a prearranged schedule. The number of liner and tramp vessels varies among the different types of vessels. Due to the lack of LNG infrastructure worldwide, vessels engaged in liner services are more suitable to be supplied with LNG given that they operate between two fixed ports (IMO, 2016a).

5.9 Environmentally Friendly Profile

LNG-fuelled engines contribute to reduce exhaust gas emissions allowing to perform environmentally sustainable operations. Nowadays, some shipping segments, like cruise or passenger vessels, look for these environmentally friendly values and consider the use of LNG as marine fuel. Another segment is PSV, which takes advantage of sustainability bonuses from charterers (IMO, 2016a).

As a result, vessels operating most of their time in ECAs and those engaged in SSS routes, like ferries, PSV, container/Ro-Ro vessels and tankers, will be the first vessel segments in implementing LNG as marine fuel. In US, most of LNG-fuelled vessels on order are ocean-going vessels, whereas in EU, the majority of LNG-fuelled vessels in operation are regional ferries and PSV (IMO, 2016a).

In the whole then, LNG as marine fuel is an attractive and feasible option to meet air pollution regulations. Owing to there are several alternatives to comply with vessel emissions limits, ship owners and operators base their decisions on a financial comparison of solutions, among other factors. When analysing the financial feasibility, decision makers take into account equipment costs, operational time inside ECAs and LNG price. Moreover, compliance strategy decisions depend on forthcoming air pollution regulations, since the deferment of the global sulphur content limit until 2025 will affect the increase of LNG as marine fuel and future worldwide LNG availability (IMO, 2016a).

Chapter 6. Upcoming Air Pollution Regulations and Technical Improvements

The IMO, through MARPOL convention Annex VI, has adopted air pollution regulations aimed to minimise main vessel emissions, e.g. NO_X, SO_X, PM and GHG. On the one hand, NO_X, SO_X and PM abatement regulations rigorously limit the emission of these pollutants from international shipping, as a result, SO_X and PM emissions are almost eliminated (95-98%) and NO_X emissions are drastically decreased (80%). On the other hand, energy efficiency measures pretend to reduce CO_2 emissions from vessels and foresee that merchant fleet will be 30% more efficient by 2025. In the whole then, NO_X, SO_X and PM emission levels have been successfully reduced, whereas, CO_2 emissions levels could be further reduced at lower levels. That is why, the Marine Environment Protection Committee (MEPC) is working to develop forthcoming measures in order to decrease even more GHG emissions from vessels (IMO, n.d.-a; Rodrigo de Larrucea, 2015).

Furthermore, CO_2 emissions from vessels are expected to grow in the near future, since shipping is the only sustainable mean of transport that can support the world's growing population. The shipping demand generated by a growth in world trade is the main driver. In spite of current GHG reduction measures, shipping CO_2 emissions will not be able to be decreased because of the continuous rise in the shipping demand. Consequently, the forecasted increase in the world trade hinders the goal of accomplishing stabilization in global temperatures. In addition, the Third IMO GHG Study 2014 defines several scenarios depending on future economic and energy developments and foresees that shipping CO_2 emissions will increase by 50% to 250% in 2050 based on the different scenarios (IMO, 2014b). For these reasons, the MEPC has started to consider further technical and operational measures so as to improve energy efficiency of vessels and therefore minimise CO_2 emissions (Hughes, 2016; IMO, n.d.-a).

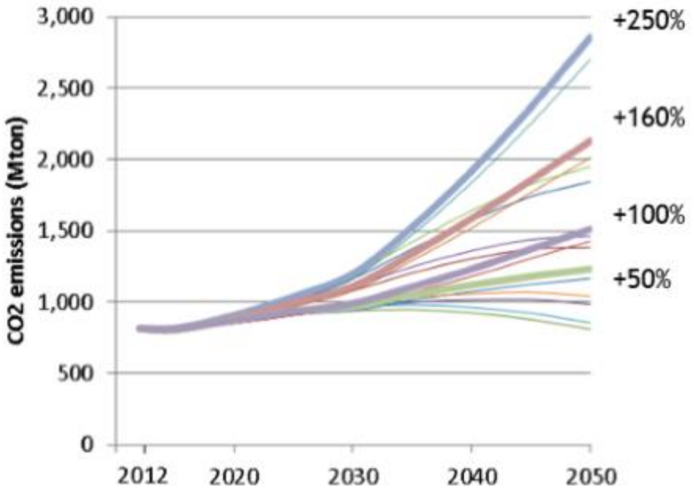


Figure 6.1: Projections of shipping CO_2 emissions based on the different scenarios (Source: IMO, 2014b).

Therefore, the IMO, through the MEPC, has started to develop mandatory requirements to minimise GHG emissions from vessels as exhaust gases contribute to global warming of the atmosphere, decomposition of methane, generation of acid rain and are potentially harmful to human health. Moreover, IMO is the unique organization that has established energy efficiency measures, which are legally binding across an entire global industry and apply to all countries (IMO, n.d.-g). IMO's efforts towards developing regulations to address the reduction of GHG emissions have lead into several outcomes, such as tightened energy efficiency requirements, a system for colleting vessel fuel oil consumption data, a roadmap for reducing GHG emissions and energy efficiency projects (IMO, n.d.-h).

6.1 Energy Efficiency Measures

The most important energy efficiency compulsory measure is the EEDI, which stimulate the use of less polluting engines and systems. New vessels have to attain a reference level based on their type and it will be toughened gradually in different stages so that encourage innovation and technical development of new efficiency solutions. Reduction rates have been set in three phases from 2015 to 2025 and forward. The first phase (January 1, 2015 to December 31, 2019) establishes a CO_2 reduction level of 10%. The second phase (January 1, 2020 to December 31, 2024) requires that new vessels to be 20% more energy efficient in comparison to the reference level. The third phase (January 1, 2025 to forward) determines that new vessels to be 30% more energy efficient contrasted with the reference level. Furthermore, EEDI is mandatory for a wide range of merchant fleet segments, e.g. tankers, bulk carriers, gas carriers, general cargo vessels, containerships, refrigerated cargo carriers, LNG carriers, Ro-Ro vessels, car carriers and RoPax and cruise vessels having non-conventional propulsion. These segments are the most energy demanding and represent around 85% of CO_2 emissions from international shipping. According to IMO, currently more than 1,900 vessels meet new energy efficiency design standards and are correspondingly certified (IMO, n.d.-b, 2016b).

Energy efficiency regulations involve IMO in reviewing the state of technological developments so as to assess whether it is necessary or not to amend time periods, EEDI reference line parameters for relevant vessel types and reduction rates. Consequently, the MEPC has taken into consideration a report regarding the state of technological developments pertinent to set the second phase of EEDI measures; and decided to keep the EEDI requirements for the second phase excluding ones for Ro-Ro vessels and passenger vessels, undertake an exhaustive analysis of the requirements for the third phase considering the possibility to implant it before schedule and contemplate the chance to introduce a fourth phase. In addition, the MEPC has adopted new methods for calculating the EEDI, such as EEDI calculations for DF engines, and updated the methods of calculation of the attained EEDI for the current vessel segments (American Bureau of Shipping, 2016; IMO, n.d.-h, 2016b).

6.2 Fuel Oil Consumption Data Collecting System

MEPC has adopted compulsory regulations for vessels to record and report their fuel consumption so that provide IMO with a clear and reliable picture about vessels fuel consumption, and therefore, GHG emissions on which on going decisions on further measures can be made. These measures apply to vessels with a GT equal or greater than 5,000 GT, which represent around 85% of total CO_2 emissions from international shipping. Vessels subject to these requirements will be required to collect consumption data for all types of fuel oil used on board, along with, further specific information. Afterwards, the recorded data will be submitted to the flag state of the vessel at the end of each calendar year. The flag state has to verify that the recorded data has been submitted in accordance with the required methodology included in the SEEMP, and then, will issue a Statement of Compliance to the vessel. Subsequently, flag states have to transfer the following information to an IMO Ship Fuel Oil Consumption Database:

- IMO number
- Technical characteristics of the vessel: vessel type, GT, NT, DWT and power output (rated power) of main and auxiliary engines
- EEDI
- Fuel oil consumption by fuel oil type and methods used for collecting fuel oil consumption data
- Over ground distance travelled while the ship is underway
- Hours underway

Moreover, the IMO has to elaborate an annual report summarizing the collected information to the MEPC. Data included in this report, specially that one regarding transport work, will be confidential and access for third parties is not allowed so as to particular vessels cannot be identified (Hughes, 2016; IMO, n.d.-i).

The main goal of this data collection system is to analyse energy efficiency of vessels and address abatement of GHG emissions from vessels engaged in international trade. This system will be developed based on a three-step approach, which involves data collection, data analysis and decision-making on forthcoming measures. Analysis of gathered information provides the grounds for an objective, transparent and inclusive policy discussion in the MEPC, and therefore, enables to determine if additional measures are required to improve energy efficiency of vessels. Additionally, these regulations update the methodologies used in the SEEMP for collecting and reporting data to the administration (American Bureau of Shipping, 2016; IMO, n.d.-h, n.d.-i).

The MEPC included these compulsory requirements into chapter 4 of Annex VI of MARPOL convention and are foreseen to come into force on March 1, 2018. The first calendar year of gathering consumption information is expected to start on January 1, 2019. These new regulations specify the information that has to be submitted to the database, the form of the Statement of Compliance and new requirements for certificates, surveys and port state control (PSC) (American Bureau of Shipping, 2016; IMO, n.d.-i).

6.3 Roadmap for Reducing GHG Emissions

The shipping industry is not specifically addressed in the Paris Agreement, which pretends to stabilize global average temperature (American Bureau of Shipping, 2016). Nevertheless, it acknowledged IMO's efforts towards minimising GHG emissions from international shipping and its existing and upcoming regulations to improve energy efficiency of vessels (Hughes, 2016; IMO, n.d.-h).

