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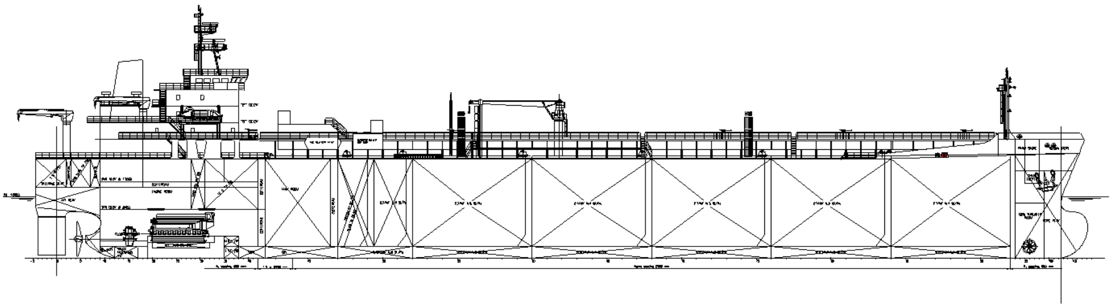
TECNOLOGIE CHIMICHE ED ENERGETICHE

XXVI CICLO

NATURAL GAS UTILIZATION FOR SHIP PROPULSION

Fabio BUREL



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SUMMARY

About 3% of the global emissions are produced by ship transport but are concentrated in coastal and small areas with high ship traffic. For these reasons, the International Maritime Organization (IMO) has developed a program for reducing the environmental impact of the maritime transport. In order to respect these new rules, natural gas used as ship fuel is an interesting solution since it allows to reduce pollutant emissions and it is available in large quantities and at a price today lower than diesel oil.

To identify the most suitable vessels for an LNG propulsion project, a statistical analysis of the world maritime traffic has been carried out. The most suitable vessels has been selected on the basis of their time spent into the Emission Controlled Area (ECA, area with strict limits on gas emissions) and the delivery forecast of new ship. Furthermore, a second analysis using traffic data of three different years has been developed to confirm the robustness of the obtained results and highlight possible trends in the considered period. The results pointed out that tanker ships are one of the best ship type for the LNG propulsion.

The use of natural gas in its liquid form need gas engines, cryogenic tank and a gas handling system: all these components have been described highlighting advantages and drawbacks. To assess the technical feasibility and highlight the main issues, dynamic simulations on the gas tank of specific ships have been developed. In particular, tank pressure variation and gas composition has been examined since influences the gas plant layout and the engine performances. The analysis highlighted that the tank insulation is one of the most critical parameters: further investigations are necessary to develop a control strategy aimed to control the tank pressure maintaining a good quality of the gas mixture.

Furthermore, the use of natural gas allows new energy recovery technologies: an energy analysis on a specific ship has been carried out to demonstrate the possible efficiency improvements and then fuel and emissions savings. The analysis encompasses several recovery technologies, starting from the simple heat recovery to more complex systems with Organic Rankine cycle adoption coupled with heat recovery. An efficiency increasing of about 5% respect to a traditional tanker ship with heat recovery has been obtained.

The last objective is to demonstrate the environmental and economic benefit of the LNG propulsion: for this reason a comparison between oil fuel and natural gas has been carried out, highlighting the gas emissions savings and the payback periods of the different plant solutions in compliance with the new emissions rules. Different plant solutions and price scenarios has been considered to verify also the reliability of the obtained results. The results demonstrated that a CO_2 emission reduction greater than 20% can be achieved and the payback period for an LNG system can be three years.

SOMMARIO

Circa il 3% delle emissioni globali sono imputabili al trasporto marittimo ma sono concentrate nelle zone costiere ed in piccole aree ad alto traffico. Per queste ragioni, l'Organizzazione Marittima Mondiale (IMO) ha redatto un programma per la riduzione dell'impatto ambientale dovuto al trasporto marittimo. Al fine di rispettare queste nuove norme, l'utilizzo del gas naturale come combustibile navale è una soluzione interessante dato che permette di ridurre le emissioni inquinanti ed è disponibile in grandi quantità ad un prezzo attualmente inferiore rispetto a quello dell'olio combustibile.

Per identificare le navi più adatte all'utilizzo del Gas Naturale Liquefatto (GNL), è stata effettuata un'analisi statistica del traffico marittimo. Le navi maggiormente adatte all'utilizzo del GNL sono state selezionate in base al loro tempo trascorso all'interno delle zone ad emissioni controllate (zone ECA, zone con severi limiti sulle emissioni inquinanti) e le previsioni di consegna di nuove navi. Inoltre, è stata effettuata una seconda analisi analizzando i dati di traffico di tre diversi anni per dimostrare la robustezza dei risultati ottenuti ed evidenziare possibili trend nel periodo considerato. I risultati mostrano che le navi cisterna sono la tipologia di nave più adatta all'utilizzo del GNL.

L'utilizzo del gas naturale in forma liquida richiede l'utilizzo di motori alimentati a gas, serbatoi criogenici ed un impianto di trattamento e distribuzione: tutti questi componenti sono stati descritti evidenziandone vantaggi ed i lati negativi.

Per valutare la fattibilità tecnica ed evidenziare le principali criticità, sono state condotte delle simulazioni dinamiche sul serbatoio di una nave specifica. In particolare sono state esaminate le variazioni di pressione e composizione del gas dato che influenzano il layout dell'impianto e le prestazioni dei motori. L'analisi ha mostrato che l'isolamento del serbatoio è uno dei parametri critici: ulteriori approfondimenti sono necessari per sviluppare una strategia di controllo finalizzata a controllare la pressione mantenendo una buona qualità della miscela di gas.

Inoltre, l'utilizzo del gas naturale consente l'utilizzo di nuove forme di recupero energetico: è stata svolta un'analisi energetica su una nave specifica per dimostrare i possibili miglioramenti dell'efficienza e le possibili riduzioni di emissioni e consumi. L'analisi comprende diverse tecnologie di recupero energetico, partendo dal semplice recupero termico fino ai complessi sistemi con cicli Rankine a fluido organico accoppiati al recupero del calore. È stato così possibile ottenere un incremento dell'efficienza del 5% rispetto ad una tradizionale nave cisterna con un sistema di recupero del calore.

L'ultimo obiettivo è quello di dimostrare i vantaggi economici ed ecologici della propulsione a GNL: per questa ragione è stato effettuato un confronto fra olio combustibile e gas naturale, evidenziando la riduzione delle emissioni gassose inquinanti ed il tempo di ritorno dell'investimento per le diverse soluzioni impiantistiche rispettanti le normative sulle emissioni. Diverse soluzioni impiantistiche e diversi scenari sui prezzi dei combustibili sono stati considerati per verificare l'affidabilità dei risultati ottenuti. I risultati dimostrano che le emissioni di CO2 sono ridotte di oltre il 20% e che il periodo di ritorno dell'investimento può essere di tre anni.

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NOMENCLATURE

Acronyms

BOG: Boil Off Gas

DWT: Deadweight Tonnage

ECA: Emission Control Area

EU: European Union

GCU: Gas Combustion Unit

GHG: Global Greenhouse Gas

GT: Gross Tonnage

HFO: Heavy Fuel Oil

HR: Heat Recovery

HT: High Temperature

IFO: Intermediate Fuel Oil

IGF: International Gas Fuelled Ship Code

IMO: International Maritime Organization

IPCC: Intergovernmental Panel on Climate Change

LFL: Lower Flammability Limit

LHV: Lower Heating Value

LNG: Liquefied Natural Gas

LT: Low Temperature

LS: Low Sulphur

MDO: Marine Diesel Oil

MGO: Marine Gas Oil

NG: Natural Gas

NMI: Nautical Miles

NO_X: Nitrogen Oxides

ORC: Organic Rankine Cycle

PM: Particulate Matter

Ro-Ro: Roll-on/Roll-off

RPT: Rapid Phase Transition

SCR:	Selective Catalytic Reduction
PTI:	Power Take In
PTO:	Power Take Off
ULCC:	Ultra Large Crude Carrier
UNFCCC:	United Nations Framework Convention on Climate Change
US:	United States
VLCC:	Very Large Crude Carrier
VLOC:	Very Large Ore Carrier

Symbols

A	Interaction parameters
C_F	Emission factor
f	Fugacity
FC	Fuel consumption
G	Coefficient
g	Energy of interaction between molecules
LHV	Lower heating value
n	Number of moles
P	Power
p	Pressure
q	Heat flux
R	Gas constant
T	Temperature
t	Time
V	Volume
x	Mole fraction
y	Mole fraction
Z	Compressibility factor
α	Adjustable parameter
φ	Fugacity coefficient
η	Efficiency
γ	Activity coefficient
τ	Adjustable parameter

Subscripts and superscripts

i	Component index
j	Component index
l	Liquid property
m	Molar property
v	Vapour property
E	Excess property
$*$	Pure component property

INTRODUCTION

The world of maritime transport is quickly changing: the recent regulations on exhaust gas emissions in the maritime sector and the increasing of fuel prices is accelerating the transition from traditional engines powered by fuel oil to new engines able to reduce emissions and operating costs.

Several study on ships gas emissions are available [1,2,3] and the results highlight that the ship pollution is about 3% of the global emissions but it is concentrated in small areas with high traffic and in the coastal areas.

In order to reduce the pollutant emissions the international Maritime Organization (IMO) has developed a document, the MARPOL [4], which defines the Emissions Controlled Areas (ECA) where stricter emissions limits applies. Also the European Union has developed a directive [5] that sets a fuel sulphur limits of 0.1% in the European ports.

Several solutions are available to comply with these new rules, like the use of fuels with lower sulphur content, engine modifications and the adoption of exhaust gases after treatment systems. A complete review of the available technology can be find in [6,7,8].

Among the possible solutions to comply with these new rules, the use of natural gas in its liquid form (LNG) is attracting great interest as it allows to strongly reduce harmful emissions, appears to be available in large quantities and at a price today lower than diesel oil.

Natural gas has been used for 40 years in the Liquid Natural Gas (LNG) carriers, at the beginning into the traditional boiler/steam turbine systems and, more recently, in dual fuel reciprocating engines. Now the gas engine is seen as a reliable technology thanks to the proven experience into the gas carriers and land-based power plants.

On the other hand there are some aspects that currently are holding back the diffusion of the LNG technology on commercial ships, such as the higher initial costs of the system, the lack of international standards for this type of ships and, especially, the lack of a terminals network for the supply of liquefied natural gas [6].

In the presented research activity, one of the first issues to be addressed is: “which is the best ship type and size that can benefit most if LNG propulsion is used?”. From the literature analysis it was not possible to obtain an answer: for this reason a statistical analysis of the world maritime traffic has been developed, with the aim of identifying the most suitable vessels for the LNG propulsion and understanding how big could be the LNG market. In fact, only for the ship that spend most of their time in ECA zones the use of LNG could be advantageous. This analysis is necessary since the articles available in literature investigated traffic in small areas like Baltic Sea [10,11], but no one investigated the entire world. For this reason, a software tool has been developed to analyse the traffic data.

The obtained results show that tanker ship, bulk carrier ship, RoRo ship, and cruise ship are the ship types that can benefit most using LNG as fuel.

After the identification of the most suitable vessels where to apply LNG propulsion, a technical analysis on the LNG system has been carried out. In fact, gas properties affect the engine performances, then a process simulation model of a LNG propulsion plant has been developed on a specific tanker ship: in literature there are studies that analyse pressure and gas composition variations in LNG tanks for buses [12] and LNG carriers [13,14] but there are no papers investigating the case of a commercial ship focusing in particular on Methane Number and heating value.

Therefore, through a dynamic process simulation model of the LNG on board plant implemented using a commercial software (Aspen Plus Dynamic), the pressure variation, vapour production, gas composition and proprieties during the ship trip have been assessed: different cryogenic tanks and gas mixture have been tested in order to select the best solution for the considered ships.

Thanks to clean exhaust gases, that do not require after-treatment systems, LNG simplifies the use of energy recovery technologies: for this reason an energy analysis on the selected ship has been carried out. Several plant solutions, which encompass different energy recovery systems, have been modelled to demonstrate the possibility of improving ship energy efficiency and reducing operating costs.

Also the economic aspect of the LNG propulsion has been examined. In fact, for a broad diffusion of the LNG propulsion it is important to prove also the economic feasibility: the obtained results highlight that the payback period for the LNG plant can be three years.

In the last part of the work a cruise ship conversion has been considered due to the results of the traffic analysis, and since a clean image is very important for market reasons.

The analysis on the cruise ship has been mainly focused on the LNG system: the LNG composition, and then properties, change from the beginning to the end of the trip. During the refuelling in the LNG tank there is an amount of unused natural gas, with a composition that can be significantly different from the starting composition, that is mixed with the new LNG introduced, that has a different composition, obtaining a mixture with different properties after each refuelling. In the long period this could lead to a kind of “ageing” of the LNG, modifying the gas properties and then affecting the engine performances. An LNG system dynamic simulation has been carried out considering a 20 cruises period. The aim of the analysis is to highlight the possible “ageing” and to evaluate the effect of operating conditions and design choices on plant performance in the long period.

A detailed description of the developed analyses and obtained results will be discussed in the following chapters, highlighting also the possible future development.

1 MARITIME TRANSPORT: ENVIRONMENTAL IMPACT AND CURRENT REGULATION

1.1 Gas emissions from ships

The global temperature is growing and an increase of more than 2°C from the pre-industrial period will leads to severe global consequences. To avoid such a development, the target of limiting temperature increases to 2°C was included in the Copenhagen Accord emerging from the COP15 meeting in December 2009, organised by the United Nations Framework Convention on Climate Change (UNFCCC). In order to reach this target, it has been estimated that global greenhouse gas (GHG) emissions in 2050 need to be 50-85 % below current levels according to the Intergovernmental Panel on Climate Change (IPCC) [15]. However, all IPCC scenarios indicate significant increases in GHG emissions up to 2050. This means that achieving the necessary reductions will be very challenging.

Gas emissions, attributable to commercial ships, have been widely studied: it emerged that, until recently, air pollution caused by ships was mostly unregulated. Ship pollution constitutes about 3% of the global air pollution [1,2,3] (Figure 1) but is concentrated in relatively small areas. Figure 2 shows the representation of the traffic distribution based on the International Comprehensive Ocean–Atmosphere Data Set (ICOADS): the distribution clearly demonstrate that ship traffic is most prominent in the northern hemisphere and along coastlines.

A combined dataset of ICOADS and AMVER (Automated Mutual-assistance Vessel Rescue system) data of a total of 1,990,000 daily ship observations at a 1° × 1° spatial resolution has been produced in [16]. These data highlight that 70% of the ship traffic is within 200 nautical miles from shore, 44% within 50 nautical miles from shore and 36% within 25 nautical miles from shore.