The MEPC elaborated a roadmap, which gathers and upgrades existing activities intended to mitigate GHG emissions from international shipping so as to define a comprehensive IMO strategy on reduction of GHG emissions from vessels. This initial GHG reduction strategy is expected to be adopted in 2018 and includes a list of activities together with their timelines and future IMO GHG studies. These forthcoming activities could be aligned with the work undertaken by the MEPC based on the three-step approach to improve energy efficiency of vessels, and consequently, this alignment enables the implementation of a revised strategy in 2023 including short, mid and long-term measures and application schedules. Furthermore, the MEPC will arrange intersessional meetings aimed to discuss issues concerning the GHG reduction strategy, which include:

- Guiding standards for the strategy
- Emissions scenarios
- Assessment of the forecasted shipping demand
- Energy efficiency parameters of vessels
- Emission reduction solutions
- Associated costs and benefits
- Capacity building and technical cooperation
- Emission reduction challenges
- Important areas for research and development
- Impact of EEDI
- Impacts of other regulations on GHG emissions

These intersessional meetings should be capable of defining a GHG reduction strategy taking into consideration the issues mentioned above, the Third IMO GHG study 2014 and the fuel oil consumption information collected, once the system will have been implemented (Hughes, 2016; IMO, n.d.-h, n.d.-i; Lloyd's Register, 2015).

In addition, this roadmap gives a long-term vision for the shipping industry and allows the MEPC to tackle important questions, such as, which perspective should the maritime industry adopt in relation to the objectives of the Paris Agreement (Hughes, 2016; IMO, n.d.-i).

6.4 Energy Efficiency Projects

IMO promotes technical cooperation and transfer of technology designed to enhance energy efficiency of vessels through chapter 4 of MARPOL convention Annex VI. This regulation involves state administrations along with the IMO and international organizations in supporting developing countries that require technical assistance, and encouraging the development and exchange of technology and information to these developing countries. Consequently, the MEPC is working on the implementation of energy efficiency measures and has established several programmes to technically assist developing countries and promote energy efficiency technology and information sharing between the maritime countries (IMO, n.d.-h, n.d.-m).

Besides, the IMO attempts to decrease carbon emissions from maritime transport through capacity building projects, which promote technical cooperation among worldwide regions and contributes to an effective adoption of new energy efficiency regulations. Nowadays, the IMO is working on two relevant capacity building projects: the Global Maritime Energy Efficiency Partnership (GloMEEP) Project and the

IMO-European Union Project on Capacity Building for Climate Change Mitigation in the Maritime Shipping Sector (IMO, n.d.-g, n.d.-m).

6.4.1 GloMEEP Project

The overall objective of the GloMEEP Project is to drastically reduce GHG emissions from vessels, and therefore, lead international shipping into a low-carbon future by promoting knowledge, comprehension and implementation of technical and operational energy efficiency regulations in developing countries. The GloMEEP Project is a two-year project developed by the IMO along with the United Nations Development Programme (UNDP) and funded by the Global Environment Facility (GEF). This project was introduced in 2015 during the IMO-Singapore International Conference on Maritime Technology Transfer and Capacity Building and includes the participation of ten Lead Pilot Countries (LPCs) where shipping is increasingly concentrated (Argentina, China, Georgia, India, Jamaica, Malaysia, Morocco, Panama, Philippines and South Africa). The GloMEEP Project aims to create global, regional and national partnerships to achieve its objectives and arranges a set of regional and national workshops on adoption of the requirements to minimise GHG emissions (GloMEEP, n.d.-a; IMO, n.d.-h).

Furthermore, the overall goal of the GloMEEP Project covers three key issues: legal, policy and institutional reforms, energy efficiency capacity building and public-private partnership. Regarding legal, policy and institutional reforms, LPCs will be assisted in adopting an approach to set legal, policy and institutional activities in order to effectively implant energy efficiency measures. Talking about energy efficiency capacity building, the GloMEEP Project promotes the comprehension and uptake of design and operational energy efficiency technologies in developing countries, and ensures their implementation and enforcement in LPCs. Finally, the GloMEEP Project tries to attract the private sector to energy efficiency activities in developing states via international workshops and forums with the objective to create a Global Industry Alliance (GIA) (GloMEEP, n.d.-a; IMO, n.d.-h).

6.4.2 IMO-European Union Project

The principal objective of the IMO-European Union Project is to establish a global network of Maritime Technology Cooperation Centres (MTCCs) in developing countries, whose duty is to spread technical information and awareness of new energy efficiency technologies in the shipping sector. The IMO-European Union Project is a four-year project developed and coordinated by the IMO's Marine Environment Division and funded by the EU. This project provides technical assistance and capacity building to developing countries, which try to mitigate GHG emissions from vessels, as they are significantly relevant in the maritime transport and usually do not have adequate tools to tackle this concern. As a consequence, developing countries capacity for facing GHG emission reduction will be improved, and uptake and sharing of energy efficiency technologies and operations will be intensified (IMO, n.d.-d, n.d.-g, n.d.-h).

MTCCs will be located in five regions (Africa, Asia, the Caribbean, Latin America and the Pacific) because of their significant number of Least Developed Countries (LDCs) and Small Island Developing States (SIDS). These centres will be hosted by local institutions of recognized competence engaged with the maritime industry and government, and are expected to reach excellent levels in spreading and implementing energy efficiency technologies and operations (IMO, n.d.-d). Moreover, MTCCs will have to:

- Work with maritime administrations, port authorities, relevant government departments and connected shipping stakeholders with the purpose of enhance their capacity for meeting current and forthcoming international regulations and feasible energy efficiency requirements.
- Foster pilot projects to spread utilization of low-carbon technologies and operations in the shipping industry.
- Ensure understanding of measures, policies and approaches to minimise GHG emissions and other air pollutants from vessels.
- Develop pilot data collection and reporting systems to support ship owners and maritime administrations.
- Allow participating countries to develop energy efficiency policies and measures for vessels.

6.5 Technical Improvements on Energy Efficiency of Vessels

Because of the development of upcoming regulations to address reduction of GHG emissions from international shipping, new abatement technologies have started to be designed and implemented on board vessels. Consequently, the GloMEEP Project has created an information portal of technical solutions for vessels aimed to enhance energy efficiency of vessels, and therefore, minimise GHG emissions (GloMEEP, n.d.-f).

To date, there is a wide range of technical measures that ship owners can take into account in order to decrease exhaust gas emissions and comply with future air pollution requirements. Although these solutions are known options, their maturity level on board vessels varies among them, since some are currently being implemented and others have not already been tested in real-world application or have only been installed on prototypes. New abatement technologies can be divided into four major groups: engine technologies, hull and propulsion technologies, operational technologies and alternative propulsion technologies (GloMEEP, n.d.-f; IMO, 2015).

Engine technologies affect propulsion and auxiliary machinery and are designed to improve their energy efficiency, for example auxiliary systems optimization, engine de-rating, engine performance optimization and waste heat recovery systems, among others (GloMEEP, n.d.-f).

Hull and propulsion technologies refer to hull and propulsion modifications or improvements aimed to enhance hydrodynamic performance and reduce resistance of the vessel while under way, for instance air lubrication, hull cleaning and coating, propeller polishing, propulsion improving devices (PIDs), and others (GloMEEP, n.d.-f).

Operational technologies are intended to enhance vessel operation through optimizing utilization of systems and equipment on board, such as autopilot adjustment, trim and draft optimization, speed management, cargo handling systems and more (GloMEEP, n.d.-f).

Alternative propulsion technologies are designed to take advantage of surrounding potential energy and turn it into useful energy for the vessel, e.g. fixed sails, kites, Flettner rotors or solar panels (GloMEEP, n.d.-f).

6.5.1 Engine Technologies

Auxiliary Systems Optimization

Auxiliary systems optimization consists of assessing energy consumption and production of auxiliary systems so that save energy and fuel, since auxiliary systems are designed to support high loads (80-100%) from main engines and they usually work at low loads (20-65%). Auxiliary systems optimization is achieved through speed control of pumps and funs, control strategies of cooling water systems, retrofitting of heat exchangers, management of auxiliary energy distribution and consumption, and others. This measure can be applied to any type of vessel, offers a reduction potential of 1-5% of the total vessel fuel consumption and has an implementation cost of 10,000 to 150,000 USD depending on whether it is a new building or retrofit (GloMEEP, n.d.-d; IMO, 2015).

Engine De-Rating

Engine de-rating consists of reducing vessel maximum speed and MCR in order to optimize working engine load point and reduce fuel consumption, as vessels nowadays have reduced their service speed, and consequently, main engines do not work at their designed load levels. Engine de-rating can be done by several methods, which vary in cost, flexibility and effort required; allows a speed decrease of 10-15% and is a reversible solution. This measure can be applied to any type of vessel, provides a reduction potential of 2-10% of main engine total fuel consumption and has an implementation cost of 60,000 to

3,000,000 USD depending on the method and engine de-rating magnitude (GloMEEP, n.d.-h; IMO, 2015).

Engine Performance Optimization

Engine performance optimization consists of enhancing cylinder pressure balance and setting maximum combustion pressures closer to rated values so as to allow more efficient combustion, which decreases fuel consumption and makes engines cleaner. Nowadays, regular testing and calibration of main engines is done manually, although, desired results are not achieved. For this reason, automatic engine performance optimization is starting to be implemented on board new vessels, and is done by adjusting and optimizing fuel injection timing, maximum combustion pressure and combustion pressure. This measure can be applied to any two-stroke engine, offers a reduction potential of 1-4% of total vessel fuel consumption and has an implementation cost of 3,000 to 7,000 USD depending on the engine type and whether it is a new building or retrofit (GloMEEP, n.d.-i; IMO, 2015).

Waste Heat Recovery Systems

Waste heat recovery systems are designed for using heat from exhaust gases to generate electrical energy, steam or hot water. These systems are addressed to main propulsion engines, even tough, have begun to be introduced into auxiliary engines. Heat recovery systems use exhaust gas boilers, gas turbines or steam turbines to recover and process the heat from exhaust gases, and as a consequence, reduce fuel consumption and improve efficiency of main and auxiliary engines. This measure can be applied to any type of engine that operates at high load, provides a reduction potential of 3-8% of fuel consumption for main propulsion engines and 1-5% for auxiliary engines, and has an implementation cost of 5,000,000 to 9,500,000 USD for main propulsion engines and 50,000 to 75,000 USD for auxiliary engines (GloMEEP, n.d.-j, n.d.-aa; IMO, 2015).

Auxiliary Engine Load Optimization

Auxiliary engine load optimization consists of enhancing load levels of auxiliary engines used to generate electrical energy to supply vessel electric systems, and therefore, decrease their fuel consumption. The number of auxiliary engines fitted on vessels ranges from 2 to 6 based on their layout, mechanical or electrical, and vessels commonly run with additional auxiliary engines because of redundancy. Auxiliary engine load optimization is achieved through raising their mean load level and reducing the number of auxiliary engines operating. This measure can be applied to any type of vessel, offers a reduction potential of 0-20% of auxiliary engine fuel consumption and has no direct implementation cost (GloMEEP, n.d.-r).