An example of high traffic area is Baltic Sea that is one of the most critical areas [16]: in fact, international shipping along the Norwegian coast and in the Northern Atlantic Ocean contributes largely to the formation of ground-level ozone and acidification of the shores. In high traffic areas emissions may affect the climate just as much or even more than other forms of emissions. This was stated during a conference on Norwegian climate research, held by the research program NORKLIMA which is a new and extensive ten year program focusing on a better understanding of climatic changes in a wide perspective [18].

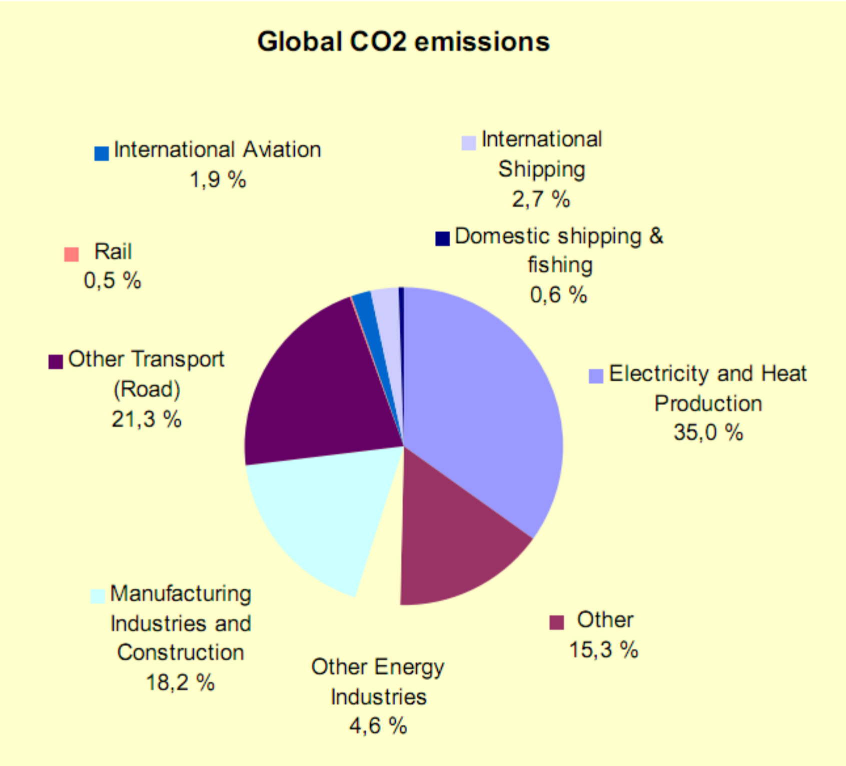

Figure 1. Global CO_2 emission (2005) [3]. It is possible to highlight that the emissions caused by ships are about 3% of the global emissions.

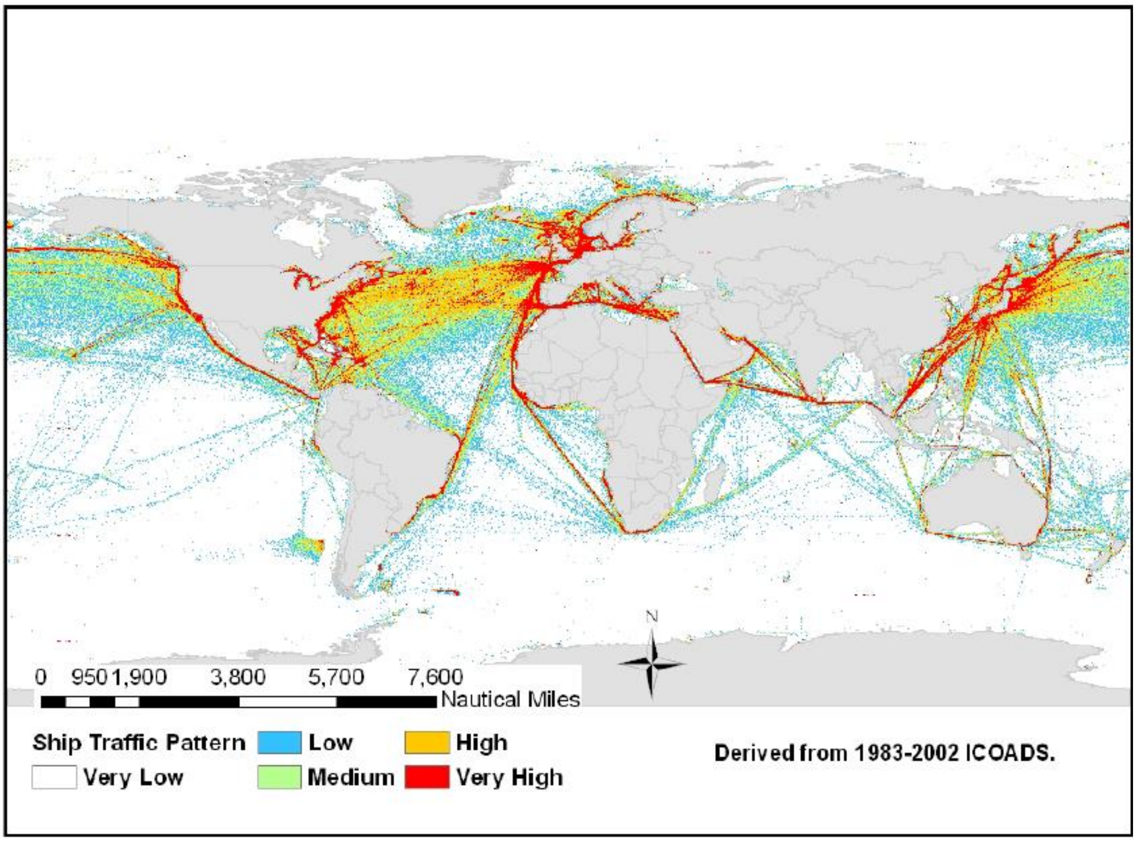

Figure 2.Ship traffic distribution, based on ICOADS data [3].

Furthermore, the pollutant emission from ships are growing, as reported in the emission forecast study [16], that compares the SO_2 and NO_X emissions from European Union (EU) land based systems and ships. The results are reported in Figure 3 and Figure 4 and show that SO_2 and NO_X emissions are expected to overtake land-based system emissions.

Future scenarios indicates that CO_2 emissions from ships will more than double by 2050 [3,19,20]. Figure 5 shows the results of the study [3] where different scenarios are modelled from 2007 to 2050. The main scenarios are named A1FI, A1B, A1T, A2, B1 and B2, according to terminology from the IPCC Special Report on Emission Scenarios (SRES) [21].

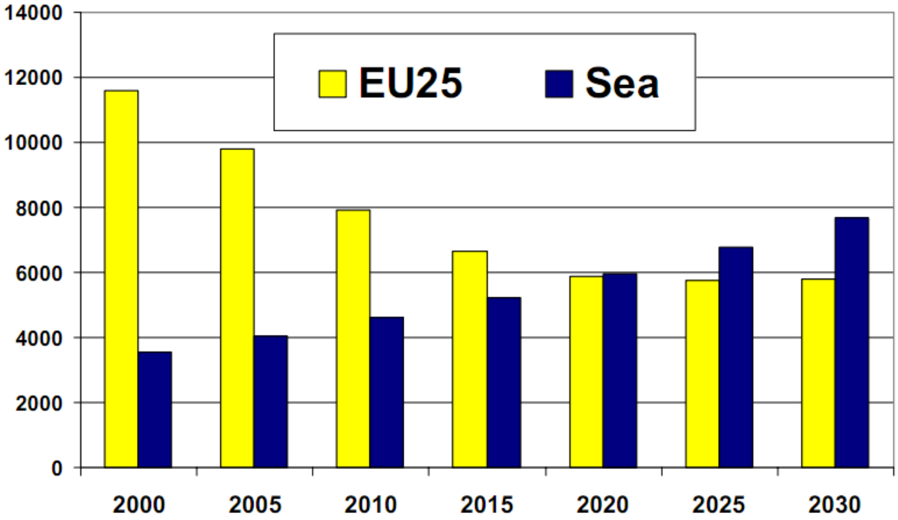

Figure 3: SO_2 emissions from the European Union land-based systems (EU25) compared to ship emissions [16]

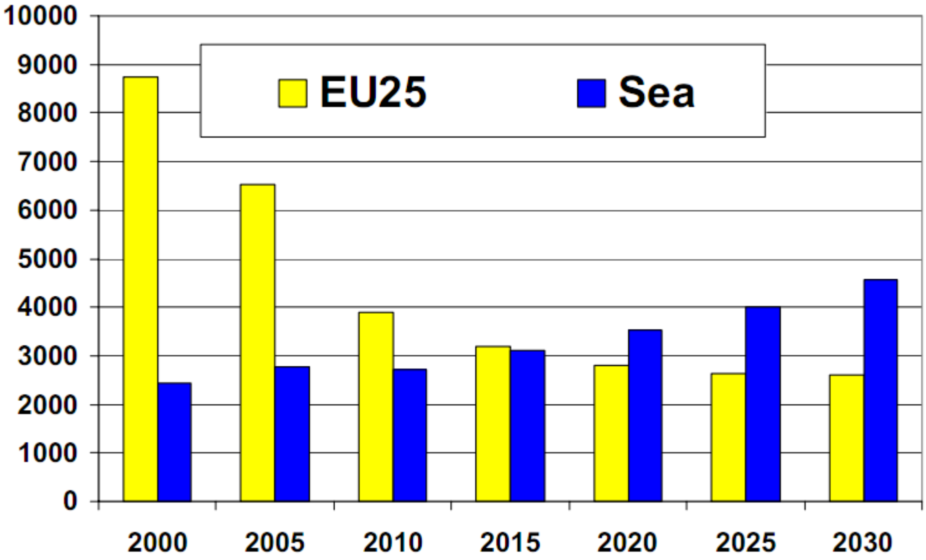

Figure 4: NO_X emissions from the European Union land-based systems (EU25) compared to ship emissions [16]

These scenarios are characterized by global differences in population, economy, land-use and agriculture which are evaluated against two major tendencies: (1) globalization versus regionalization and (2) environmental values versus economic values. However, in almost all scenarios it is possible to note an increase of the emissions.

Given the expected growth, achieving emission reductions will be difficult. The global target of 2°C will affect maritime transportation, and the extent to which the maritime sector should be expected to reduce emissions and how this reduction might be achieved are the subjects of an ongoing debate. The International Maritime Organization (IMO) is currently working to establish GHG regulations for international shipping [3], and it is under pressure, from bodies such as the EU and UNFCCC, to implement regulations that will have a substantial impact on emissions. The major policy instruments under consideration by IMO are technical, operational, and market-based.

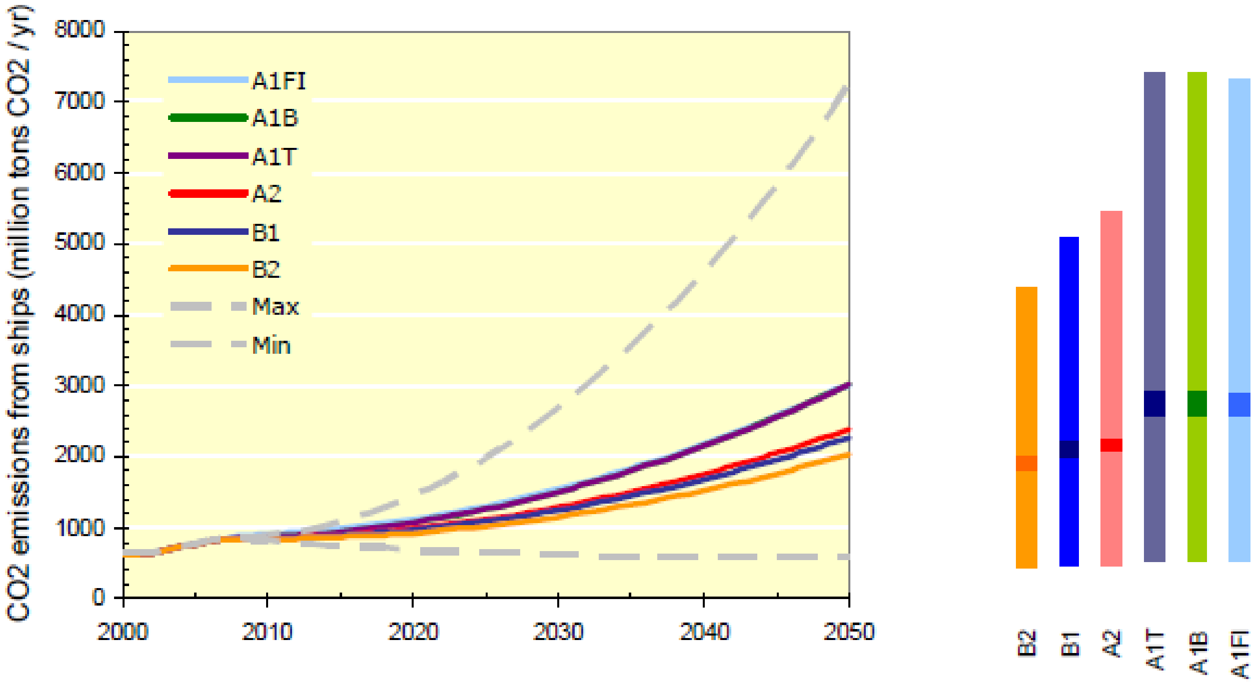

Figure 5. Trajectories of the emissions from international shipping. Columns on the right-hand side indicate the range of results for the scenarios within individual families of scenario [3].

Although the outcome of the IMO process is currently unresolved, it seems clear that within a few years CO_2 emissions from shipping will be regulated. This, along with an expectation of high fuel prices in the long run, will provide incentives for the shipping industry to focus on new ways to achieve greater cost- and energy-effectiveness, and better environmental performance.

1.2 Current regulation

1.2.1 IMO’s Marpol

The IMO's MARPOL 73/78 (short for Marine Pollution; 73/78 short for the years 1973 and 1978) is the International Convention for the Prevention of Pollution from Ships agreed in 1973 and then modified by the Protocol of 1978. Marpol 73/78 is one of the most important international marine environmental conventions. It was designed to minimize pollution of the seas, including dumping, oil and exhaust pollution. Its declared object is to preserve the marine environment through the complete elimination of pollution caused by oil and other harmful substances and the minimization of accidental discharge of such substances. The original MARPOL Convention was signed on 17 February 1973 but did not come into force. The current Convention is a combination of the 1973 Convention and the 1978 Protocol. It entered into force on 2 October 1983. As of 31 December 2005, 136 countries, representing 98% of the world's shipping tonnage, are parties to the Convention. All ships flagged under countries that are signatories to MARPOL are subject to its requirements, regardless of where they sail and member nations are responsible for vessels registered under their respective nationalities.

In particular, MARPOL Annex VI sets limits on sulphur oxide and nitrogen oxide emissions from ship exhausts and prohibits deliberate emissions of ozone depleting substances. The annex includes a global cap on the sulphur content of fuel oil and calls on IMO to monitor the worldwide average sulphur content of fuel. Furthermore, MARPOL Annex VI define the Emission Control Areas (ECA) where there are strict limits on gas emission (Figure 6). Currently the ECA zone are the North American coast, the North Europe Seas and the Baltic Sea but in the next future will be extended to other coastal areas like Mediterranean Sea.

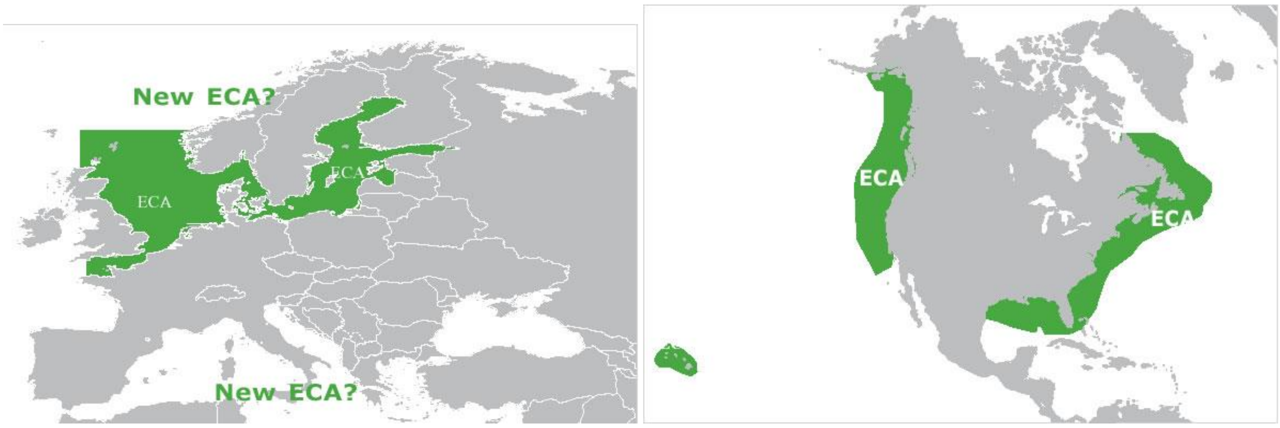

Figure 6. ECA zones as defined in the Marpol Annex VI (http://actechpower.com).

Table 1 describes fuel sulphur content restrictions imposed by MARPOL: sulphur content has to decrease constantly in the next years. Table 2 describes restrictions on NO_X emissions as a function of the maximum engine operating speed: a three-tier reduction program has been established. Tier II is currently effective, while Tier III will come into effect in 2016 with the aim of reducing, stepwise, the NO_X emissions allowed, to 80% by 2016. Tier I and Tier II limits are global, while Tier III standards will apply only in ECA zones.

Table 1. Fuel sulphur contents: global and ECA limits [22].

Date	Global limit [% mass]	Date	ECA limit [% mass]
Prior to 1/1/2010	4.5 %	Prior to 1/7/2010	1.5 %
After 1/1/2012	3.5 %	After 1/7/2010	1.0 %
After 1/1/ 2020	0.5 %	After 1/1/2015	0.1 %

Table 2. NO_X emission reduction program [22].

Tier	Date	NO_x limit [g/kWh]		
		n<130	130 ≤ n ≤2000	n ≥ 2000
Tier I	2000	17.0	$45 \times n^{-0.2}$	9.8
Tier II	2011	14.4	$44 \times n^{-0.23}$	7.7
Tier III	2016*	3.4	$9 \times n^{-0.2}$	1.96

*Only for NO_x ECAs (TIER II applies outside ECAs)
n = engine speed [rpm]

1.2.2 European Union Directive

From January 1st 2010 the European Parliament Directive2005/33/EC came into force. As well as reinforcing the limits of sulphur for vessels operating in ECA, and limiting the sulphur content of fuels used ashore in the EU, it also introduced legislation governing the maximum sulphur content of fuels used by inland waterway vessels and ships at berth in Ports which are part of the European Community. The limit placed is 0.1% Sulphur, which is the maximum sulphur content of Gas Oil.

The rules state that the limit applies for ships at berth in EU ports allowing sufficient time for the crew to complete any necessary fuel change over operation as soon as possible after arrival at the berth and as late as possible before departure. The change over must be recorded in ships log books.

1.3 Ship fuels

1.3.1 Fuel Oils

Fuels oils are blended products based on the residues from refinery distillation and cracking processes. They contain high levels of asphalt, carbon residues, sulphur and metallic compounds.

The chief drawback to residual fuel oil is its high initial viscosity which requires a correctly engineered system for storage, pumping, and burning: it has to be stored at around 40°C, heated to 50°C before it can be easily pumped, and finalising for burning at around 90-120°C. It can be heavier than water (specific gravity usually ranging from 950 to 1030 kg/m^3) and in cooler temperatures it can congeal into a tarry semisolid, for these reasons, usually, it is called HFO or MFO.

This kind of fuel can be also mixed with a small amount of distillates, in order to reduce the viscosity, obtaining an IFO.

HFOs are used widely in marine applications in combustion equipment such as main engines, auxiliary engines and boilers.

As a residual product, HFO is a relatively inexpensive fuel (typically its costs around 30% less than distillate fuels) and the cheapest among liquid fuels on the market. It has become the standard fuel for large, slow speed marine diesel engines, this being especially so during the oil crises of the 1970s and 1980s. Its use required extensive research and development of the fuel injection system and other components of low and medium speed engines [23].

1.3.2 Distillates

There are mainly two type of distillates: MGO and MDO. MGO is made from distillate only and has a maximum sulphur content of 0.1% by weigh to comply with EU ports emission limits, while MDO is a blend of MGO and residual oils up to 10-15%, with a maximum sulphur content of 0.5% by weight to comply with ECA emission limits. These fuels are more expensive than residual oils but allow to comply with emissions rules without using sulphur abatement systems.

1.3.3 Natural Gas

Natural Gas (NG) is composed primarily of Methane with a small amount of Ethane and higher level Hydrocarbons (Propane, Butane). Methane is a colourless, odourless and non-toxic gas which is lighter than air. The majority of Methane originates from NG fields or is associated with other Hydrocarbon fuels. However, Methane fuel is also produced in significant quantities from landfill sites due to the decay of organic waste or by manufacture i.e. biogas from the fermentation of organic matter. Some gas fields produce gas with a significant quantity of Hydrogen Sulphide which is also known as sour gas. This gas is highly toxic and has to be treated before use.

Historically, the world gas reserves have generally witnessed a growing trend as shown in Figure 7 [24]. The increase of reserves is attributed to new extraction technologies, such as hydrofracking, that allow the extraction of NG from gas fields that have not been exploited yet.

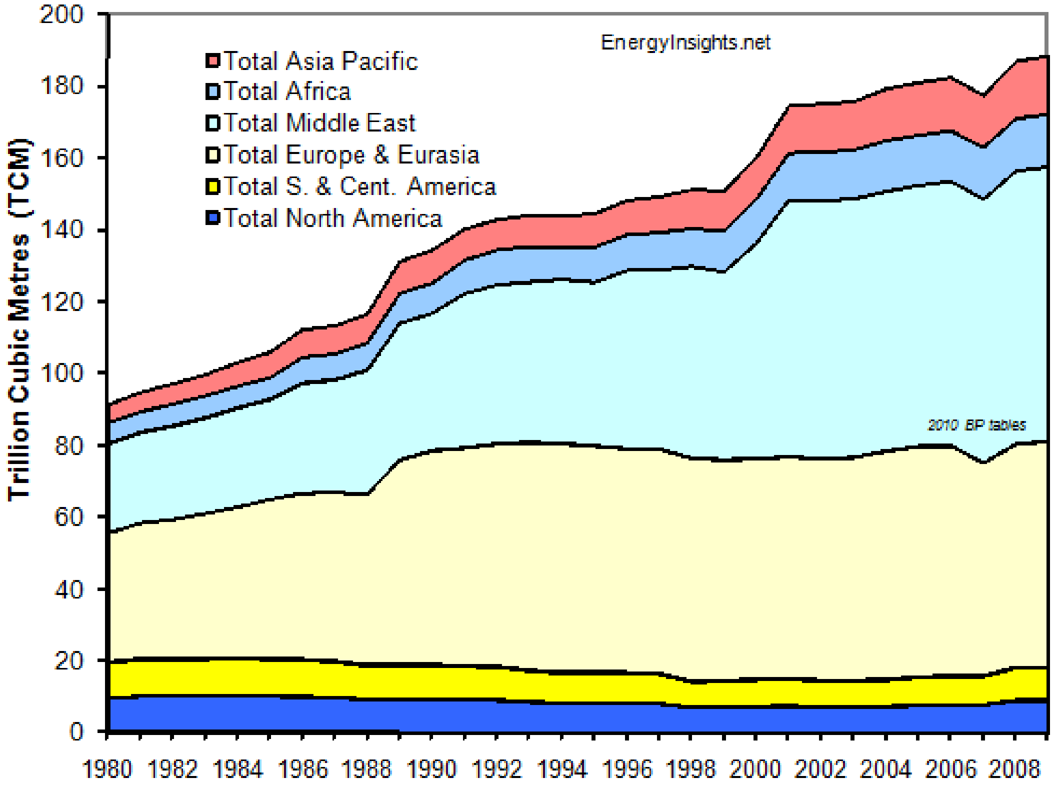

Figure 7. Growth in gas reserves in global world since1980 [24].

In January 2011 the NG reserves were 190,078 billion cubic meters [25], and almost three quarters of the world’s NG is located in the Middle East and Eurasia (Figure 8). As for the gas production and consumption, in 2010 were produced 3,231 billion cubic meters (Figure 9) and used 3,253 (Figure 10).

Natural Gas has a higher hydrogen-to-carbon ratio compared with oil-based fuels, which results in lower specific CO_2 emissions (kg of CO_2/kg of fuel).

In addition, LNG is a clean fuel, containing no sulphur; this eliminates the SO_x emissions and almost eliminates the emissions of particulate matter. Additionally, the NO_x emissions are reduced by up to 90% due to reduced peak temperatures in the combustion process. Unfortunately, the use of LNG will increase the emissions of methane (CH_4), hence reducing the net global warming benefit from 25% to about 15% [26].

NG has the higher energy content among the traditional fuels, in particular comparing NG and HFO an energy difference of about 10% can be highlighted. In Table 3 are reported the energy content of some common fuels.

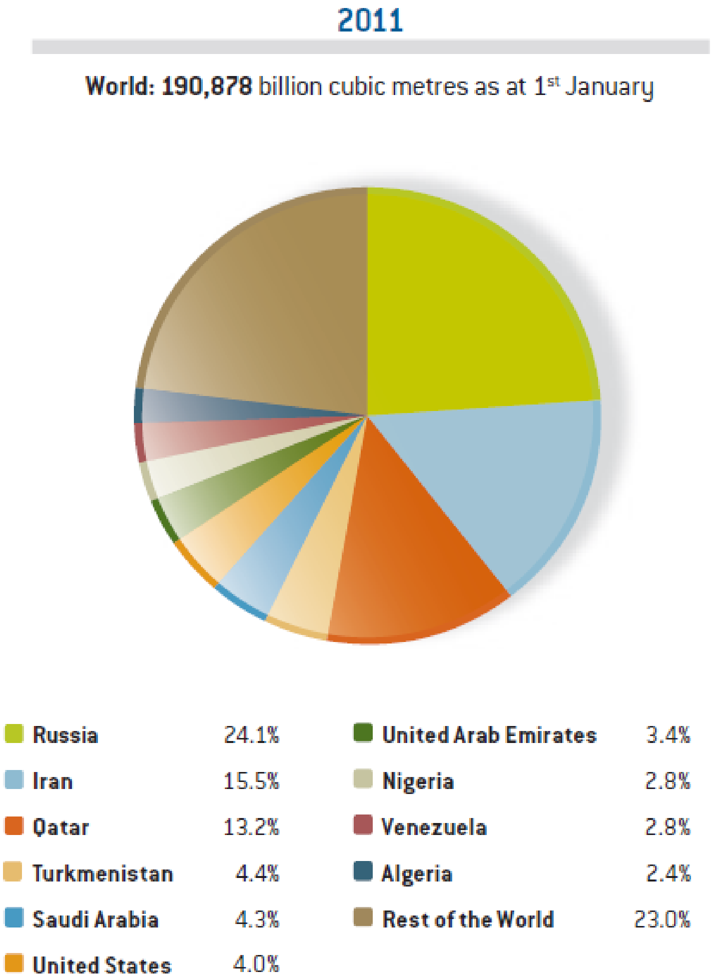

Figure 8. World natural gas reserves in January 2011 divided by nation [25].

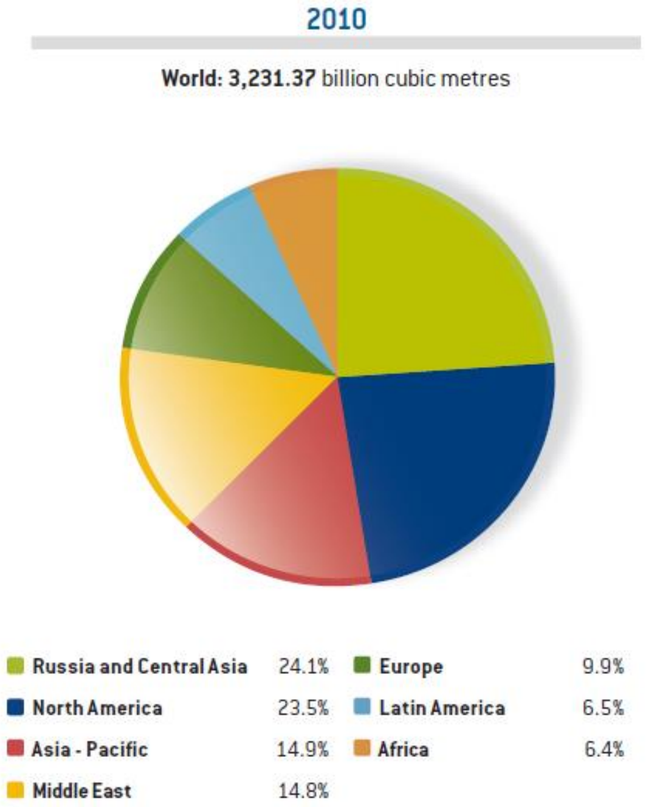

Figure 9. World natural gas production in 2010 divided by nation [25].