Shore Power

Shore power consists of supplying vessels when berthed with electrical energy from shore grid power so that replace energy from auxiliary engines, and therefore, eliminate exhaust gas emissions and local noise while at harbour. However, shore power requires relatively expensive installations on board and on shore owing to the necessity to improve the grid capacity, frequency convertors and sophisticated power connectors. For this reason, shore power supply for vessels with large electric power needs has not been widely established. This measure can be applied to any type of small vessel, provides a reduction potential of 50-100% for the auxiliary engines at harbour and the implementation cost depends on the type and size of vessel and plant design (GloMEEP, n.d.-w; IMO, 2015).

Hybridization

Hybridization consists of installing batteries on vessels in order to cover entire or partial electrical demand of on board systems. Batteries provide additional power when electrical demand is high and are charged when electrical demand is low using the surplus of energy produced by engines, as a result, smaller engines can be installed and constantly run within optimal loads improving their performance. Hybridization presents three degrees: full-electric vessels, which are equipped only with batteries that provide propulsion and auxiliary power; plug-in hybrid vessels, which are fitted with combustion engines and batteries that are charged by shore power; and conventional hybrid vessels, in which batteries are charged by on board engines. This measure can be applied to vessels with large load changes, for example ferries, OSV and tugs; offers a reduction potential of 15-30% of the total vessel fuel consumption depending on vessel consumption and operating characteristics; and has an implementation cost of 600,000 to 2,000,000 USD for conventional hybrid vessels, 1,800,000 to 3,000,000 USD for plug-in hybrid vessels and 4,800,000 to 6,000,000 USD for full-electric vessels (GloMEEP, n.d.-q; IMO, 2015).

6.5.2 Hull and Propulsion Technologies

Air Lubrication

Air lubrication consists of injecting air under vessel keel so as to create an air cavity, which decreases fuel consumption, and therefore, air emissions on account of enhancing hull hydrodynamic performance and reducing viscous resistance. Air lubrication is driven by an auxiliary engine and involves supplementary pumps, piping and a special hull design able to retain the injected air and create the air cavity. This measure can be applied to any new building, especially bulk carriers, tankers and containerships; provides a reduction potential of 15-40% of drag resistance and 10% of main engine fuel consumption; and the implementation cost oscillates from 2% to 3% of the new building cost for the vessel (GloMEEP, n.d.-b).

Hull Improvements

Hull improvements refer to modifications of hull condition, design and shape aimed to improve its hydrodynamic performance, such as hull cleaning, hull coating, hull shape optimization and hull retrofitting. Hull cleaning consists of removing attached biological fouling, which increases hull resistance, fuel consumption, causes cavitation and turbulence, makes noise and affects hull devices performance. Hull cleaning can be done by a diver or a remotely operated vehicle (ROV) when vessel is stopped and eliminates all remains of fouling without damaging hull coating and causing surface roughness. This measure can be applied to any type of vessel, offers a reduction potential of 1-5% of main engine fuel consumption depending on the amount of fouling and vessel size, and has an implementation cost of 5,000 to 50,000 USD depending on the method used (GloMEEP, n.d.-m).

Hull coating consists of applying advanced coatings, which decrease hull resistance, and therefore, minimise fuel consumption. Full benefits of using advanced coatings are achieved through adequate hull maintenance, since vessels require sandblasting and recoating every five years. This measure can be applied to any type of vessel, provides a reduction potential of 1-4% of main engine fuel consumption depending on vessel size, type and operation; and has an implementation cost of 30,000 to 500,000 USD (GloMEEP, n.d.-n).

Hull shape optimization consists of designing the most hydrodynamic hull form possible so that reduce hull resistance and fuel consumption. It is done by several model tests and computational fluid dynamic assessments, and provides large benefits when optimized hull shape differs from the standard design. This measure can be applied to any vessel design, offers a reduction potential of 4-8% of main engine fuel consumption depending on vessel size, type and operation; and has an implementation cost of 150,000 to 500,000 USD (GloMEEP, n.d.-o).

Hull retrofitting consists of modifying specific parts of the hull, e.g. bulbous bow, bilge keels and bow thruster tunnels, so as to enhance hull performance and decrease hull resistance and fuel consumption. Hull retrofitting is achieved through optimizing bulbous bow design, location of bilge keels and shape of bow thruster tunnels. This measure can be applied to any type of vessel, provides a reduction potential of 3-5% of main engine fuel consumption for bulbous bows, 0.5-1% for bow thruster tunnels and 0.25-1% for bilge keels; and the implementation cost varies depending on the design and size of the modification (GloMEEP, n.d.-p).

Propeller Improvements

Propeller improvements refer to any modification aimed to enhance propeller efficiency, for example propeller polishing or retrofitting. Propeller polishing consists of polishing or coating the surface of the propeller as a consequence of the damaged generated by cavitation and strain. It can be done twice a year while the vessel is in dry-dock or by a diver when the vessel is stopped. This measure can be applied to any propeller, offers a reduction potential of 3-4% of main engine fuel consumption and has an implementation cost of 4,000 to 8,000 USD depending on the number and complexity of the propeller (GloMEEP, n.d.-t).

Propeller retrofitting consists of exchanging the propeller by a new optimized design in order to obtain a higher efficiency and minimise fuel consumption. This measure can be applied to any vessel, provides a reduction potential of 2-5% of main engine fuel consumption and has an implementation cost of 400,000 to 500,000 USD (GloMEEP, n.d.-u).

Propulsion Improving Devices (PIDs)

PIDs consist of improvements made to the propeller or hull whose aim is to enhance propulsion efficiency and reduce fuel consumption, for instance contra-rotating propellers, rudders, fins or ducts. Higher propulsion efficiency is achieved through enhancing water flow around the propeller, specifically, in front of the propeller, behind or on the propeller. These devices offer a reduction potential of 0.5-5% of main engine fuel consumption, their implementation cost varies according to the device used and their applicability depends on the type of vessel (GloMEEP, n.d.-v).

6.5.3 Operational Technologies

Autopilot Adjustment

Autopilot adjustment consists of using small angle rudder movements to follow a course, though, enables small deviations to the course-line. Efficient and adaptive autopilot operation decreases fuel consumption, as it minimises rudder movements. This measure can be applied to any vessel fitted with an autopilot, provides a reduction potential of 0.25-1.25% of main engine fuel consumption and has no direct implementation cost (GloMEEP, n.d.-c).

Speed, Trim and Draft Optimization

Speed optimization consists of efficiently adjusting sailing speed taking into consideration voyage parameters, like ship particulars, weather forecasts or schedules, so that reduce fuel consumption. However, savings in fuel can also be achieved by sailing at slow steaming, which consists of reducing sailing speed 10% and therefore increase voyage time. This measure can be applied to any vessel, offers a reduction potential of 10-50% of main engine fuel consumption and has no direct implementation cost (GloMEEP, n.d.-y).

Trim and draft optimization consists of efficiently adjusting these parameters through a careful planning of cargo operations. Advanced loading computers set optimum trim and draft in order to decrease fuel consumption and emissions. This measure can be applied to all vessels, provides a reduction potential of 0.5-3% of main engine fuel consumption and has an implementation cost of 15,000 to 75,000 USD depending on the complexity of the software (GloMEEP, n.d.-z).

Cargo Handling Systems Optimization

Optimization of cargo handling systems consists of analysing the operation of unloading systems and their performance so as to propose efficient discharging strategies to minimise energy consumption of cargo pumps and other equipment used during unloading operations. This measure can be applied to crude oil carriers with steam turbines, offers a reduction potential of 5-15% of the total boiler fuel consumption and has an implementation cost of 15,000 to 25,000 USD (GloMEEP, n.d.-e).

Energy Efficient Lighting

Energy efficient lighting consists of fitting vessels with low energy halogen lamps, fluorescent tubes or LED lighting along with electronically controlled systems for automating power off or dimming. Energy efficient lighting equipment reduces electric power consumption and has started to be installed on cruise and passenger vessels, since they require a huge amount of electric power. This measure can be applied to all vessels, provides a reduction potential higher than 10% of the total electric power consumption for cruise and passenger vessels, and has an implementation cost of 200,000 to 1,000,000 USD for cruise and passenger vessels (GloMEEP, n.d.-g; IMO, 2015).

6.5.4 Alternative Propulsion Technologies

Alternatives propulsion technologies refer to those systems that use wind or solar power to reduce the propulsion power required to move the vessel, for example fixed sails, Flettner rotors, kites and solar panels. Fixed sails use wind power through flexible or rigid sails installed on vessel’s main deck to substitute part of power generated by main engines. This measure requires a significant amount of deck space, depends on wind conditions and it is estimated that it only will be able to be used 15% of the time (GloMEEP, n.d.-k). Then, Flettner rotors are vertical rotating cylinders that generate a thrust when wind blows across them. Cylinders may restrict vessel operability due to their height and their efficiency depends on vessel speed and wind (GloMEEP, n.d.-l). Kites reduce part of the energy required to propel the vessel on account of a pulling force generated by the wind power, although, it is estimated that they only will be able to be used 20-30% of the time (GloMEEP, n.d.-s). Finally, solar panels turn sunlight into electric power used to cover part of the vessel electrical needs, though, this system can only be installed on board vessels with large free deck surface, since solar panels require a large area (GloMEEP, n.d.-x). These technologies offer a reduction potential up to 10% of the main engine fuel consumption, and are far from being widely introduced in the shipping industry, as they have only been installed on board vessel for pilot projects.

Chapter 7. Conclusions

This paper ends with the most relevant points and conclusions obtained throughout the development of the entire paper. First of all, it will be described separately the most important facts and conclusions extracted from each chapter so as to understand and remark their key issues. Afterwards, it will be explained the finals conclusions reached taking into consideration the thorough analysis performed during this paper and the partial conclusions.

7.1 Shipping Emissions and Air Pollution Regulations

International shipping emissions are arriving to significantly high levels, which have a severe impact not only on the environment (global warming of the atmosphere) but also on the society causing serious health problems, for example. In addition, world seaborne trade is foreseen to grow even more in the near future giving rise to more air pollution from vessels. For these reasons, it is needed an exhaustive regulation framework as the maritime industry is one of the principal contributors of the environment detriment.