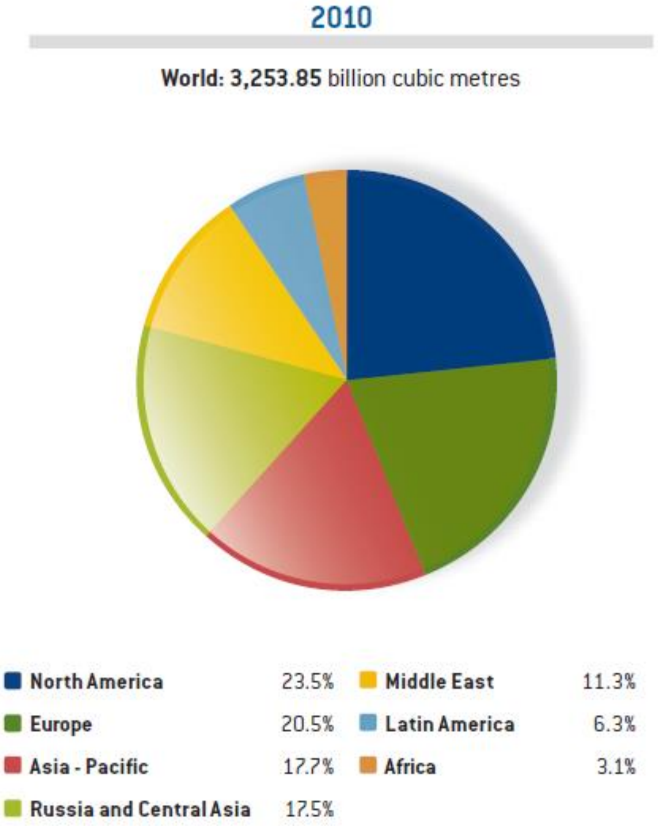

Figure 10. World natural gas consumption in 2010 divided by nation [25].

Methane is highly flammable and when mixed with air in the right quantities forms an explosive mixture. To ignite a quiescent homogeneous Methane air mixture at ambient conditions requires a 5 -15% Methane content and an ignition energy between 0.3 – 3.5 mJ as shown in Figure 11.

Table 3. Average fuel energy contents.

Fuel	Energy content [GJ/ton]
North Sea Crude Oil	42.7
LPG (Liquefied petroleum gas)	46.0
Petrol (Gasoline)	43.8
JP1 (Jet aircraft fuel)	43.5
Diesel / Light Fuel oil	42.7
HFO (Heavy Fuel Oil)	40.9
Orimulsion	28.0
Natural Gas	49.0
Steam Coal	28.5
Other Coal	26.5

However, it should be noted that the minimum ignition energy is also a function of the gas temperature. The total energy supplied, the rate, duration and the area of the ignition source all have an effect upon the ability to ignite the gas. Typically, more energy is required for rich mixtures than for lean. Increasing the gas mixture temperature also widens the flammability limits as the Lower Flammability Limit (LFL) decreases and the upper flammability limit increases. As the temperature keeps increasing the gas mixture will auto-ignite and this is around 540 °C. The auto-ignition temperature is approximately 1.7 times greater than Diesel fuel which at first glance suggests a lesser chance of ignition when coming into contact with hot surfaces.

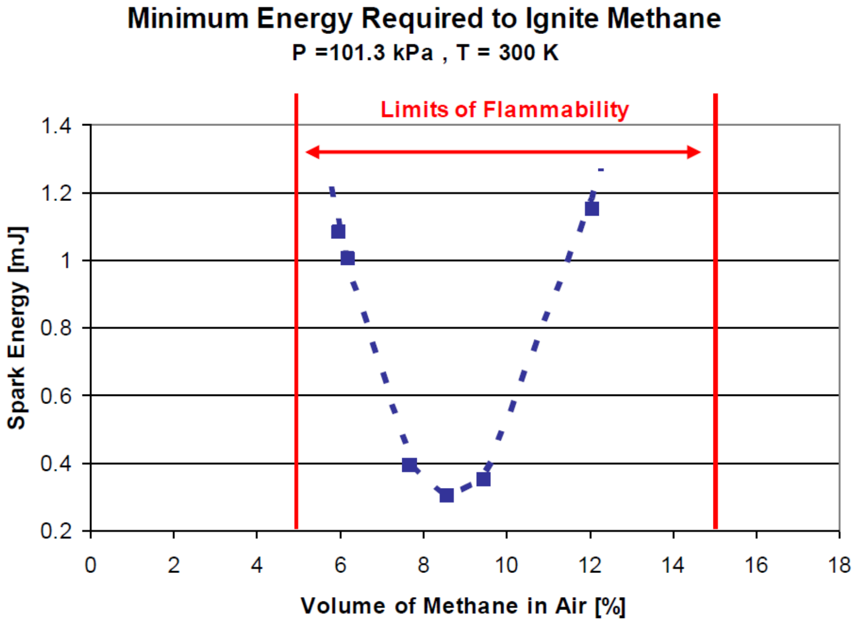

Figure 11. Methane flammability range [27].

However, comparison of auto-ignition between gases and liquid fuels must also consider the latent heat of vaporization where liquid fuels would have absorbed energy to change state and therefore the margin of safety offered by gas is slightly reduced. For comparison purposes Table 4 reports the main properties of methane, the main component of NG, and the properties of diesel fuel: it has to be highlighted the lower density of methane both in gaseous and in liquid form.

Then, the space required for the same energy content is about twice than that required from diesel fuel. Furthermore the boiling point of methane is -162°C and then it is necessary to use special cryogenic vessel for the LNG.

Table 4. Physical properties of methane compared to diesel fuel [27].

	Methane	**Diesel fuel**
Formula	CH_4	avg. $C_{12}H_{23}$
Molecular Weight	16	200 (approx.)
Carbon / Hydrogen, weight [%]	75/25	84-87/13-16
Density (gas @ STP)	0.717 kg/m^3	-
Density (liquid)	415 kg/m^3	810 - 890 kg/m^3
Freezing point [°C]	-182	-40 to -1
Boiling point [°C]	-162	188 ÷ 343
Lower heating value [MJ/kg]	50.0	40.8
Flash point [°C]	-188	74
Auto ignition temperature [°C]	540	316
Flammability limits, Vol. [%]	5-15	1-6
Stoichiometric air to fuel ratio	17.2	14.7

To maximize storage capacities, NG is usually refrigerated to change its state to a liquid. The potential hazards in handling LNG are substantially three:

- The extreme cold temperature (-162°C) may cause frostbite to personnel and/or brittleness to structures.
- The high expansion ratio of about 600:1 means that even a small volume of liquid gas yields a large amount of gas.
- The wide flammability range (compared to conventional Diesels) may lead to ignition in case of gas release.

Another problem related to LNG is the spillage onto structures, because spillage can cause catastrophic failures if the wrong materials are used as the material becomes brittle and fractures. Consideration should be given to materials that are in direct contact or accidental contact with LNG. When LNG is spilled onto the ground, there will be an initial period of intense boiling, after which the rate of evaporation will decay to a near constant rate. This rate will be a function of the thermal characteristics of the ground and the heat absorbed from the surrounding air. When LNG is spilled into water, explosive forces can occur due to the different temperature profiles and is known as rapid phase transition (RPT). When the temperature of one liquid is greater than 1,1 times the boiling point of the cooler liquid, a rapid rise in temperature is initiated such that the surface layer temperature can exceed the spontaneous nucleation temperature and bubbles appear. In some situations this superheated liquid vaporizes within a minute time producing vapour at an explosive rate. The evaporation rate is a function of the spillage area and is usually constant. The area of any LNG spillage will extend until the rate of evaporation is equivalent to the amount of liquid gas produced by the leak. Therefore the rate of evaporation of spilt LNG can be controlled by the appropriate selection of materials.

1.3.3.1 Methane Number

The knock resistance of a fuel is determined by comparing the compression ratio at which the fuel knocks to a reference fuel blend that knocks at the same compression ratio. Different scales have been used to rate the knock resistance of natural gas including the Motor Octane Number (MON) and the Methane Number (MN). The differences in these ratings are the reference fuel blends used for comparison to the natural gas. The reference fuel blend used for comparison to the natural gas for the MON is composed of iso-octane, with an octane number of 100, and n-heptane with an octane number of 0. However, since natural gas has a higher knock resistance than iso-octane, tetraethyl lead (TEL) must be blended with the reference fuel to increase the reference MON. The MON for natural gas fuels range from approximately 115 to over 130. Methane Number uses a reference fuel blend of methane, with a Methane Number of 100, and hydrogen, with a Methane Number of 0 [28].

To evaluate the Methane Number of a gas mixture from its composition several methods are available. In this study, the formulation proposed by Gas Research Institute (GRI), reported into the ISO 15403:2006 [29], has been considered. This formulation allows calculating the MON knowing the mole fraction (x_i) of each component of the gas mixture as a linear coefficient relation as reported below:

$$\begin{aligned} MON = {} & 137.78\, x_{methane} + 29.948\, x_{ethane} - 18.193\, x_{propane} - 167.062\, x_{butane} + \\ & + 181.233\, x_{CO2} + 26.994\, x_{nitrogen} \end{aligned}$$

The standard proposes also a formulation based on the hydrogen/carbon ratio as that proposed by the California Air Research Board (CARB) [28], but it is not valid for H/C ratios below 2.5 or for inert concentrations greater than 5%:

$$MON = -406.14 + 508.04\,(H/C) - 173.55\,(H/C)^2 + 20.17\,(H/C)^3$$

Due to these limitations this formulation will not be used this thesis.

From the MON, the ISO provides a formulation to calculate the Methane Number:

$$MN = 1.445\, MON - 103.42$$

1.4 Approaches to meet gas emissions limits

In order to reduce gas emissions from existing ships, a combination of cleaner fuels, engine modifications, add-on retrofits and other measures are currently adopted. A complete review of the emission reduction options can be found in [6,7,8]: in Table 5 a summary of the emission reduction systems currently used in ships is presented. In particular, the focus is to reduce SO_X and NO_X emissions.

SO_X emission control. Sulphur emissions are directly proportional to the sulphur content of fuel. For this reason the first approach towards reducing SO_X emissions is to decrease its fuel sulphur content. For instance, the reduction of sulphur levels from 2.7% to 0.5% would reduce SO_X emissions by about 80%. Furthermore, as most of the Particulate Matter (PM) emissions from marine engines are related to fuel sulphate contents, sulphur fuel reduction leads to lower sulphate formations and therefore minor PM emissions. Low sulphur content fuels, such as Marine Diesel Oil (MDO) and Marine Gas Oil (MGO), allow also for a more efficient use of gas after-treatment measures for NO_X abatement. MDO is currently used for sailing in ECA zones (1% sulphur limit), while MGO is used in EU ports where the fuel sulphur limit is 0.1%. However, the chemical processes that are used to produce MDO/MGO imply higher energy consumption and higher costs and CO_2 emissions compared to HFO. For this reason, other SO_X reduction options are used as well. Among them, seawater scrubbing is a well-established control methodology that can achieve a SO_X removal level in compliance with MARPOL limits.

NO_X emission control. NO_X emission reduction can be achieved with engine modifications or/and with gas after-treatment systems. Engine modifications comprise exhaust gas recirculation, internal engine modifications, humid air motors and direct water injection, while the most common after-treatment system is the Selective Catalytic Reduction (SCR) that involves the treatment of exhaust gases with ammonia or urea with a catalyst. SCR allows for a higher than 80% NO_X abatement.

Table 5. Gas emission reduction resulting from operating with different emission control systems compared to the use of LNG [16,8].

Abatement technology / Measure	**Emission reduction (%)**			
	SO_X	**NO_X**	**PM**	**CO_2**
Basic internal engine modifications for 2 strokes, slow speed only	0	-20	0	0
Advanced internal engine modifications	0	-30	0	0
Direct water injection	0	-50	0	0
Humid air motors	0	-70	0	0
Exhaust gas recirculation + scrubbing	-93	-35	-63	0
Selective Catalytic Reduction (2.7% S residual oil fuel)	0	-90	0	0
Sea water scrubbing	-75	0	-25	0
Fuel switching (from 2.7% S to 1.5% S HFO)	-44	0	-18	0
Fuel switching (from 2.7% > 0.5% S HFO)	-81	0	-20	0
Low S marine diesel (from 0.5 to >0.1 % S)	-80	0	0	0
Liquefied Natural Gas (LNG)	-90	-80	-100	-20

2 NATURAL GAS FOR SHIP PROPULSION

2.1 Gas propulsion: advantages and challenges

For 40 years LNG has been used as fuel in LNG carriers [30]: the boiled off gas produced inside the LNG tank is used in traditional boiler/steam turbine systems and, more recently, in dual fuel reciprocating engines. These latter have been operated for 6 million hours [31] and therefore, the dual fuel engine is now seen as a reliable technology to be used in ships other than LNG carriers. Thanks to the proven experience in land-based power plants, LNG can be used not only in dual fuel engines but also in other gas-fuelled engine types, such as lean burn gas engines, when a suitable redundancy/back-up system is introduced [6].

At the time of writing, 34 ships are using LNG for propulsion and the construction of 31 new ships is already planned for the next two years (excluding LNG carriers and inland navigation vessels) [32]. Most LNG ships are in Norway where about 20 small cross fjord ferries and offshore support vessels are fuelled by LNG. Among them, the “Viking Lady” is an interesting offshore vessel that uses LNG both in a dual fuel engine for propulsion purposes and for feeding a fuel cell to produce electricity. Another example is the LNG powered ferry called “M/F Bergensfjord”: a 129 m long vessel that can carry 212 cars and 587 passengers. A complete review of the world LNG fleet can be found in [33].

Nowadays, thanks to experience gained from operating LNG carriers, ship design challenges, related to LNG security issues, have been mostly overcome: it is actually possible to design any ship to run on LNG but the introduction of LNG depends on some key factors:

- *Gas availability.* LNG handling is limited, at the moment, to gas terminals for gas carriers or to special applications. In order to introduce LNG on a large scale, bunker infrastructures have to be built to make LNG available wherever ship operators may ask to have it. LNG bunkering installations need to be as close as possible to oil fuel bunkering: usually any “extra” stop at a refuelling station would not be acceptable for any kind of ship. Therefore, the presence of an adequate infrastructure is crucial for the introduction of LNG, because it will allow operators to have a safe and reliable LNG supply chain, without extra stops [34].
- *Demand for ships.* Ship retrofitting should be seen as a valid possibility for converting ships to LNG: *Bit Viking* is a successful example of ship conversion [35]. However, a hull structure modification might be necessary in order to contain the LNG tank. For this reason, the introduction of LNG is easier in new ship projects.
- *Emission limits (ECA zones).* The introduction of LNG in ships that spend most of their time in ECA zones is more attractive from an economic point of view. Therefore, the extension of Emission Controlled Areas can foster the conversion to LNG.
- *LNG tank installation.* Standard LNG storage tanks are bigger than traditional bunker tanks that fit easily into a steel ship structure. LNG storage requires additional space since natural gas, in its liquid state, takes up roughly twice the volume occupied by diesel oil for the same energy content. Furthermore, several safety requirements have to be met when planning an LNG storage tank installation [6].

- *Safety requirements*. An increased awareness about gas fuel as a safe means of propulsion and its acceptance by country and state port authorities are today's biggest challenges. Therefore, the finalization of the still incomplete International Gas-Fuelled Ships code (IGF code, International Code of Safety for ships using gas or other low flash-point fuels) might lead to a wider acceptance of gas-fuelled ships. A more detailed analysis of LNG safety issues can be found in [36].

2.2 Gas engines

The development of gas engines has started in 1980 for the installation on LNG carrier. For commercial engines the development started in 1984: from 1988 and 1996 has been presented for power-plant generation three different design concept:

- Dual Fuel engines
- Lean Burn engines
- Gas Diesel engines

The first marine gas engine application in a non LNG carrier ship was in 2000 on the Norwegian ferry “MF Glutra” [37]. Meanwhile the development and improvement of these engine has continued and in 2011 there was a growing interest for deep sea shipping application due to the development of large slow engine, the retrofitting possibility of existing ship, the emission control legislation and fuel cost increasing.

In November 2013 the successful test of the first 2 stroke duel fuel engine has been announced, that will be available from the end of 2014 [38].

Due to the high autoignition temperature, methane cannot replace Diesel fuel directly for internal combustion engines. Ignition of the fuel is either provided by a spark plug or the use of a Diesel pilot injection. The peak flame temperature, when operating on methane, is similar to that of conventional fuels but when operating in lean burn mode the peak temperatures are significantly reduced leading to lower heat losses and a higher thermal efficiency.

Another advantage of methane as a fuel for internal combustion engines is its resistance to detonation when compared to gasoline, but the presence of higher hydrocarbons will quickly lower the methane rating, add to this that the compression ratio for dual fuelled engines would have been optimised for Diesel combustion means that careful control of fuelling is required in order to avoid knock. Figure 12 shows the typical operational area for a dual fuel diesel engine operating on natural gas.

Therefore the mixture has to be carefully controlled to avoid knocking when going slightly richer or moving into the misfire region should be mixture become slightly leaner. Whilst this is relatively easy for steady state operation, transient manoeuvres introduces more difficulties where would be easy to move the engine operation outside its specified operational region.

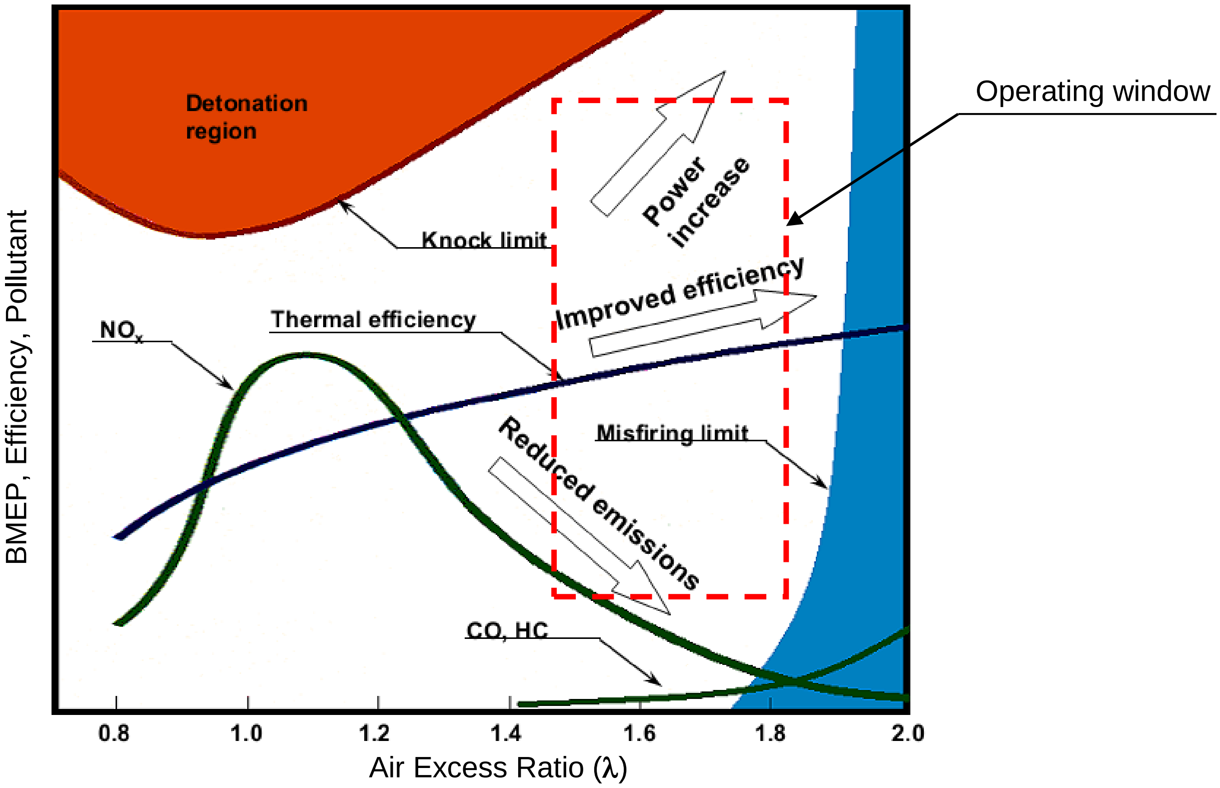

Figure 12. Internal combustion performance and pollutant as function of air excess ratio. Highlighted the operating window of the lean burn engines [39].

2.2.1 Lean Burn spark ignition engines

This engine uses only gas at low pressure (4-5 bar) as fuel. To overcome the lean flammability limitation, a spark ignition stratified charge combustion concept can be used. The principle is to arrange a rich mixture around the region of the spark plug whilst the bulk of the cylinder is overall lean. Typically, this can be achieved by the use of a prechamber or timed i.e. late injection for direct injection arrangements. Figure 13 shows a schematic of the prechamber type, during the intake stroke a very lean homogeneous gas air mixture is drawn into the cylinder. During compression some of the lean cylinder charge is pushed into the prechamber and will mix with the rich gas mixture which has be injected directly into the prechamber. A high energy spark plug is used to initiate combustion within the prechamber which then propagates out into, and throughout the cylinder volume. The main advantage with this concept is the induction of a leaner main charge increases the knock margin.

These engines have low emissions, in compliance with IMO tier III, an high efficiency at high load (higher than the corresponding diesel engine) and a GHG reduction potential in the range of 20–30% respect HFO, depending on methane slip. The term methane slip is given to the uncontrolled emission of methane. Re-inspection of Figure 12 shows that whilst the production of NO_x is reduced during extreme lean burn operation the level of unburnt hydrocarbons, in this case methane, is starting to increase. Extremely lean operation is fast approaching the lean flammability limit of the air/fuel mixture and at this condition partial burns or misfires can occur resulting in unburnt methane being exhausted from the engine. Typically, the methane slip occurs during rapid engine load transients or low engine loads where the in-cylinder charge air movement is reduced.

Methane has a 100-year global warming potential (GWP100) that is 25 times higher than CO_2 [40]. This means that 1 kg of methane has the same warming potential of 25 kg of CO_2 and therefore, if the methane slip is not controlled, the benefits of using LNG are reduced.

Another problem of these engines is the sensitivity to gas quality (Methane Number) that could cause knocking problems: for this reason a knocking detector is installed in each cylinder.

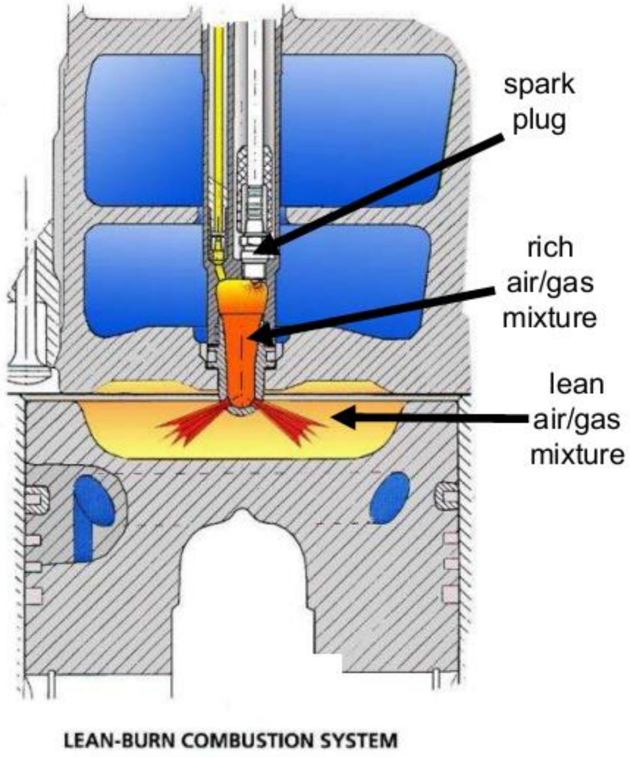

Figure 13. Stratified charge arrangement [41].

2.2.2 Dual Fuel engines

These engines are able to run both using natural gas and fuel oil. When fuel oil is used, the engine works on the basis of the Diesel cycle. Otherwise, when natural gas is used as fuel, the engine works as a lean burn Otto cycle engine, with a pilot fuel injection as ignition (Figure 14). The pilot injection is obtained by means of a special common rail injector (Figure 15) placed in the centre of the head and account for less than 1% of the fuel at full load, while NG is injected into the intake manifold at low pressure (4-5 bar) by means of a gas admission valve for each cylinder. At low load the engines automatically switch from gas to diesel fuel to avoid knocking problems.

These engines have low emissions, in compliance with IMO tier III, a high efficiency at high load and a GHG reduction potential in the range of 20–30% respect HFO, depending on methane slip. Methane slip is a challenge for these engines due to the limited possibility to control the combustion process. Another problems of these engines is the sensitivity to gas quality (Methane Number) that could cause knocking problems: for this reason a knocking detector is installed in each cylinder.

A big advantage of these engines is the possibility of conversion from diesel to gas: in this way during an engine overhauling the ship engine can be converted to run on natural gas reducing the installation cost of the LNG system.

These engines, as mentioned before, have been operated for 6 million hours and therefore, the dual fuel engine is now seen as a reliable technology to be used in ships other than LNG carriers [31]. Furthermore, before the end of 2014, the dual fuel technology will be available into 2 stroke engines also [38].

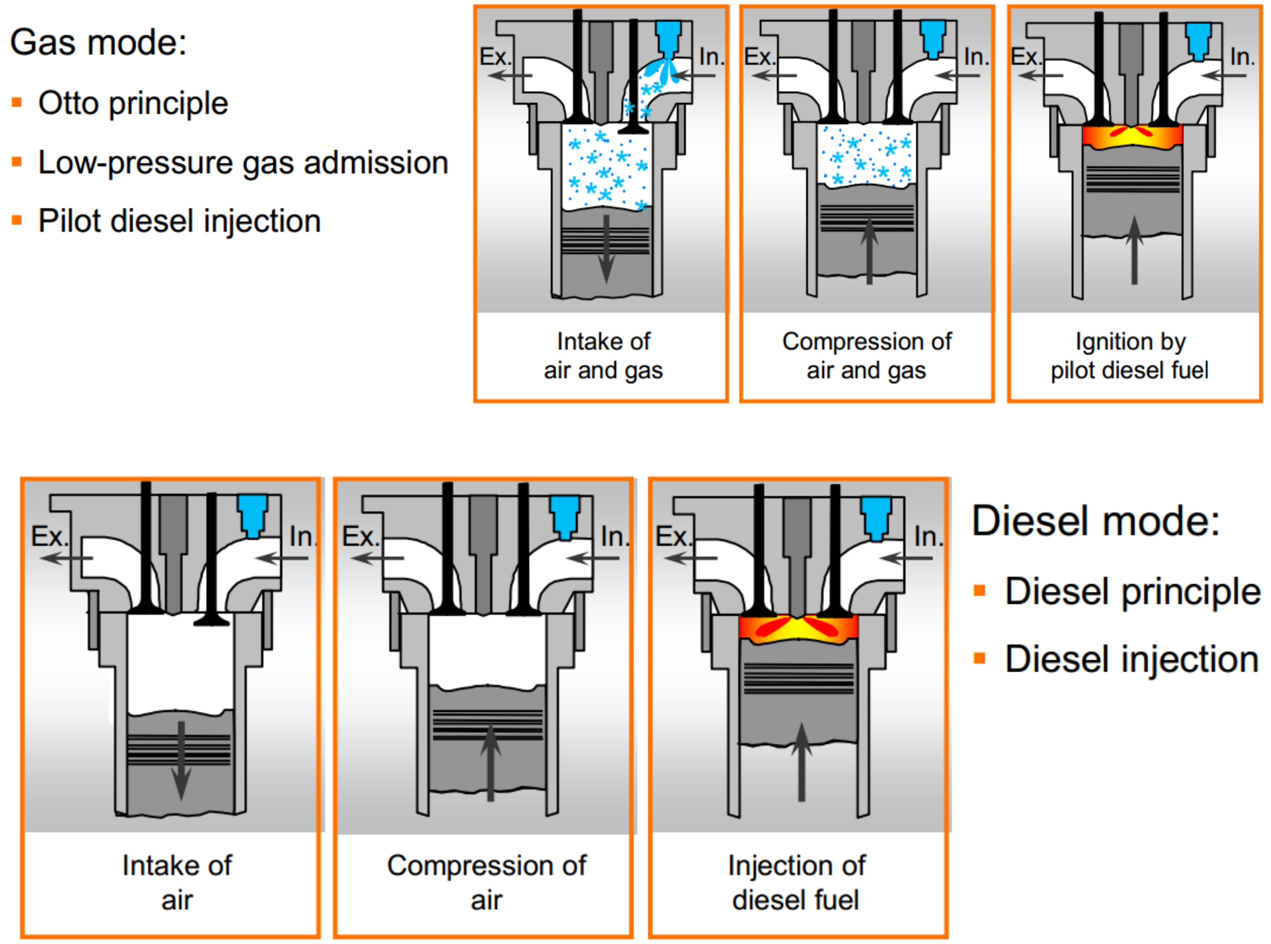

Figure 14. Working principle of dual fuel engines working in gas mode (top) and diesel mode (bottom) [41].