Annex VI of MARPOL convention gathers IMO international regulations aimed to decrease emissions of vessels, which focus on CO_2, NO_X, SO_X and PM reduction. Regulations governing CO_2 emissions involve two energy efficiency measures, the EEDI, which promotes the development of more energy efficient engines, and the SEEMP, which enhance vessels operational energy efficiency through controlling and monitoring their performance. With these measures, the IMO estimates that in 2025 vessels will be 30% more efficient, and therefore, CO_2 emissions will be mitigated. Then, NO_X regulations restrict NO_X emissions of vessels based on three different limits (Tier I, II and III), in which the most stringent limit only applies to NECAs and the other two apply to global waters. Finally, according to SO_X regulations, vessels operating in global waters will have to use marine fuels with a maximum sulphur content of 0.5% m/m in 2020 (or 2025), and 0.1% m/m in 2015 when operating in SECAs. With these measures, the IMO foresees a reduction in NO_X emissions of 15-20% in global waters and 80% in NECAs, and a reduction in SO_X emissions of 80% in global waters and 96% in SECAs. Furthermore, the MEPC in its 70th session announced the adoption of North Sea and Baltic Sea areas as NECAs in January 1, 2021, and the 0.50%

m/m global cap in January 1, 2020 in accordance with the favourable result of the review aimed to assess the availability of complaint fuel oil in 2020 (IMO, n.d.-h).

Moreover, the European Parliament and the Council of the European Union have also adopted SO_X reduction measures, which set limits on the sulphur content of marine fuels based on ports, territorial seas, exclusive economic zones and pollution control zones of Member States.

7.2 Technological Solutions to Comply with Air Pollution Regulations

Technology developers have designed and developed a wide variety of abatement solutions, which seek to meet limits on CO_2, NO_X and SO_X emissions, as a consequence of the adoption of new air pollution regulations. These technologies can be classified into CO_2 reduction technologies, e.g. reduction of vessel's resistance, increase in propulsive efficiency and reduction in auxiliary consumption; NO_X reduction technologies, for instance LNG as marine fuel, EGR, SCR and water injection systems; and SO_X reduction technologies, for example EGS and low sulphur fuels.

When comparing the range of options, LNG as ship fuel seems to be an available and potential solution because of LNG removes SO_X emissions and PM, reduces NO_X emissions up to 90% and minimise CO_2 emissions around 20%; it is a mature technology in the maritime industry and it is commercially attractive. Nevertheless, the implementation of LNG has to overcome several challenges: LNG-fuelled engines, fuel storage tanks, gas supply systems and LNG infrastructure.

Concerning LNG-fuelled engines, manufacturers have principally developed two different types, lean-burn gas engines and DF engines. On the one hand, lean-burn gas engines present a high gas quality tolerance and do not require additional fuels (HFO, IFO, MGO or MDO), though, they restrict vessel operability within areas with LNG bunkering facilities given that they only can be supplied with LNG. On the other hand, DF engines can be fuelled either with LNG or liquid fuels allowing vessels to operate in areas where LNG infrastructure is not available, even tough, DF engine fuel supply systems involve more equipment due to DF engines can run with both LNG and MDO or MGO. Besides, DF engines can be divided into four-stroke DF engines, which operate at low pressure, and two-stroke DF engines, which operate at high-pressure and require additional pumps to increase LNG pressure. Furthermore, high-pressure DF engines require a bigger amount of pilot fuel than low-pressure DF engines and natural gas combustion is not guaranteed at low loads, and therefore, they can only be installed in vessels with high and constant engine loads. To conclude, passenger vessels and PSV are frequently equipped with four-stroke DF engines, as they constantly vary their engine load and large vessels are fitted with two-stroke DF engines.

Regarding LNG fuel tanks, insulation materials used to maintain LNG at very low temperatures and its density significantly increase the size of fuel storage tanks reducing cargo space. On the one hand, large vessels can be equipped with three different types of tanks, although, they require a further development. On the other hand, small vessels are fitted with vacuum insulated C-type tanks. That is why, LNG as marine fuel has not spread over large vessels, such as bulk carriers or crude oil carriers, and has been implemented to an extent in small vessels, e.g. passenger ferries, PSV and tugs. With respect to gas supply systems, they are designed based on the engine operational pressure. Gas supply systems for low-pressure engines require less space, since they do not have to increase natural gas pressure and offer a compact configuration, which maximise LNG storage and optimizes required space, whereas, gas supply systems for high-pressure engines require cryogenic pumps and compressors so as to increase natural gas pressure, and thereby, reduce even more cargo space.

Despite the fact that exportation of LNG from production and liquefaction plants to import terminals is a well-established industry, it does not entail LNG availability from export or import terminals to bunker LNG-fuelled vessels. Furthermore, the uncertainty of the market for LNG-fuelled vessels hinders the development of LNG bunkering infrastructures, as they require a huge investment. However, the adoption of new air pollution regulations has stimulated the proposal and planning of LNG bunkering installations, especially in ports located in ECAs. To date, the majority of existing LNG bunkering facilities are located in the European SECA because of most LNG-fuelled vessels operate in the North Sea and Baltic Sea area.

7.3 Rules for Gas-Fuelled Vessels

In spite of the fact that LNG-fuelled vessels have several aspects in common with gas carriers and rules for this type of vessels already exist, LNG-fuelled vessels are equipped new systems (LNG fuel tanks and gas supply systems, for instance), and therefore, it is needed specific standards, which assess the impact of new associated risks on safety issues. In addition, LNG as marine fuel involves safety challenges, such as extremely low temperatures, ignitable in mixture with air, high auto ignition temperature and high-energy content, owing to its properties and have to be evaluated in order to ensure adequate safety levels under all conditions.

Both safety and operational issues of LNG-fuelled vessels have to be taken into consideration from the beginning of the design. The principal goal of guidelines is to provide criteria capable of maintaining safety levels and minimising risks for the vessel, its crew and environment. That is why, the IMO and classification societies have developed rules for LNG-fuelled vessels, which offer a clear guidance for building new ships and arranging their systems, specially those that require special attention (engine room and LNG storage tanks).

7.4 Main LNG-Fuelled Vessel Segments

After the analysis of main LNG-fuelled vessel segments, some important conclusions are obtained. LNG-fuelled vessels are an emerging market encouraged by the implementation of strict air pollution regulations; the wide development of LNG-fuelled engines, LNG fuel tanks and gas supply systems; and the forthcoming LNG infrastructure projects. Indeed, it is expected a prominent growth of LNG-fuelled market in the next decade, tough, it can be affected by external factors, e.g. LNG price and availability. To date, the main segments that dominate the LNG-fuelled fleet are car/passenger ferries, PSV, harbour tugs, gas carriers and containerships. Once compared the dominant LNG-fuelled vessel segments, the following points are extracted:

- Notwithstanding the type of ship, LNG-fuelled vessels operate in a liner service covering prearranged routes and spend the majority of their time inside ECAs or sail between ports located within ECAs.
- Most of the LNG-fuelled vessels (Car/passenger ferries, PSV, gas carriers and containerships) are equipped with DF engines, which allow them to continue operating in case of unavailability of LNG.
- Harbour tugs are the unique analysed segment that is fitted with lean-burn gas engines, since they only operate in ports where LNG is available.
- LNG-fuelled vessels engaged in short routes, with variable engine loads and frequently enter and leave ports are designed according to a DF-electric concept, such as car/passenger ferries and PSV.
- LNG-fuelled vessels engaged in larger routes and constant engine loads are designed according to a DF-mechanic concept, like gas carriers and containerships.
- All LNG-fuelled vessel segments analysed are equipped with vacuum insulated C-type tanks, except LNG carriers, as they use the LNG stored in their cargo tanks.
- Usually bunkering operations are performed by truck, which indicate that small amounts of LNG are currently transferred to supply LNG-fuelled engines.
- LNG bunkering operations are undertaken at the same time as loading and unloading so as to not delay vessel’s schedule and spend more time at ports.

To sum up, car/passenger ferries are the biggest LNG-fuelled vessel segment, followed by PSV, gas carriers and harbour tugs.

7.5 Potential for LNG-Fuelled Vessels

All types of vessels are able to implement LNG, but certain vessel segments present a higher potential, which depends on several features. After analysing them, several conclusions about LNG-fuelled vessel potential are reached. First, LNG as ship fuel is available either for LNG-fuelled new buildings or existing vessels, although, most of LNG-fuelled vessels are new buildings due to retrofitting of existing vessels require a huge investment and entails major modifications in the engine room. Second, local ships, coasters and vessels covering SSS routes spend most of their time inside ECAs, therefore, ferries, tugs, PSV and containerships are likely to fuel their engines with LNG. Third, vessels operating in areas where availability of LNG infrastructures is guaranteed and price of LNG is lower than traditional marine fuels are potential consumers of LNG in order to fuel their engines. Then, vessels engaged on a fixed route with LNG bunkering installations at homeport, ports of call or port of destination are quite suitable to be supplied with LNG as a result of the lack of LNG availability worldwide. Furthermore, vessel segments, like cruise ships, passenger vessels and PSV, looking for green values or taking advantage of sustainability bonuses require an environmentally friendly solution to minimise emissions like LNG as marine fuel. Finally, equipment costs, operational time inside ECAs and LNG price are taken into consideration when assessing the financial feasibility of LNG-fuelled vessels.

7.6 Upcoming Air Pollution Regulations and Technical Improvements

During the assessment of shipping emissions contribution to the environment detriment, further air pollution regulations and new abatement technical improvements, the following points can be highlighted. Currently air pollution regulations drastically reduce NO_X emissions and almost eliminate SO_X and PM emissions, while, CO_2 emissions are reduced only 20-30%. Besides, maritime transport is expected to expand as a consequence of the world's growing population, which will increase shipping demand in the years ahead. For these reasons, CO_2 emissions will continue to augment, whereas, NO_X, SO_X and PM will be minimised. According to the Third IMO GHG Study 2014, CO_2 emissions are foreseen to reach extremely high levels regardless of air pollution regulations. Owing to the critical situation in terms of environmental pollution, the IMO and the MEPC have started to work on the proposal and adoption of measures aimed to mitigate CO_2 emissions and improve energy efficiency of vessels, such as tightened energy efficiency requirements, fuel oil consumption data collecting system, roadmap for reducing GHG emissions and energy efficiency projects.