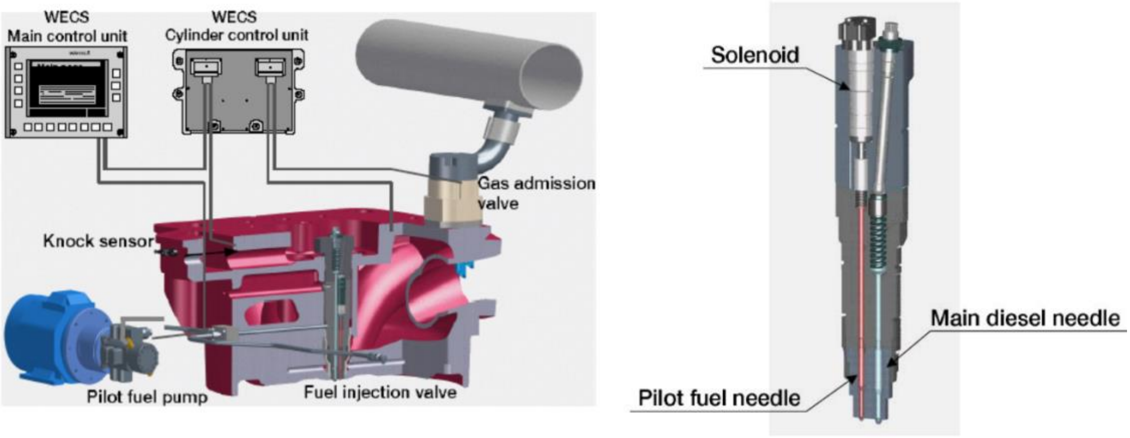

Figure 15. Dual fuel diesel injector [41].

2.2.3 Gas Diesel engines

These engines are dual fuel also but works on the basis of the Diesel cycle and can be either four or two stroke engines. In these engines also a Diesel fuelled pilot injection is required as shown in Figure 16. The amount of pilot fuel injected has to be carefully controlled, not enough and the charge will fail to ignite, too much will witness increased levels of emissions negating reducing the benefits of burning gas. These engines require the use of high gas pressure gas injection (250–350 bar) during the gas operation, but pumping LNG to 350 bar and evaporate is simple and with low energy requirement.

Furthermore they are not sensitive to gas quality, maintain the same performance during gas operation and does not have methane slip issue obtaining a GHG reduction potential in the range of 30% respect HFO. On the contrary, since work on the basis of diesel cycle, they needs NO_x reduction techniques to meets IMO tier III.

These engines are always started on Diesel fuel and then changed over to gas operation once the conditions are right. The changeover to gas has to be completed carefully and slowly. As the gas amount is increased the amount of main diesel fuel is reduced in order to maintain suitable combustion stability especially when operating close to the lean flammability limit. In the event of a fault with the gas supply or a leak being detected the change over back to Diesel operation is near instantaneous with claims of no loss in power identified. At low load the engines automatically switch from gas to diesel fuel.

Like dual fuel engines, they are suitable for conversion of existing engines.

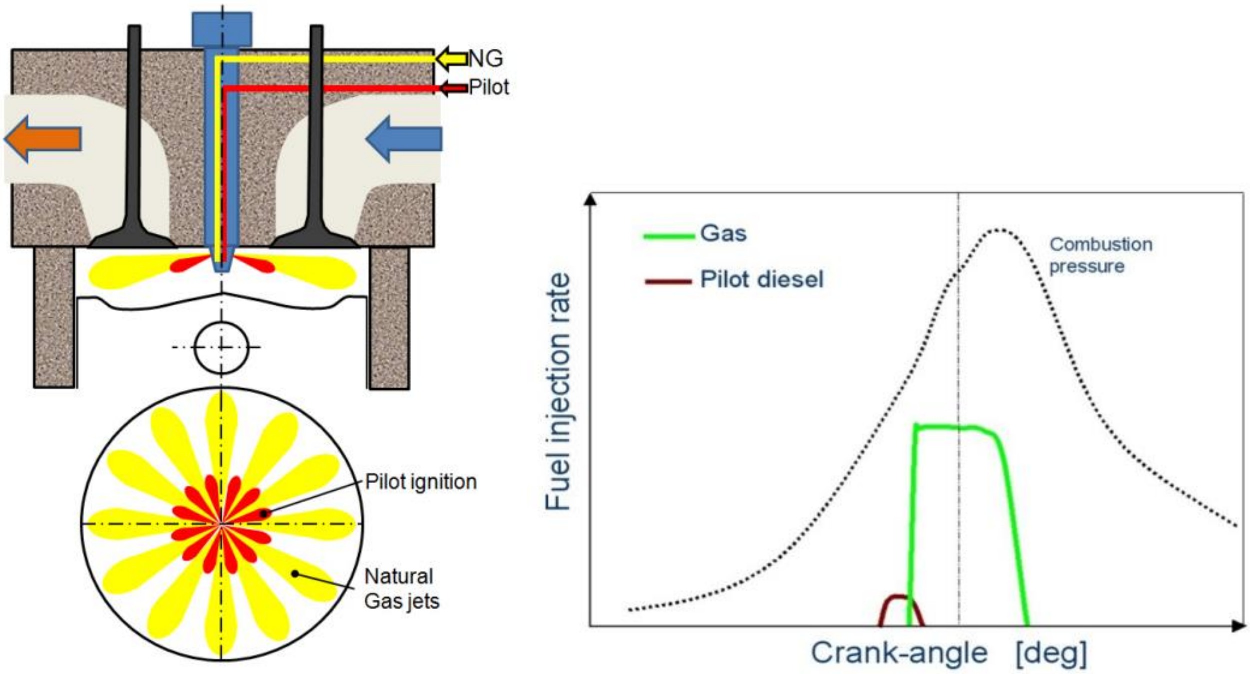

Figure 16. Gas diesel arrangement (left) and fuel injection timing (right) [42].

2.3 LNG Tank types

LNG can be stored in different types of insulated tanks, but all types are composed of a primary barrier (the tank) which contains the LNG, an insulation and a secondary barrier. The most important property to consider in the selection of tank materials is the low-temperature toughness. This consideration is vital as most metals and alloys (except aluminium) become brittle below a certain temperature. For this reason the primary barrier is usually made of nickel-alloyed steels, stainless steels (such as Invar) or aluminium. Thermal insulation must be fitted to minimize heat flux into cargo tanks, thus reducing boil-off and to protect the ship structure around the tanks from the effects of low temperature. Typical materials are perlite, polyurethane, polystyrene.

LNG tanks can be divided in two types: self-supporting “independent” tanks and membrane tanks [43].

2.3.1 Independent tanks

These type of tanks are completely self-supporting and are not part of the ship structure, they are classify by IGC code into three types (A, B and C), mainly on the basis of their design pressure.

2.3.1.1 Type A

Type 'A' tanks are constructed primarily of flat surfaces. The maximum allowable tank design pressure in the vapour space for this type of system is 0.7 barg; this means cargoes must be carried in a fully refrigerated condition at or near atmospheric pressure (normally below 0.25 barg).

The material used for Type 'A' tanks is not crack propagation resistant. Therefore, in order to ensure safety, in the unlikely event of cargo tank leakage, a secondary containment system is required. This secondary containment system is known as a secondary barrier, which must be a complete barrier capable of containing the whole tank volume at a defined angle of heel and may form part of the hull. By this means appropriate parts of the tanker's hull are constructed of special steel capable of withstanding low temperatures. The alternative is to build a separate secondary barrier around each tank.

2.3.1.2 Type B

Type 'B' tanks can be constructed of flat surfaces or they may be of the spherical type. This type of containment system is the subject of much more detailed stress analysis compared to Type 'A' systems. These controls must include an investigation of fatigue life and a crack propagation analysis.

Because of the enhanced design factors, a Type 'B' tank requires only a partial secondary barrier in the form of a drip tray.

The hold space in this design is normally filled with dry inert gas. However, when adopting modern practice, it may be filled with dry air provided that inerting of the space can be achieved if the vapour detection system shows cargo leakage. A protective steel dome covers the primary barrier above deck level and insulation is applied to the outside of the tank.

The prismatic Type 'B' tank has the benefit of maximizing hull volumetric efficiency and having the entire cargo tank placed beneath the main deck. Where the prismatic shape is used, the maximum design vapour space pressure is, as for Type 'A' tanks, limited to 0.7 barg.

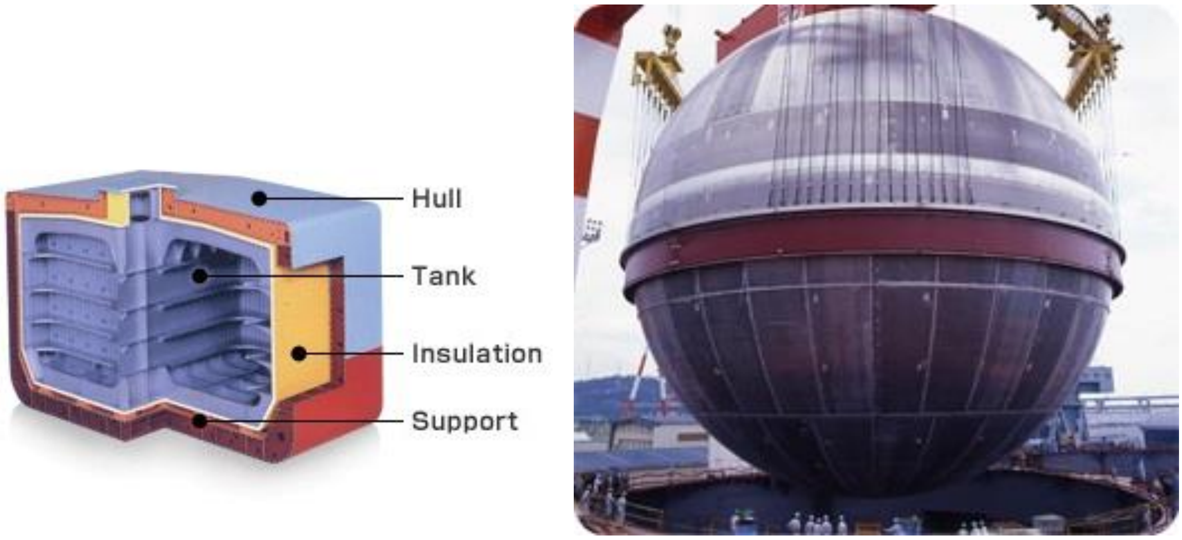

Figure 17. Typical prismatic and spherical B type tank [44, 45].

2.3.1.3 Type C

Type 'C' tanks are normally spherical or cylindrical pressure vessels having design pressures higher than 4 barg and should be lower than 10 barg. The cylindrical vessels may be vertically or horizontally mounted. Type 'C' tanks are designed and built to conventional pressure vessel codes and, as a result, have to be subjected to accurate stress analysis. Accordingly, no secondary barrier is required for Type 'C' tanks and the hold space can be filled with either inert gas or dry air.

The tanks and associated equipment are designed for a working pressure of approximately 5 to 7 barg and a vacuum of 0.3 barg.

With such an arrangement, there is comparatively poor utilization of the hull volume; however, this can be improved by using intersecting pressure vessels or *bi-lobe* type tanks which may be designed with a taper at the forward end of the tanker.

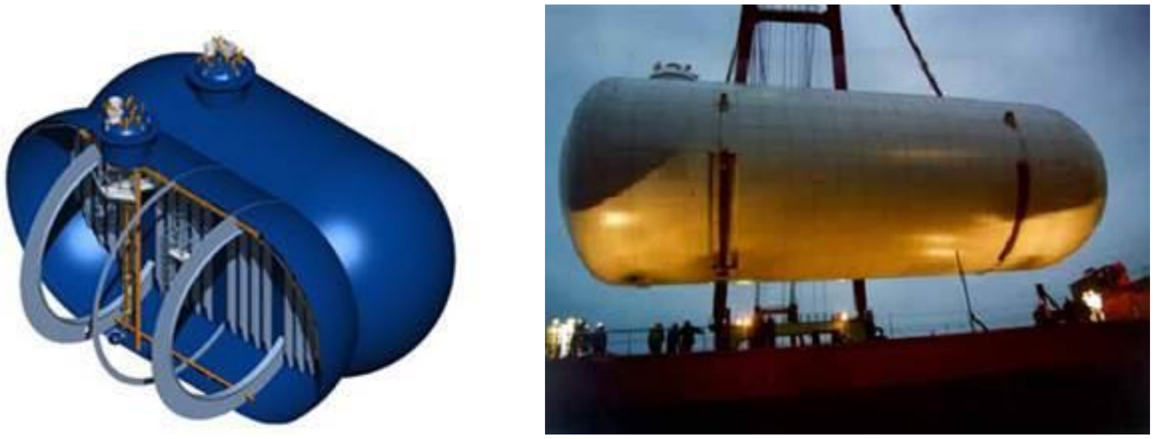

Figure 18. Typical cylindrical and bi-lobe C type tank [46].

2.3.2 Membrane tanks

The concept of the membrane containment system is based on a very thin primary barrier (membrane - 0.7 to 1.5 mm thick) which is supported by the insulation. Such tanks are not self-supporting like the independent tanks; the inner hull forms the load bearing structure. Membrane containment systems must always be provided with a secondary barrier to ensure the integrity of the total system in the event of primary barrier leakage. The membrane is designed in such a way that thermal expansion or contraction is compensated without over-stressing the membrane itself. The maximum allowable design pressure for this type of containment system is 0.7 barg.

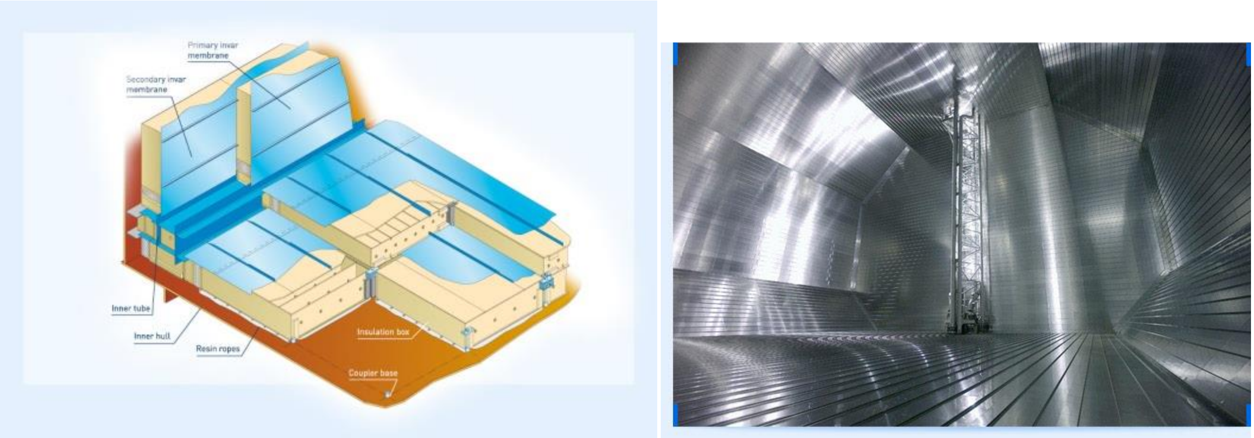

Figure 19. Typical membrane tank [47].

2.4 LNG plant

In the previous paragraphs the two main components of an LNG plant has been described, but between the LNG tank and the engine there is a complex piping system and some auxiliary components. Each LNG plant is a tailor-made solutions, because depends on LNG tank size & type, engine type and general ship arrangement. Furthermore, the whole system has to fulfil the current safety rules.

Anyway, the LNG system aim is to fed the engines with natural gas at the right pressure and temperature (on the basis of engine type) and maintain the correct pressure in the LNG tank(s).

The main component of an LNG system are:

- Pipe system
- Machinery
- Gas detection system

2.4.1 Pipe system

The fuel supply pipework should be either routed within a sealed ventilated duct or be of a double walled construction. Where double walled piping is used, either inert gas, at a pressure higher than the gas pressure or continuous ventilation should be used within the outer section; this is to of gas tight construction. Both systems require pressure monitoring to detect leakage. The pipework should be double walled right up to the point of the gas admission valve on the engine. Experience has shown that this can be difficult to achieve as due to the vibration of the engine, there is the inherent risk of leakage. An alternative is to fit a hood over the engine thereby facilitating the use of single walled piping anywhere under the hood.

Appropriate materials should be used for any pipework designated to convey liquid LNG as well as adequate insulation to prevent excessive warming of the gas and to protect for inadvertent touching by personnel.

Any sections of piping that can be isolated from the fuel system and which can trap gas must have arrangements to automatically remove the liquid or be fitted with a pressure relief valve. Any trapped liquid will eventually vaporise increasing the gas pressure leading to the potential failure of the pipework and with an expansion ratio of 600:1, significant quantities of gas could be released. Furthermore, all compartments that store, contain pipework or gas equipment should be adequately ventilated.

2.4.2 Machinery

The main components used in an LNG system are the vaporizer, cryogenic pumps and cryogenic compressor.

The vaporizer is necessary in all plant layouts, because the gas engines have to be fed with NG in gaseous form with a temperature between 0 and 60°C. Usually the vaporizer used in LNG ships are shell and tube exchanger and uses glycol as heat transfer fluid. On the basis of the engine type they could work at low pressure (5-10 bar) or high pressure (up to 350 bar).

As for the cryogenic pumps, two different types are used on the basis of the operating pressure: in case of low pressure system a centrifugal pumps is used, while for high pressure system a reciprocating piston pump is used. Anyway, these pumps are very expensive because they require special materials and components due to the very low operating temperature. In case of a system with a pressurized LNG tank and low pressure NG engine it is not necessary to use of any kind of LNG pump: in this case the pressure in the tank is given by the vapour in the tank. In order to increase the pressure in the tank a pressure build up circuit is installed: this circuit vaporize and reintroduce a small amount of NG into the tank.

In some cases, especially in LNG carriers, a reciprocating compressor is necessary for BOG using. In this case also special materials and components are used due to the very low operating temperature.

2.4.3 Gas detection system

The last line in defence with gas equipment is the use of gas detection. Should anything go wrong, the gas detection system should identify the presence of a leak well before it reaches the LFL. The safety system will then isolate and remove the gas. Gas sensors can broadly be divided into direct and indirect sensor arrangements. With direct measurement a physical parameter of the gas is sensed.

With indirect, a chemical reaction or indication is used to detect the concentration of the gas. However, gas detection is complicated by the ventilation arrangements. High ventilation airflows quickly dilute the leaking gas concentration and whilst this might be considered safe from an explosion perspective, the continuous exhausting of gas to the outside air does little for the greenhouse gas abatement. In this situation, the leak would have to become excessive before a gas detector could identify the leak. Add to this that the relative location of the detector or sampling point in respect to the leak may mean that there is a more flammable mixture elsewhere within the space as the air/gas ratio will be varying throughout the compartment volume.

However, it should also be remembered that tracing leaks within a machinery space is going to be problematic as upon detection, the gas supply is isolated and any gas within the space removed. If the leak is within a double pipe then the source of the leak is going to be very difficult to find and a trial and error method will have to be used to test all the pipe joint connections in the first instance. Therefore all the number of pipe connections should be kept to a minimum Gas detection for pipe ducts and machinery spaces shall be continuous.

3 WORLD MARITIME TRAFFIC ANALYSIS

3.1 Statistical analysis of world maritime traffic

After the literature analysis on ship emissions, an overview on the use of LNG as ship fuel, it is necessary to identify which is the type of vessel that can benefit most ecologically and economically from the installation of an LNG propulsion system: the answer can be obtained through a statistical analysis of the world maritime traffic.

The aim of this statistical analysis is to find the time spent in ECA zones for each ship type and size: vessels that spend most of their time sailing in ECA zones are more economically suitable for LNG fuelling. The number of trips made by each type of ship was taken into consideration as well.

In the next paragraphs the methodology of this analysis and the obtained results will be described.

3.1.1 Development of the software tool

3.1.1.1 Preliminary operations on traffic database

For the traffic analysis a traffic database supplied from a classification society has been examined. The data cover a 6 days period in October 2008 and are composed by 323,587 records.

Each record of the traffic database includes:

- Ship specification (IMO number, type, size, speed, power, owner, ...)
- Current, previous and next port
- Current, previous and next port date

For the analysis a software tool has been developed using Matlab. The first operation of the software is to read the traffic database and load the data.

Unfortunately, some records were incomplete and therefore discarded obtaining 147,254 usable records (at least 2 ports recorded, non-redundant records). Then, in order to increase the number of useful records and implement the traffic database, two auxiliary databases have been created. This phase was very time-consuming because it was not possible to automate it but, thanks to the implemented new databases, an 88% records usage was achieved.

The first auxiliary database contains all the information of all the ports in the world, including official ONU code, geographical coordinates, official port name and official port country name (Table 6). Table 7 and Table 8 show samples of how this database is structured.

Then, using the ports database it is possible to format and complete the traffic database. In case of missing information or no match, the software enables the user to manually insert it, otherwise the record is discarded.

Table 6: Official ONU ports list (selection from the complete table)

Location Code	Name	Complete Code	Country	LAT °	LAT '	LAT N/S	LONG °	LONG '	LONG E/W
ABU	Abu al Bukhoosh	AEABU	United Arab Emirates	25	29	N	53	8	E
AJM	Ajman	AEAJM	United Arab Emirates						
AMF	Mussafah	AEAMF	United Arab Emirates	24	23	N	54	29	E
AMU	Abu Musa	AEAMU	United Arab Emirates	25	52	N	55	1	E
ARZ	Arzanah Island	AEARZ	United Arab Emirates						
AUH	Abu Dhabi	AEAUH	United Arab Emirates	24	28	N	54	22	E

The second auxiliary database contains the ships information: these database is necessary to classify the vessels by segment, category, size, and also assign them a speed (calculated as the average of the known vessel of that specific category and size) when it lacks in the Lloyd's register. The assignment of the vessel speed permit to recover some records as will be described later.

Table 7 - Alternative ports names (selection of the about 4000 manually created)

Alternative Name	Official Name	Complete Code	Country Code	Country
Aagotnes	Ågotnes	NOAGO	NO	Norway
Aalesund	Ålesund	NOAES	NO	Norway
Aalst	Renkum	NLRNK	NL	Netherlands
Aalvik	Alvik	NOAAV	NO	Norway
Aandalsnes	Åndalsnes	NOAND	NO	Norway
Aardalstangen	Årdalstangen	NOARD	NO	Norway
Aarhus	Århus	DKAAR	DK	Denmark

Table 8: Alternative country names (selection from the complete table)

Alternative Name	Official Name
Aland Islands	Finland
American Pacific Territories	American Samoa
American Virgin Islands	Virgin Islands, U.S.
Antigua & Barbuda	Antigua and Barbuda
Arab Republic of Egypt	Egypt

Table 9 and Table 10 show samples of the database's internal structure. As can be seen from the tables, the only information about vessel type, segment or category is the three-letter code. Therefore, to obtain more direct information on the vessel itself, a database of 152 three-letter codes have been implemented, and to each code, a type, a segment and a category have been manually assigned. After the assignment of the vessel category, the software completes the classification of the vessel and assign other information, such as the size and the weight unit.

Table 9: Vessels classification by code (selection)

VESSEL TYPE CODE	VESSEL TYPE DECODE	SEGMENT	VESSEL CATEGORY
OYT	Yachts	Cruise & Ferry	Yachts
PRR	Passenger & RoRo Vessels	Cruise & Ferry	Passengers & Cargo
PZZ	Passenger Vessels (Unspecified)	Cruise & Ferry	Passengers
RHR	Hydrographic Research Vessels	Special Vessels	Research Vessels
RMR	Meteorological Research Vessel	Special Vessels	Research Vessels
ROR	Oceanographic Research Vessels	Special Vessels	Research Vessels
RRB	Research Vessels / Buoy Ships	Special Vessels	Research Vessels
RRE	Research Vessels	Special Vessels	Research Vessels
RRS	Research Vessels / Supply Ships	Special Vessels	Research Vessels
RSR	Seismographic Research Vessels	Special Vessels	Research Vessels
TAC	Acid Tankers	Merchant	Tankers
TAS	Asphalt Tankers	Merchant	Tankers
TBK	Bunkering Tankers	Merchant	Tankers
TCH	Chemical Tankers	Merchant	Tankers
TCO	Combined Chemical and Oil Tan	Merchant	Tankers

Table 10: Vessels classification by size (selection)

VESSEL CATEGORY	VESSEL SIZE	UNITS	FROM	TO	SPEED
Bulk Carriers	Very Small	DWT	1	5000	11
Bulk Carriers	Small	DWT	5000	10000	13
Bulk Carriers	Handysize	DWT	10000	40000	14.5
Bulk Carriers	Handymax	DWT	40000	60000	14.5
Bulk Carriers	Panamax	DWT	60000	80000	14.5
Bulk Carriers	Capesize	DWT	80000	200000	14.5
Bulk Carriers	VLOC, Very Large Ore Car	DWT	200000		14.5
Cargo Vessels	Very Small	DWT	1	5000	11.5
Cargo Vessels	Small	DWT	5000	20000	14.5
Cargo Vessels	Medium	DWT	20000	40000	15.5
Cargo Vessels	Large	DWT	40000		15
Combination Carri	Very Small	DWT	1	5000	12
Combination Carri	Small	DWT	5000	10000	14
Combination Carri	Handysize	DWT	10000	40000	14
Combination Carri	Handymax	DWT	40000	60000	15

Analysing the traffic data in detail, significant deficiencies of sailing/arrival dates and vessels speed were found: for this reason a lot of records had to be discarded at the beginning of the analysis. But, some of the discarded records have at least two ports and then it has been decided to calculate the distance between the ports and assign a speed to the vessel. These simple operations allow to calculate the days at sea for each vessel, and recover many records, allowing to use the 88% of traffic records instead of the 70%.

The vessel speed has been assigned as the mean value of the speed of the same vessel type and size contained in the database, while obtaining and implementing a port-to-port distances matrix to calculate the distances was more difficult. In fact, the official ONU ports database contains 16,708 ports: the use of a matrix with that dimension it is not possible for computational reasons. Then it was decided, loosing precision in the analysis, to regroup some near ports into a smaller number of reference ports, 178 in the current case. The 178 reference ports have been chosen taking into account the traffic volume and the geographic area of the ports: in high traffic and in ECA zone the subdivision is more refined, considering a low number of ports for each reference port. In Figure 20 it can be seen the specific association of 19 ports to Bordeaux's port in France. The assignment of the reference port was time-consuming because could not be automated.

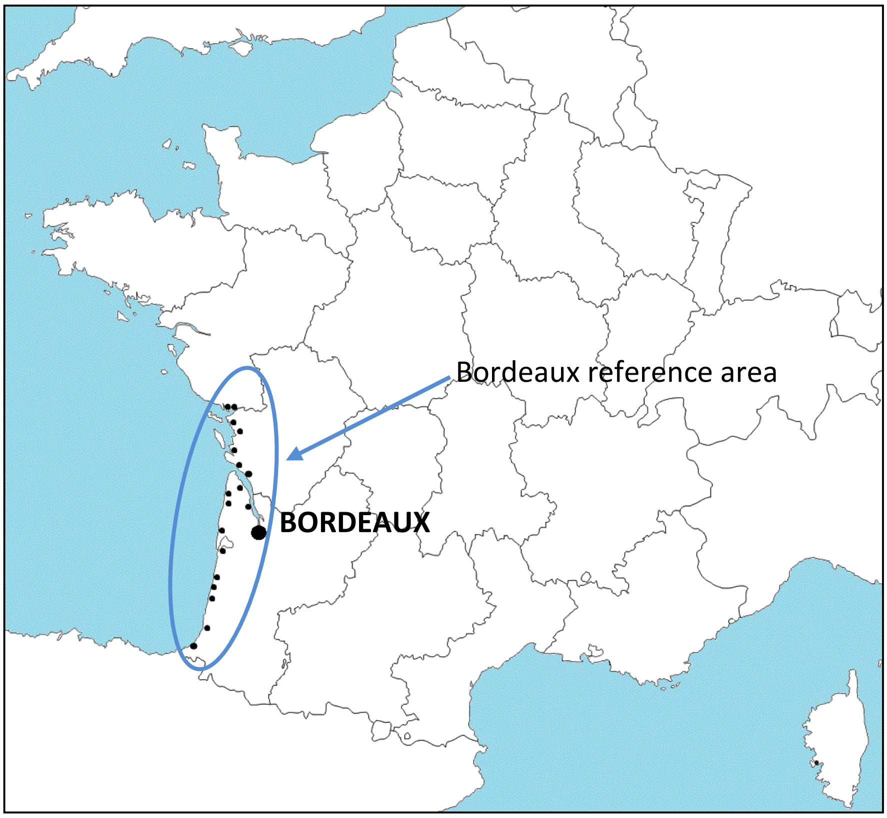

Figure 20: Reference area example

At the end of this process the traffic database is formatted and completed and can be used for the statistical analysis.

3.1.1.2 Traffic database analysis

After the operations necessary to format and complete the database, an algorithm for obtaining the time spent in ECA zone from the ships has to be developed.

For the analysis the world has been divided in 14 ECA zones, grouped in 7 ECA areas as can be seen in Figure 21 and Table 11. In add to current ECA zone (area 1 and 2) also the possible future ECA zone have been considered.