First, EEDI sets a reference level based on the type of ship toughened gradually in three stages, which new vessels have to meet. At the third stage vessels will be 30% more energy efficient, although, the MEPC will assess third stage requirements considering the possibility to implant them before schedule and contemplate the chance to introduce a fourth stage. Second, the MEPC will adopt a system for recording vessel's fuel consumption and thereby obtain a clear picture of their GHG emissions on account of the lack of reliable information. The collected data will be thoroughly analysed with the objective to propose regulations that decrease GHG emissions of vessels. Third, the MEPC elaborated a roadmap, which gathers, upgrades and proposes new GHG abatement solutions and activities, with the goal to implant a compressive GHG reduction strategy for the maritime sector. This strategy will be developed taking into consideration IMO GHG studies and results obtained from the fuel oil consumption data collecting system so that implement short, mid and long-term measures. Finally, the IMO along with the MEPC have created two capacity building projects (GloMEEP Project and IMO-European Union Project), which seek to promote technical cooperation and transfer of technology designed to enhance energy efficiency of vessels between developed and developing countries.

As a result of the proposal and future adoption of stringent regulations aimed to reduce GHG emissions from the maritime industry, new abatement technologies have started to be designed and implemented on board vessels. The principal objective of these technical improvements is to enhance energy efficiency of vessels and thereby reduce their fuel consumption. These technical measures can be classified according to the area in which upgrades are focused: engine, hull and propulsion, operation and alternative energy sources. Engines technologies enhance energy efficiency of propulsion and auxiliary engines, for example engine de-rating, waste heat recovery systems or engine optimization. Hull and propulsion technologies modify and improve hull and propellers so as to achieve optimum hydrodynamic performance and minimise resistance of the vessel, for instance hull cleaning and coating, propeller polishing or air lubrication. Operational technologies optimize vessel operation and systems used on board, such as autopilot adjustment, trim and draft optimization or speed management. Alternative propulsion technologies use wind or solar power to reduce the propulsion energy required to move the vessels, e.g. fixed sails, Flettner rotors, kites or solar panels.

7.7 Final Conclusions

During the whole paper, it has been studied and detailed the environmental situation in which the shipping industry is involved in, the challenges overcome in order to implement LNG as marine fuel, the main LNG-fuelled vessel segments and their potential, and finally, future air pollution regulations and technical solutions proposed to comply with them.

On the whole then, the final conclusions reached throughout this paper on the implementation of LNG as marine fuel are explained as follows:

- The maritime transport is facing an alarming situation in terms of air pollution because of high levels of emissions from vessels, which provoke global warming of the atmosphere, deterioration of the environment, dense air pollution in cities located next to important harbours and serious health problems, among others.
- Due to the forecasted rise in the global seaborne trade triggered by world's growing population, shipping emissions are expected to increase even more emphasising the necessity to elaborate an exhaustive regulation framework that drastically mitigates emissions from vessels.
- The IMO, together with other European organizations have adopted regulations aimed to reduce emissions of vessels. These requirements have decreased CO_2 emissions around 20-30%, NO_X emissions 80% and SO_X emissions and PM 95-98%.
- LNG as marine fuel complies with current air pollution regulations, has been used on board vessels for several decades and has a lower price as compared with other marine fuels. Nevertheless, the scarce availability of LNG bunkering facilities distributed around areas with high shipping activity and the uncertainty of LNG price in the future are the main disadvantages for the implementation of LNG as ship fuel.
- Nowadays, utilization of LNG as marine fuel is a technologically feasible solution; since manufacturers have designed and developed a wide range of LNG-fuelled engines (Lean-burn gas engines and DF engines), vacuum insulated C-type tanks and gas supply systems.
- The lack of LNG bunkering installations owing to entailed huge investments and LNG is not yet well established in the market, hinders the implementation of LNG as ship fuel in the maritime industry. Nonetheless, the adoption of new air pollution regulations has stimulated the proposal and planning of LNG infrastructure projects.
- Rules for gas-fuelled vessels have been elaborated to provide a clear guidance for the construction and equipment of gas-fuelled vessels capable of reducing risks for the vessel, its crew and environment.
- Car/passenger ferries is the dominant LNG-fuelled vessel segment, followed by PSV, gas carriers and harbour tugs. Moreover, containerships are potential LNG-fuelled vessel segment.
- Regardless of the LNG-fuelled vessel segment, LNG-fuelled vessels operate in fixed routes and spend the majority of their time inside ECAs or navigate between ports located within ECAs.
- Most of the LNG-fuelled vessels are equipped with DF-engines. Indeed, propulsion systems of vessels with variable engine loads and engaged in short routes (Car/passenger ferries and PSV) are designed based on a DF-electric concept, whereas, propulsion systems of vessels with constant engine loads and engaged in large routes (Gas carriers and containerships) are designed based on a DF-mechanic concept.

- Potential for LNG-fuelled vessels depends principally on the following features: new building vessels, operational time within ECAs, operational regions with LNG availability, price of LNG, liner vessels and environmentally friendly profile. As a result, in accordance with main LNG-fuelled vessel segments, car/passenger ferries covering routes in the North Sea and Baltic Sea present a high potential for implementing LNG as marine fuel, as their characteristics are aligned with the features mentioned above.
- Current air pollution regulations significantly minimise NO_X, SO_X and PM emissions from vessels, even though, CO_2 emissions are not sufficiently reduced and still being an environmental concern to solve. Legislative bodies should severely tackle this problem and implant highly restrictive measures.
- The IMO, along with the MEPC will introduce measures aimed to improve energy efficiency of vessel and decrease GHG emissions, though, are not rigorously restrictive measures. The overall purpose of these requirements is to collect and share reliable information about how to address energy efficiency of vessels and GHG emissions.
- Latest abatement technologies so as to enhance energy efficiency of vessels and decrease GHG emissions do not exhaustively mitigate CO_2 emissions, they merely provide small improvements for different areas and items of the vessel, which lead to small benefits on vessel's environmental efficiency. Only when a combination of technical improvements is installed in different areas of the vessels a reduction of CO_2 emissions can be obtained to some extent.

I would like to conclude this paper by saying that LNG as marine fuel is an attractive, potential and technically feasible solution for new building vessels to comply with short-term air pollution regulations because of it does not sufficiently minimise CO_2 emissions. As of now, technologies applied on board vessels appear to not be able to noticeably decrease CO_2 emissions from their combustion engines, being only possible by means of replacing combustion engines with an alternative propulsive energy source that does not emit CO_2. Despite prototype projects partially propelled with wind or solar power, under my point of view, it does not exist a reliable solution to move merchant vessels in an environmentally friendly manner, and therefore, significantly reduce CO_2 emissions.

Bibliography

Adamchak, F., & Adede, A. (2013). *LNG As Marine Fuel*. *LNG-17 Conference*. Retrieved from http://www.gastechnology.org/Training/Documents/LNG17-proceedings/7-1-Frederick_Adamchak.pdf

American Bureau of Shipping. (n.d.). ABS Record - Isla Bella. Retrieved December 11, 2016, from https://www.eagle.org/safenet/record/record_vesseldetailsprinparticular?ImoNum=9680841

American Bureau of Shipping. (2016). *MEPC 70 Brief Rev. 1* (Vol. 219). Retrieved from http://ww2.eagle.org/content/dam/eagle/regulatory-news/2016/MEPC 70 Brief Update_31Oct16.pdf

Andersen, J. H. (2015). *LNG Basics and status of LNG fuelled ships*. Retrieved from http://www.caribbeanshipping.org/images/Documents/LNG_Basics_and_Satus_of_LNG_Fuelled_Ships_-_Jan_Hagen_Anderson.pdf

Anthony Veder. (n.d.). Naming of the new Anthony Veder LNG carrier Coral Energy. Retrieved December 10, 2016, from http://www.anthonyveder.com/home/naming-coral-energy/

AVIC Dingheng Shipbuilding Co., L. (n.d.). *4700 CBM LPG/LEG CARRIER (DFDM PROPULSION)*. Retrieved from http://www.avicdh.com/en/uploadfile/2015/0422/20150422044520124.pdf

Baumgart, M., & Bolsrad, J. H. (2010). *LNG-Fueled Vessels in the Norwegian Short-Sea Market*. NORGES HANDELSHØYSKOLE. Retrieved from https://brage.bibsys.no/xmlui/bitstream/handle/11250/168425/Bolstad mfl.PDF?sequence=1&isAllowed=y

Brynolf, S., Magnusson, M., Fridell, E., & Andersson, K. (2014). Compliance possibilities for the future ECA regulations through the use of abatement technologies or change of fuels. *Transportation Research Part D: Transport and Environment*, *28*(X), 6–18. https://doi.org/10.1016/j.trd.2013.12.001

Buksér og Berging AS. (n.d.). LNG Powered Escort Tugs. Retrieved December 9, 2016, from http://www.bube.no/Technology/LNG-Powered-Escort-Tugs/

Bureau Veritas. (n.d.-a). Bureau Veritas - Equasis - Coral Energy. Retrieved December 10, 2016, from http://www.veristar.com/portal/veristarinfo/equasis?IMO=9617698

Bureau Veritas. (n.d.-b). Bureau Veritas - Equasis - Coral Star. Retrieved December 10, 2016, from http://www.veristar.com/portal/veristarinfo/equasis?IMO=9685499

CE Delft, Germanischer Lloyd, Marintek, & Det Norske Veritas. (2006). *Greenhouse Gas Emissions for Shipping and Implementation Guidance for the Marine Fuel Sulphur Directive*. Retrieved from http://ec.europa.eu/environment/air/pdf/transport/final_report.pdf%5Cnhttp://ec.europa.eu/geninfo/query/index.do?swlang=en#queryText="Greenhouse+Gas+Emissions+for+Shipping+and+Implementation+Guidance+for+the+Marine+Fuel+Sulphur+Directive"&ta

DNV-GL. (n.d.-a). DNV GL Vessel Register - M/T BORGØY. Retrieved December 9, 2016, from http://vesselregister.dnvgl.com/vesselregister/vesseldetails.html?vesselid=32428

DNV-GL. (n.d.-b). LNG as ship fuel. A focus on the current and future use of LNG as fuel in shipping. Retrieved December 15, 2016, from https://www.dnvgl.com/maritime/lng/index.html

DNV-GL. (n.d.-c). LNG Safety. Retrieved December 15, 2016, from https://www.dnvgl.com/maritime/lng/lng-safety.html

DNV-GL. (2012). *Shipping 2020*. Retrieved from http://www.lngbunkering.org/sites/default/files/2012_DNV_Shipping 2020 - final report.pdf

DNV-GL. (2014a). *LNG as Ship Fuel: The Future - Today*. Retrieved from https://www.dnvgl.com/Images/LNG_report_2015-01_web_tcm8-13833.pdf

DNV-GL. (2014b). *Rules for classification of ships, Part 6, Chapter 13 Gas-Fuelled Ship Installations. Ships/High Speed, Light Craft and Naval Surface Craft*. Retrieved from https://rules.dnvgl.com/docs/pdf/DNV/rulesship/2014-01/ts613.pdf

DNV-GL. (2015a). *IMO NOX TIER III REQUIREMENTS TO TAKE EFFECT ON JANUARY 1 ST 2016*. Retrieved from http://www4.dnvgl.com/l/62522/2015-12-17/v32ys/62522/71333/DNV_GL_Technical_Regulatory_News_No27_2015.pdf

DNV-GL. (2015b). *IN FOCUS - LNG AS SHIP FUEL*. Retrieved from https://www.google.es/?gws_rd=ssl#q=in+focus+lng+as+ship+fuel+dnv

DNV-GL. (2016a). *DNV GL – LNG fuelled vessels*. Retrieved from http://www4.dnvgl.com/e/62522/rld-

LNG-fuelled-fleet-list-pdf/22xnjt/277672848

DNV-GL. (2016b). *UPCOMING ENVIRONMENTAL REGULATIONS FOR EMISSIONS TO AIR – IMO NOx TIER III*. Retrieved from http://www4.dnvgl.com/l/62522/2015-10-28/qw226/62522/65651/DNV_GL_Technical_and_regulatory_news_No21_2015.pdf

Eidesvik. (n.d.). Viking Energy. Retrieved December 8, 2016, from http://www.eidesvik.no/viking-energy/category500.html

Equasis. (n.d.). Ship search - Ship info - Viking Grace. Retrieved December 8, 2016, from http://www.equasis.org/EquasisWeb/restricted/ShipInfo?fs=ShipList#classification

Faber, J., Nelissen, D., Ahdour, S., Harmsen, J., Toma, S., & Lebesque, L. (2015). *Study on the Completion of an EU Framework on LNG-fuelled Ships and its Relevant Fuel Provision Infrastructure. Analysis of the LNG market development in the EU*. Retrieved from http://ec.europa.eu/transport/sites/transport/files/modes/maritime/studies/doc/2015-12-lng-lot3.pdf

GloMEEP. (n.d.-a). ABOUT THE PROJECT. Retrieved December 30, 2016, from http://glomeep.imo.org/about/about-the-project/

GloMEEP. (n.d.-b). AIR CAVITY LUBRICATION. Retrieved January 5, 2017, from http://glomeep.imo.org/technology/air-cavity-lubrication/

GloMEEP. (n.d.-c). AUTOPILOT ADJUSTMENT AND USE. Retrieved January 5, 2017, from http://glomeep.imo.org/technology/autopilot-adjustment-and-use/

GloMEEP. (n.d.-d). AUXILIARY SYSTEMS OPTIMIZATION. Retrieved January 5, 2017, from http://glomeep.imo.org/technology/auxiliary-systems-optimization/

GloMEEP. (n.d.-e). CARGO HANDLING SYSTEMS (CARGO DISCHARGE OPERATION). Retrieved January 5, 2017, from http://glomeep.imo.org/technology/cargo-handling-systems-cargo-discharge-operation/

GloMEEP. (n.d.-f). ENERGY EFFICIENCY TECHNOLOGIES INFORMATION PORTAL. Retrieved January 5, 2017, from http://glomeep.imo.org/resources/energy-efficiency-techologies-information-portal/

GloMEEP. (n.d.-g). ENERGY EFFICIENT LIGHTING SYSTEM. Retrieved January 5, 2017, from http://glomeep.imo.org/technology/energy-efficient-lighting-system/

GloMEEP. (n.d.-h). ENGINE DE-RATING. Retrieved January 5, 2017, from http://glomeep.imo.org/technology/engine-de-rating/

GloMEEP. (n.d.-i). ENGINE PERFORMANCE OPTIMIZATION (AUTOMATIC). Retrieved January 5, 2017, from http://glomeep.imo.org/technology/engine-performance-optimization-automatic/

GloMEEP. (n.d.-j). EXHAUST GAS BOILERS ON AUXILIARY ENGINES. Retrieved January 5, 2017, from http://glomeep.imo.org/technology/exhaust-gas-boilers-on-auxiliary-engines/

GloMEEP. (n.d.-k). FIXED SAILS OR WINGS. Retrieved January 7, 2017, from http://glomeep.imo.org/technology/fixed-sails-or-wings/

GloMEEP. (n.d.-l). FLETTNER ROTORS. Retrieved January 7, 2017, from http://glomeep.imo.org/technology/flettner-rotors/

GloMEEP. (n.d.-m). HULL CLEANING. Retrieved January 5, 2017, from http://glomeep.imo.org/technology/hull-cleaning/

GloMEEP. (n.d.-n). HULL COATING. Retrieved January 5, 2017, from http://glomeep.imo.org/technology/hull-coating/

GloMEEP. (n.d.-o). HULL FORM OPTIMIZATION. Retrieved January 5, 2017, from http://glomeep.imo.org/technology/hull-form-optimization/

GloMEEP. (n.d.-p). HULL RETROFITTING. Retrieved January 5, 2017, from http://glomeep.imo.org/technology/hull-retrofitting/

GloMEEP. (n.d.-q). HYBRIDIZATION (PLUG-IN OR CONVENTIONAL). Retrieved January 5, 2017, from http://glomeep.imo.org/technology/hybridization-plug-in-or-conventional/

GloMEEP. (n.d.-r). IMPROVED AUXILIARY ENGINE LOAD. Retrieved January 5, 2017, from http://glomeep.imo.org/technology/improved-auxiliary-engine-load/

GloMEEP. (n.d.-s). KITE. Retrieved January 7, 2017, from http://glomeep.imo.org/technology/kite/

GloMEEP. (n.d.-t). PROPELLER POLISHING. Retrieved January 5, 2017, from http://glomeep.imo.org/technology/propeller-polishing/

GloMEEP. (n.d.-u). PROPELLER RETROFITTING. Retrieved January 5, 2017, from http://glomeep.imo.org/technology/propeller-retrofitting/

GloMEEP. (n.d.-v). PROPULSION IMPROVING DEVICES (PIDS). Retrieved January 5, 2017, from http://glomeep.imo.org/technology/propulsion-improving-devices-pids/

GloMEEP. (n.d.-w). SHORE POWER. Retrieved January 5, 2017, from http://glomeep.imo.org/technology/shore-power/

GloMEEP. (n.d.-x). SOLAR PANELS. Retrieved January 7, 2017, from http://glomeep.imo.org/technology/solar-panels/

GloMEEP. (n.d.-y). SPEED MANAGEMENT. Retrieved January 5, 2017, from http://glomeep.imo.org/technology/speed-management/

GloMEEP. (n.d.-z). TRIM AND DRAFT OPTIMIZATION. Retrieved January 5, 2017, from http://glomeep.imo.org/technology/trim-and-draft-optimization/

GloMEEP. (n.d.-aa). WASTE HEAT RECOVERY SYSTEMS. Retrieved January 5, 2017, from http://glomeep.imo.org/technology/waste-heat-recovery-systems/

Haraldson, L. (2011). *LNG as a fuel for environmentally friendly shipping: Retrofit perspective*. *33rd Motorship Propulsion & Emissions Conference*. Retrieved from http://www.dma.dk/themes/LNGinfrastructureproject/Documents/Bunkering operations and ship propulsion/Wartsila-SP-ppt-2011-LNGretrofit.pdf

Hughes, E. (2016). *Recent developments at IMO to address GHG emissions from ships*. Retrieved from http://www.imo.org/en/OurWork/Environment/PollutionPrevention/AirPollution/Pages/UN Joint side event presentation.pdf

IMO. (n.d.-a). Air Pollution, Energy Efficiency and Greenhouse Gas Emissions. Retrieved November 15, 2016, from http://www.imo.org/en/OurWork/Environment/PollutionPrevention/AirPollution/Pages/Default.aspx

IMO. (n.d.-b). Energy Efficiency Measures. Retrieved November 15, 2016, from http://www.imo.org/en/OurWork/Environment/PollutionPrevention/AirPollution/Pages/Technical-and-Operational-Measures.aspx

IMO. (n.d.-c). Greenhouse Gas Emissions. Retrieved November 12, 2016, from http://www.imo.org/en/ourwork/environment/pollutionprevention/airpollution/pages/ghg-emissions.aspx

IMO. (n.d.-d). IMO-European Union Project on Capacity Building for Climate Change Mitigation in the Maritime Shipping Sector. Retrieved December 30, 2016, from http://www.imo.org/en/OurWork/Environment/SupportToMemberStates/MajorProjects/Pages/IMO-EuropeanUnionProject.aspx

IMO. (n.d.-e). International Code of Safety for Ship Using Gases or Other Low-flashpoint Fuels (IGF

Code). Retrieved December 15, 2016, from http://www.imo.org/en/OurWork/Safety/SafetyTopics/Pages/IGF-Code.aspx

IMO. (n.d.-f). Introduction to IMO. Retrieved November 12, 2016, from http://www.imo.org/en/about/pages/default.aspx

IMO. (n.d.-g). Low carbon shipping and air pollution control. Retrieved December 27, 2016, from http://www.imo.org/en/MediaCentre/HotTopics/GHG/Pages/default.aspx

IMO. (n.d.-h). Marine Environment Protection Committee (MEPC), 70th session, 24-28 October 2016. Retrieved December 27, 2016, from http://www.imo.org/en/MediaCentre/MeetingSummaries/MEPC/Pages/MEPC-70th-session.aspx

IMO. (n.d.-i). New requirements for international shipping as UN body continues to address greenhouse gas emissions. Retrieved December 28, 2016, from http://www.imo.org/en/mediacentre/pressbriefings/pages/28-mepc-data-collection--.aspx

IMO. (n.d.-j). Nitrogen oxides (NOx) – Regulation 13. Retrieved November 15, 2016, from http://www.imo.org/en/OurWork/Environment/PollutionPrevention/AirPollution/Pages/Nitrogen-oxides-(NOx)-–-Regulation-13.aspx

IMO. (n.d.-k). Prevention of Air Pollution from Ships. Retrieved November 12, 2016, from http://www.imo.org/en/ourwork/environment/pollutionprevention/airpollution/pages/air-pollution.aspx

IMO. (n.d.-l). Sulphur oxides (SOx) – Regulation 14. Retrieved November 15, 2016, from http://www.imo.org/en/OurWork/Environment/PollutionPrevention/AirPollution/Pages/Sulphur-oxides-(SOx)-–-Regulation-14.aspx

IMO. (n.d.-m). Technical Co-operation (TC). Retrieved December 30, 2016, from http://www.imo.org/en/OurWork/Environment/PollutionPrevention/AirPollution/Pages/Technical-Co-operation.aspx

IMO. (2011a). *International Convention for the Prevention of Pollution from Ships (MARPOL) - Annex VI Prevention of Air Pollution from Ships*. Retrieved from http://vp.imo.org/Customer/Subscriptions/IMOVEGA/MemberPages/Contents.aspx?nodeId=IDCC83AD65

IMO. (2011b). *Investigation of appropriate control measures (abatement technologies) to reduce Black Carbon emissions from international shipping*. Retrieved from http://www.imo.org/en/OurWork/Environment/PollutionPrevention/AirPollution/Documents/Air pollution/Black Carbon.pdf

IMO. (2014a). *DRAFT INTERNATIONAL CODE OF SAFETY FOR SHIPS USING GASES OR OTHER LOW-FLASHPOINT FUELS (IGF CODE)*. Retrieved from http://www.lng-info.de/fileadmin/Normen/Draft_IGF-Code_26.04._2013_rev.12.07.2013.pdf

IMO. (2014b). *Third IMO GHG Study 2014*. Retrieved from http://www.imo.org/en/OurWork/Environment/PollutionPrevention/AirPollution/Documents/Third Greenhouse Gas Study/GHG3 Executive Summary and Report.pdf

IMO. (2015). *Study of emission control and energy efficiency measures for ships in port area*. *AIr Pollution and energy efficiency studies*. https://doi.org/10.1017/CBO9781107415324.004

IMO. (2016a). *Studies on the feasibility and use of LNG as a fuel for shipping*. Retrieved from http://www.imo.org/en/OurWork/Environment/PollutionPrevention/AirPollution/Documents/LNG Study.pdf

IMO. (2016b). *Update on IMO's work to address GHG emissions from fuel used for international shipping* (Vol. 10). Retrieved from http://www.imo.org/en/OurWork/Environment/PollutionPrevention/AirPollution/Pages/IMO SBSTA 45 submission.pdf

Karlsson, S., & Sonzio, L. (2008). Enabling the safe storage of gas onboard ships with the Wärtsilä LNGPac. *Wärtsila Technical Journal*, 52–56. Retrieved from http://www.lngbunkering.org/lng/sites/default/files/2010 Wartsila safe-storage-gas-lngpac.pdf

Kluijven, P. C. van. (2003). *The international maritime language programme*. Alk & Heijnen.

Krüger, S. (2011). *The Energy Efficiency Design Index (EEDI) for RoRo-Vessels*. Retrieved from www.theicct.org

Levander, O. (2011). *Fuel selection for Ro-Ro Vessels*. Retrieved from http://www.dma.dk/themes/LNGinfrastructureproject/Documents/Bunkering operations and ship propulsion/Wartsila-SP-ppt-2011-RoRo.pdf

Lloyd's Register. (2015). *IMO Marine Environment Protection Committee Seventieth session (MEPC 70) Summary Report*. Retrieved from http://www.lr.org/en/_images/229-103721_MEPC_70_Summary_Report_-_Rev_1.pdf

LNG Fuelled Vessels Working Group. (n.d.-a). Engine types. Retrieved November 24, 2016, from http://www.lngbunkering.org/lng/technical-solutions/engine-types

LNG Fuelled Vessels Working Group. (n.d.-b). Existing fleet and current orderbooks. Retrieved December 7, 2016, from http://www.lngbunkering.org/lng/vessels/existing-fleet-orderbooks

LNG Fuelled Vessels Working Group. (n.d.-c). Future developments in the LNG fleet. Retrieved December 7, 2016, from http://www.lngbunkering.org/lng/vessels/future-developments-lng-fleet

LNG Fuelled Vessels Working Group. (n.d.-d). Tank types. Retrieved November 30, 2016, from http://www.lngbunkering.org/lng/technical-solutions/tank-types

MAN Diesel. (2013). *ME-GI Dual Fuel MAN B&W Engines*. Retrieved from http://www.dma.dk/themes/LNGinfrastructureproject/Documents/Bunkering operations and ship propulsion/ME-GI Dual Fuel MAN Engines.pdf

Munko, B. (2013). *Supply, storage and handling of LNG as ship's fuel*. Retrieved from http://www.lngbunkering.org/sites/default/files/2013 TGE Supply, storage and handling of LNG as ship's fuel.pdf

Osberg, T. G. (2008). *Gas engine propulsion in ships*. Retrieved from http://www.glmri.org/downloads/lngMisc/DNV-Gas Engine Propulsion in Ships (safety considerations)-Torill Grimstad Osberg- I.pdf

Rodrigo de Larrucea, J. (2015). *Seguridad marítima : teoría general del riesgo*. Marge Books.

Rolls-Royce. (n.d.-a). Engines and turbines for cruise and ferry. Retrieved November 28, 2016, from http://www.rolls-royce.com/products-and-services/marine/market-sectors/cruise-and-ferry/engines-and-turbines.aspx

Rolls-Royce. (n.d.-b). LNG. Retrieved November 28, 2016, from http://www.rolls-royce.com/products-and-services/marine/lng.aspx#section-overview

Rolls-Royce. (n.d.-c). LNG - Cruise and ferry. Retrieved November 28, 2016, from http://www.rolls-royce.com/products-and-services/marine/market-sectors/cruise-and-ferry/lng.aspx

Rolls-Royce. (n.d.-d). LNG – Systems - Explore our ship systems. Retrieved November 30, 2016, from http://www.rolls-royce.com/products-and-services/marine/lng.aspx#section-systems

Rolls-Royce. (n.d.-e). Medium-speed power systems solutions. Retrieved November 28, 2016, from https://bergen.rolls-royce.com/

Rolls-Royce. (n.d.-f). Medium speed gas engines – Rolls-Royce. Retrieved November 28, 2016, from http://www.rolls-royce.com/products-and-services/marine/product-finder/diesel-and-gas-engines/medium-speed-gas-engines.aspx#section-product-search

Rolls-Royce. (n.d.-g). Tugs and workboats - LNG. Retrieved November 28, 2016, from http://www.rolls-royce.com/products-and-services/marine/market-sectors/tugs-workboats/lng.aspx

Rolls-Royce. (2012). *Diesel & Gas Engines*. Retrieved from http://www.rolls-royce.com/~/media/Files/R/Rolls-Royce/documents/customers/marine/diesel-gas-engines-brochure.pdf

SABIC. (2015). *SABIC LNG vessels. Sustainable Innovation in Marine Shipping. Fact and Figures Facts and Figures*. Retrieved from http://www.sabic.com/europe/en/images/SHell-LNG-Vessels-Facts-Figures-2015_tcm41-16121.pdf

SABIC. (2016). SABIC and Anthony Veder pioneer LNG as a clean marine fuel in the North Sea and commission an LNG-bunker facility in the UK, (January), 1–4. Retrieved from https://www.sabic.com/europe/en/news-and-media/news/2016/europe/20160111-Anthony-Veder

Sanmar A.S. (n.d.). LNG Powered Escort Tugs. Retrieved December 9, 2016, from http://www.sanmar.com.tr/portfolio-items/lng-powered-escort-tugs/

Semolinos, P., Olsen, G., & Giacosa, A. (2013). LNG As Marine Fuel: Challenges To Be Overcome. *17th International Conference & Exhibition on Liquified Natural Gas*, 1–20. Retrieved from http://www.gastechnology.org/Training/Documents/LNG17-proceedings/7-2-Pablo_Semolinos.pdf

Ship Technology. (n.d.). Marlin-Class, LNG-Powered Container Ships. Retrieved December 11, 2016, from http://www.ship-technology.com/projects/marlin-class-lng-powered-container-ships/

Stenersen, D. (2011). *Gas Fuelled Ships. Marintek, SINTEF, Shanghai*. Retrieved from http://www.lngbunkering.org/sites/default/files/2011 marintek LNG fuelled ships.pdf

The European Parliament, & The Council of the European Union. (2012). *DIRECTIVE 2012/33/EU regards the sulphur content of marine fuels*. *Official Journal of the European Union*. Retrieved from http://www.lngbunkering.org/lng/sites/default/files/2012 Directive 2012 33 EU as regards the sulphur content of marine fuels.pdf

TOTE Inc. (2012). World's FIrst LNG-Powered Container ships To Serve Puerto Rico For TOTE, Inc. Retrieved December 11, 2016, from http://toteinc.com/worlds-first-lng-powered-container-ships-to-serve-puerto-rico-for-toteinc/

TOTE Inc. (2016). TOTE Maritime Puerto Rico Successfully Performs First LNG Bunkering at Jacksonville Port. Retrieved December 11, 2016, from http://toteinc.com/tote-maritime-puerto-rico-successfully-performs-first-lng-bunkering-at-jacksonville-port/

Wan, C., Yan, X., Zhang, D., Shi, J., Fu, S., & Ng, A. K. Y. (2015). Emerging LNG-fueled ships in the Chinese shipping industry: a hybrid analysis on its prospects. *WMU Journal of Maritime Affairs*, *14*(1), 43–59. https://doi.org/10.1007/s13437-015-0080-6

Wärtsilä. (n.d.-a). Dual-fuel LNG tanker CORAL ENERGY. Retrieved December 10, 2016, from http://www.wartsila.com/encyclopedia/term/dual-fuel-lng-tanker-coral-energy

Wärtsilä. (n.d.-b). Natural gas-fuelled ferry VIKING GRACE. Retrieved December 8, 2016, from http://www.wartsila.com/encyclopedia/term/natural-gas-fuelled-ferry-viking-grace

Wärtsilä. (n.d.-c). Platform supply vessel VIKING ENERGY. Retrieved December 8, 2016, from http://www.wartsila.com/encyclopedia/term/platform-supply-vessel-viking-energy

Wärtsilä. (n.d.-d). Viking Energy. Retrieved December 8, 2016, from http://www.wartsila.com/resources/customer-references/view/viking-energy

Wärtsilä. (n.d.-e). Viking Grace. Retrieved December 8, 2016, from http://www.wartsila.com/resources/customer-references/marine/cruise-ferry/viking-grace

Wärtsilä. (2014). *The New Wärtsilä LNGPac*. Retrieved from http://cdn.wartsila.com/docs/default-source/product-files/ogi/fuel-gas-handling/brochure-o-ogi-lngpac-new.pdf?sfvrsn=2

Wärtsilä. (2015). *DUAL-FUEL ENGINES*. Retrieved from http://cdn.wartsila.com/docs/default-source/product-files/engines/df-engine/brochure-o-e-df-engines-2015.pdf?sfvrsn=6

Wärtsilä. (2016). *LNG SHIPPING SOLUTIONS*. Retrieved from http://cdn.wartsila.com/docs/default-source/oil-gas-documents/brochure-lng-shipping-solutions.pdf?sfvrsn=6

Woodyard, D. (2004). *Pounder's Marine Diesel Engines and Gas Turbines* (Eighth Edi). Retrieved from http://www.albadr.org/www/pdf/library/487.pdf

Yang, Z. L., Zhang, D., Caglayan, O., Jenkinson, I. D., Bonsall, S., Wang, J., … Yan, X. P. (2012). Selection of techniques for reducing shipping NOx and SOx emissions. *Transportation Research Part D: Transport and Environment*, *17*(6), 478–486. https://doi.org/10.1016/j.trd.2012.05.010

Annex A. List of LNG-Fuelled Vessels in Operation Worldwide

Year	**Type of vessel**	**Ship owner**	**Classification Society**
2000	Car/passenger ferry	Fjord1	DNV-GL
2003	PSV	Simon Møkster	DNV-GL
2003	PSV	Eidesvik	DNV-GL
2006	Car/passenger ferry	Fjord1	DNV-GL
2007	Car/passenger ferry	Fjord1	DNV-GL
2007	Car/passenger ferry	Fjord1	DNV-GL
2007	Car/passenger ferry	Fjord1	DNV-GL
2007	Car/passenger ferry	Fjord1	DNV-GL
2008	PSV	Eidesvik Shipping	DNV-GL
2009	PSV	Eidesvik Shipping	DNV-GL
2009	Car/passenger ferry	Tide Sjø	DNV-GL
2009	Car/passenger ferry	Tide Sjø	DNV-GL
2009	Car/passenger ferry	Tide Sjø	DNV-GL
2009	Patrol vessel	Remøy Management	DNV-GL
2009	Car/passenger ferry	Fjord1	DNV-GL
2010	Patrol vessel	Remøy Management	DNV-GL

2010	Car/passenger ferry	Fjord1	DNV-GL
2010	Patrol vessel	Remøy Management	DNV-GL
2010	Car/passenger ferry	Fjord1	DNV-GL
2010	Car/passenger ferry	Fjord1	DNV-GL
2010	Car/passenger ferry	Fosen Namsos Sjø	DNV-GL
2011	PSV	DOF	DNV-GL
2011	Oil/chemical tanker	Tarbit Shipping	DNV-GL
2011	Car/passenger ferry	Fjord1	DNV-GL
2011	PSV	Solstad Rderi	DNV-GL
2012	Car/passenger ferry	Fjord1	DNV-GL
2012	PSV	Eidesvik	DNV-GL
2012	PSV	Olympic Shipping	DNV-GL
2012	PSV	Island Offshore	DNV-GL
2012	General cargo vessel	Nordnorsk Shipping	DNV-GL
2012	PSV	Eidesvik Shipping	DNV-GL
2012	PSV	Island Offshore	DNV-GL
2012	Car/passenger ferry	Torhatten Nord	DNV-GL
2012	Car/passenger ferry	Torhatten Nord	DNV-GL
2012	Car/passenger ferry	Torhatten Nord	DNV-GL
2013	PSV	REM	DNV-GL
2013	RoPax	Viking Line	LR
2013	Car/passenger ferry	Torhatten Nord	DNV-GL
2013	Tug	Incheon Port Authority	KR
2013	General cargo	Eidsvaag	DNV-GL
2013	RoPax	Fjordline	DNV-GL
2013	High speed RoPax	Buquebus	DNV-GL

2013	Tug	CNOOC	CCS
2013	Tug	CNOOC	CCS
2013	Car/passenger ferry	Norled	DNV-GL
2014	Car/passenger ferry	Norled	DNV-GL
2014	Tug	Buksér & Berging	DNV-GL
2014	RoPax	Fjordline	DNV-GL
2010	Patrol vessel	Finish Border Guard	DNV-GL
2014	Tug	Buksér & Berging	DNV-GL
2014	Gas carrier	Anthony Veder	BV
2014	Gas carrier	Anthony Veder	BV
2014	PSV	Remøy Shipping	DNV-GL
2014	General cargo	Egil Ulvan Rederi	DNV-GL
2014	General cargo	Egil Ulvan Rederi	DNV-GL
2014	PSV	Siem Offshore	DNV-GL
2014	PSV	Harvey Gulf Int.	ABS
2015	Ro-Ro	Norlines	DNV-GL
2015	Car/passenger ferry	Samsoe municipality	DNV-GL
2015	PSV	Simon Møkster Shipping	DNV-GL
2015	PSV	Siem Offshore	DNV-GL
2015	Ro-Ro	Norlines	DNV-GL
2015	Oil/chemical tanker	Bergen Tankers	LR
2015	Car/passenger ferry	Society of Quebec Ferries	LR
2015	Gas carrier	Evergas	BV
2015	Gas carrier	Evergas	BV
2015	Tug	CNOOC	CCS

2015	Car/passenger ferry	AG Ems	DNV-GL
2015	Tug	NYK	NK
2015	Gas carrier	Chemgas Shipping	BV
2015	Gas carrier	Evergas	BV
2015	PSV	Harvey Gulf Int.	ABS
2015	Containership	TOTE Shipholdings	ABS
2015	Car/passenger ferry	AG Ems	DNV-GL
2015	Bulk ship	Erik Thun	LR
2016	Containership	TOTE Shipholdings	ABS
2016	Gas carrier	Evergas	BV

According to DNV-GL as of March 21, 2016 (DNV-GL, 2016a).

Annex B. List of Confirmed LNG-Fuelled New Buildings

Year	Type of vessel	Ship owner	Classification Society
2016	Car/passenger ferry	Society of Quebec Ferries	LR
2016	Car/passenger ferry	Society of Quebec Ferries	LR
2016	PSV	Harvey Gulf Int.	ABS
2016	Tug	CNOOC	CCS
2016	Tug	Drydocks Wolrd	
2016	PSV	Harvey Gulf Int.	ABS
2016	PSV	Harvey Gulf Int.	ABS
2016	PSV	Siem Offshore	DNV-GL
2016	PSV	Siem Offshore	DNV-GL
2015	Oil/chemical tanker	Furetank Rederi	BV
2016	Gas carrier	Evergas	BV
2016	Gas carrier	Evergas	BV
2016	PSV	Harvey Gulf Int.	ABS
2016	Icebreaker	Finnish Transport Agency	ABS
2016	PSV	Siem Offshore	DNV-GL
2016	PSV	Siem Offshore	DNV-GL

2016	Gas carrier	Chemgas Shipping	
2016	Oil/chemical tanker	Temtank	BV
2016	Oil/chemical tanker	Temtank	BV
2016	Oil/chemical tanker	Temtank	BV
2016	Ro-Ro	TOTE Shipholdings	ABS
2016	Car carrier	UECC	LR
2016	Car carrier	UECC	LR
2016	Car/passenger ferry	Boreal	DNV-GL
2016	Car/passenger ferry	Boreal	DNV-GL
2016	Containership	GNS Shipping	ABS
2016	Containership	GNS Shipping	ABS
2016	Ro-Ro	Searoad Holdings	DNV-GL
2016	Car/passenger ferry	BC Ferries	LR
2016	Car/passenger ferry	BC Ferries	LR
2016	Gas carrier	Ocean Yield	DNV-GL
2016	Gas carrier	Ocean Yield	DNV-GL
2016	Gas carrier	Ocean Yield	DNV-GL
2016	Car/passenger ferry	Seaspan Ferries Corp.	BV
2016	Car/passenger ferry	Seaspan Ferries Corp.	BV
2016	Gas carrier	Navigator Gas	ABS
2016	Gas carrier	Navigator Gas	ABS
2016	Gas carrier	Navigator Gas	ABS
2016	Gas carrier	Navigator Gas	ABS
2016	RoPax	Balearia	BV
2016	Dredger	DEME	BV
2016	Dredger	DEME	BV

2016	Containership	Wessels Rederi	ABS
2016	Hoper barge	Bremenports	DNV-GL
2017	Cable layer	DEME Tideway	DNV-GL
2017	Gas carrier	Evergas	BV
2017	Gas carrier	Evergas	BV
2017	Tug	Østensjø Rederi	
2017	Tug	Østensjø Rederi	
2017	Tug	Østensjø Rederi	
2017	RoPax	Rederi AB Gotland	DNV-GL
2017	Car/passenger ferry	Caronte & Tourist	RINA
2017	Oil/chemical tanker	Groupe Desgagnés	BV
2017	Oil/chemical tanker	Groupe Desgagnés	BV
2017	Containership	GNS Shipping	ABS
2017	Containership	GNS Shipping	ABS
2017	Car/passenger ferry	BC Ferries	LR
2017	Oil/chemical tanker	Temtank	BV
2017	Containership	Crowley Maritime Corp.	DNV-GL
2017	Containership	Crowley Maritime Corp.	DNV-GL
2017	RoPax	Tallink	BV
2017	Containership	Brodosplit	DNV-GL
2018	Containership	Brodosplit	DNV-GL
2018	Bulk ship	ESL Shipping	DNV-GL
2018	Bulk ship	ESL Shipping	DNV-GL
2018	Containership	Brodosplit	DNV-GL
2018	Containership	Brodosplit	DNV-GL

2018	Car/passenger ferry	CHFS	LR
2018	Car/passenger ferry	CHFS	LR
2018	Ro-Ro	TOTE Shipholdings	ABS
2018	RoPax	Rederi AB Gotland	DNV-GL
2018	General cargo vessel	Nordnorsk Shipping	
2018	Containership	Containerships	ABS
2018	Containership	Containerships	ABS
2018	Heavy lift vessel	Heerema Offshore	LR
2018	Oil/chemical tanker	Furetank Rederi	
2018	Oil/chemical tanker	Furetank Rederi	
2018	Dredger	DEME	
2018	Cruise vessel	Carnival Corporation	RINA
2019	Cruise vessel	Carnival Corporation	RINA
2019	Oil/chemical tanker	Älvtank	
2019	Oil/chemical tanker	Thun Tankers	
2019	RoPax	Balearia	BV
2020	Cruise vessel	Carnival Corporation	RINA
2022	Cruise vessel	Carnival Corporation	RINA

According to DNV-GL as of March 21, 2016 (DNV-GL, 2016a).