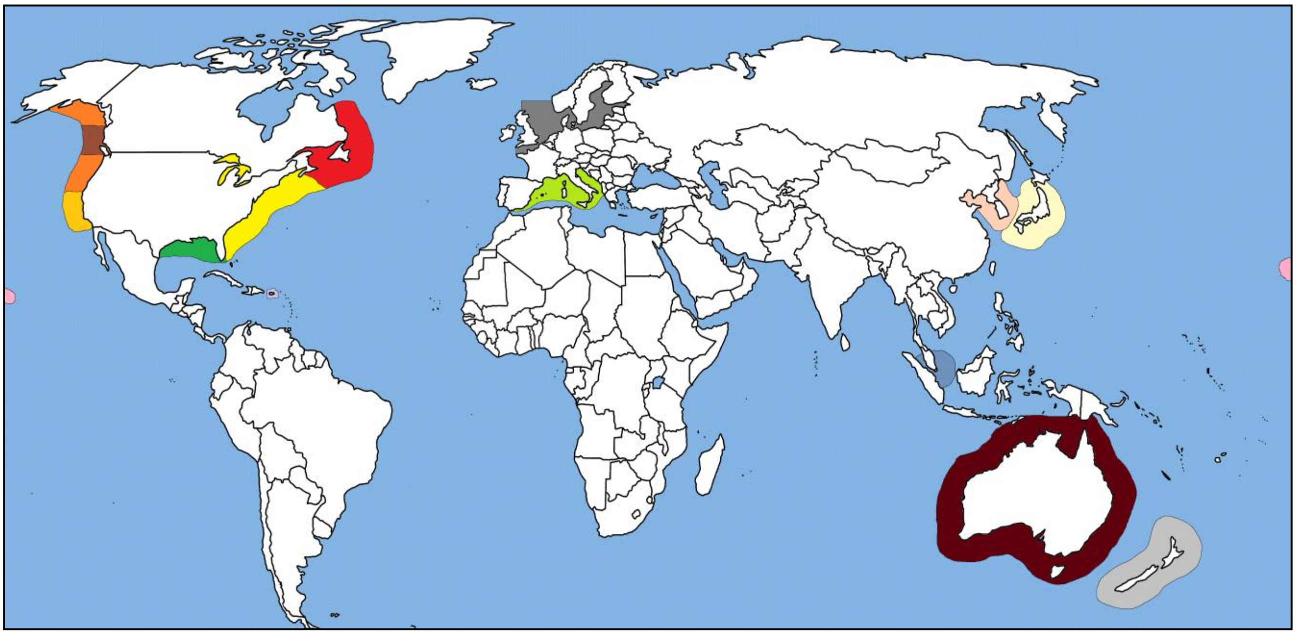

Figure 21: ECA zones

Table 11: ECA zones internal assignments

ECA Zone	ECA Area	ECA Zone N. rif	Extension (miles)	Color
Not in ECA zone	0	0	0	⬜
US East Coast / Lakes	2	1	Multiple Values	🟨
US West Coast Nord	2	2	200	🟧
US West Coast Sud	2	7	200	🟧
Hawaii	2	3	200	🟥
Gulf of Mexico	2	4	200	🟩
Puerto Rico	2	5	200	🟫
North Sea / Baltic Sea	1	6	Multiple Values	⬛
East Canada	2	8	Multiple Values	🟥
West Canada	2	9	200	🟫
Mediterraneo	3	10	Multiple Values	🟩
Singapore	4	11	200	🟦
Nuova Zelanda	5	12	200	⬜
Australia	5	13	200	🟫
Giappone	6	14	200	🟨
Korea	7	15	200	🟥

The reason of two different divisions, ECA areas and zones, is the extension of the American coasts. Considering the higher costs of shipping sailing in ECA zones, a vessel that has to travel from New York to New Orleans, would not spend all its time in ECA zone, but will sail strait out of ECA and re-enter near the arrival port.

Then, the American coasts has been subdivided in 7 zone, in order to avoid to the software to consider all the sailing time in ECA in case of shipment in the same area, but considering that the ship will exit and re-enter in ECA.

Now, the problem is how to implement the ECA zone for an automated analysis without the use of a program able to trace maritime routes. It was decided to use the distance matrix previously developed and assigning the distance to leave the ECA zone sailing from each reference port. Then, to each one of the 178 reference ports, an ECA zone, ECA area, and miles to leave it were manually assigned, and those data were automatically attributed to all the ports since each port is linked to a reference port as described previously (Table 12).

Table 12: ECA zones information structure (selection)

PortCode	ReferencePort	RefCode	ECA Zone rif	Miles to leave ECA Zone
DEECK	Rostock (Germany)	DE0091	6	750
DEELS	Bremen (Germany)	DE0013	6	650
DEEME	Bremen (Germany)	DE0013	6	650
DEESU	Amsterdam (Netherland	NL0002	6	550
DEFLF	Rostock (Germany)	DE0091	6	750
DEGLU	Hamburg (Germany)	DE0044	6	700
DEGRD	Rostock (Germany)	DE0091	6	750
DEHAM	Hamburg (Germany)	DE0044	6	700

Once the database has been formatted and the additional data have been added, the developed software tool analyses the global traffic following these steps:

- Creation of empty matrices to store values in order to save computational time;
- Copy the traffic records into the matrices;
- Sailing and arrival ports are analysed and time spent in ECA for the analysed vessel is stored in an appropriated position of the matrix, which is subdivided in different ECA zones and vessel segment (Table 13 and Table 14) or vessel category and size (Table 15 and Table 16);
- Matrices are stored in an Excel® result file.

The obtained results can now be elaborated in order to find the most proper vessel for the LNG propulsion.

Table 13: Time spent in ECA zones (effective days), classification by segment

Vessel Segment	Number of Trips	Days at Sea	Days in ECA 1	Days in ECA 2
Cruise & Ferry	6148	11778	1661	653
Merchant	168218	834969	60011	16496
Navy	463	1109	152	22
Offshore	1991	9180	1003	158
Special Vessels	17320	49077	8698	3049
Other	144	198	30	0
Grand Total	194284	906311	71556	20379
Percentages			7,9%	2,2%

Table 14: Time spent in ECA zones (%), classification by segment

Vessel Segment	Number of Trips	Days at Sea	%Days in ECA 1	%Days in ECA 2
Cruise & Ferry	6148	11778	14,1%	5,5%
Merchant	168218	834969	7,2%	2,0%
Navy	463	1109	13,7%	1,9%
Offshore	1991	9180	10,9%	1,7%
Special Vessels	17320	49077	17,7%	6,2%
Other	144	198	15,4%	0,0%

Table 15: Time spent in ECA zones (days), classification by type (selection)

Vessel Category	Vessel Size	Number of Trips	Days at Sea	Days in ECA 1	Days in ECA 2
Bulk Carriers	Very Small	931	2057	465	23
Bulk Carriers	Small	1039	3058	309	48
Bulk Carriers	Handysize	13200	92110	3133	3600
Bulk Carriers	Handymax	7178	63236	809	1095
Bulk Carriers	Panamax	6237	60346	1156	1173
Bulk Carriers	Capesize	4041	37843	579	202
Bulk Carriers	VLOC	541	5163	59	15
Cargo Vessels	Very Small	32510	115365	22375	332
Cargo Vessels	Small	21633	113775	7488	1571

Table 16: Time spent in ECA zones (%), classification by type (selection)

Vessel Category	Vessel Size	Number of Trips	Days at Sea	% in ECA 1	% in ECA 2
Bulk Carriers	Very Small	931	2057	22,6%	1,1%
Bulk Carriers	Small	1039	3058	10,1%	1,6%
Bulk Carriers	Handysize	13200	92110	3,4%	3,9%
Bulk Carriers	Handymax	7178	63236	1,3%	1,7%
Bulk Carriers	Panamax	6237	60346	1,9%	1,9%
Bulk Carriers	Capesize	4041	37843	1,5%	0,5%
Bulk Carriers	VLOC	541	5163	1,1%	0,3%
Cargo Vessels	Very Small	32510	115365	19,4%	0,3%
Cargo Vessels	Small	21633	113775	6,6%	1,4%

3.1.2 Results of the traffic analysis and selection of the most suitable vessels for LNG fuelling

The aim of the statistical analysis is to identify the most suitable vessels for LNG fuelling, i.e. the vessels that spent most of their time in ECA zone. For the vessels selection only the current ECA zone has been considered (ECA area 1 and 2) but the complete results of the statistical analysis can be found in Annex 1: Results of the traffic analysis in tabular form.

For the selection it has been considered the percentage of vessels that spend more than 80% of their time in ECA zone but also the days at sea: multiplying the two parameters, it has been obtained the numbers of days at sea for each type of vessel. The results obtained are shown in the graph below (Figure 22).

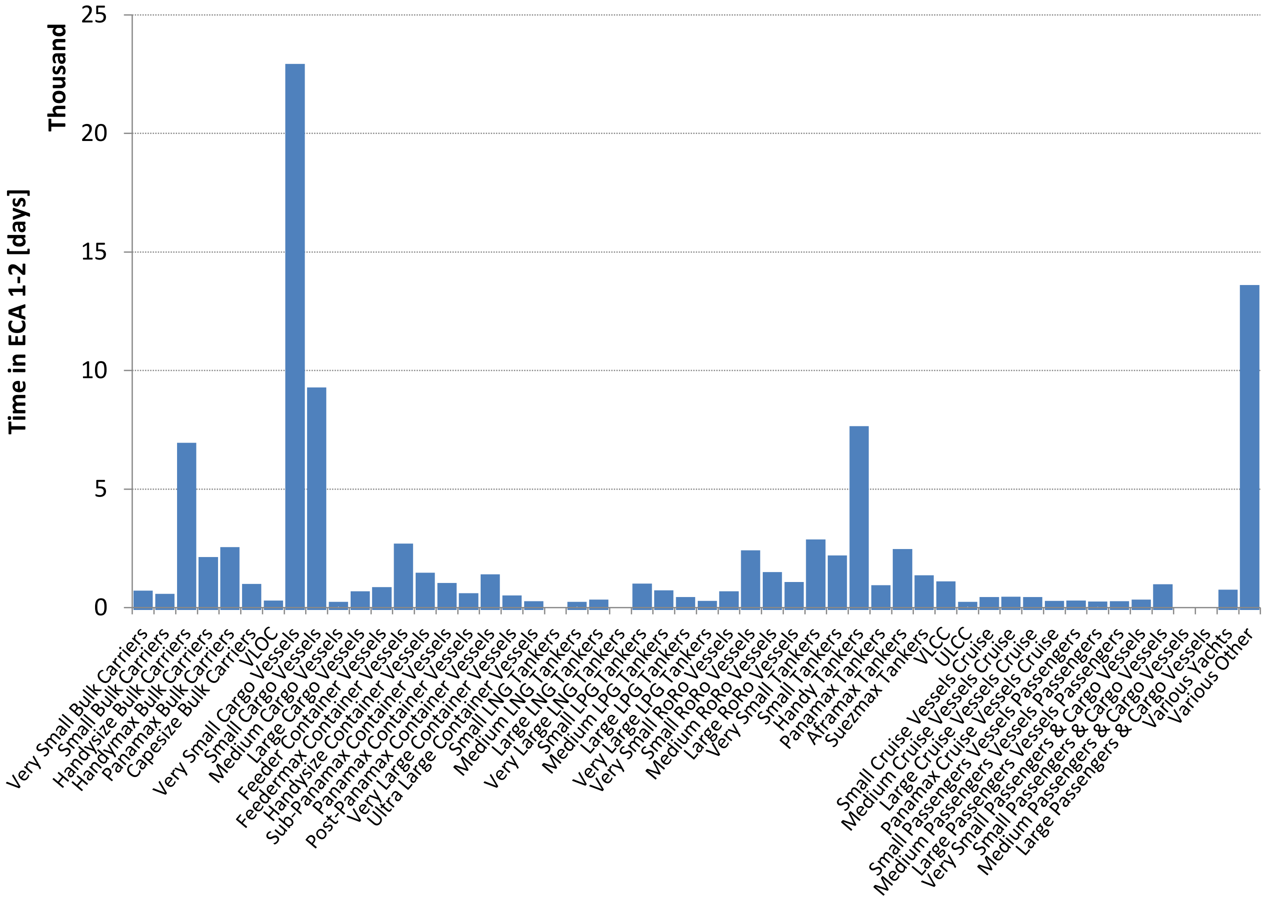

Figure 22: Average number of days in ECA 1-2 zones.

From this graph the first eight highest values have been chosen. The types of vessel that seem to be the best choice for LNG propulsion are:

- Very Small Cargo
- Small Cargo
- Feedermax Container
- Very Small Tanker
- Handysize Tanker
- Handysize Bulk Carrier
- Small Ro-Ro[1]
- Medium Ro-Ro
- Various / Other

In addition to the traffic analysis the deliveries forecast of new ship until 2022 has been examined. Starting again from the vessels that spent more than 80% of their time in ECA1-2 and the delivery forecast of new vessels until 2022, multiplying these two values it is possible to obtain a number

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[1] *Ro-Ro* (Roll on – Roll off ship) Vessels designed to carry wheeled cargo such as automobiles, trucks, semi-trailer trucks, trailers or railroad cars that are driven on and off the ship on their own wheels.

of ships where it is potentially favourable the installation of LNG propulsion system. The results obtained are shown in Figure 23. The ships are:

- Handysize Tankers
- Various / Other
- Small Tankers
- Large Passengers
- Handysize Bulk Carrier
- Aframax Tanker
- Panamax Container
- Small Ro-Ro

Cross checking the data of traffic analysis and the data of deliveries forecast it is possible to choose the best candidates for LNG propulsion (see

Table 17).

The best candidate ships for LNG propulsion are:

- Handysize Tanker
- Small and Medium Ro-Ro
- Handysize Bulk Carrier
- Large Passenger ship

All tanker sizes are suitable for the LNG propulsion but the handysize has a higher time spent in ECA and a higher number of deliveries in the next years. The other ships has been discarded due to the lower delivery forecast, low time spent in ECA zone or size too small: the very small sizes are not the focus of this research. As for Various/Other category, it does not represent a ship type but collect all the ship that cannot be classified in the previous categories and then has been discarded.

Table 17: candidate ships for LNG propulsion

Vessel Category	Vessel Size	% ships that spend more than 80% time in ECA 1-2	N. of ships that spend more than 80% time in ECA 1-2	Total ordered ships (2010 - 2022)	Total days spent in ECA 1-2 by ships that spend more than 80% of their time in ECA 1-2
Bulk Carriers	Handysize	9.6%	1263	1249	3096
Cargo Vessels	Very Small	25.8%	8385	210	18887
Cargo Vessels	Small	9.5%	2049	188	4787
Container Vessels	Feedermax	25.6%	1412	204	2182
Container	Panamax	8.6%	162	1021	194
RoRo Vessels	Small	31.1%	1115	264	1782
RoRo Vessels	Medium	38.0%	740	210	1046
Tankers	Very Small	21.2%	1486	-	2374
Tankers	Small	17.9%	920	933	1648
Tankers	Handy	17.2%	2180	2105	4612
Tankers	Aframax	15.4%	671	607	1335
Passengers	Large	86.7%	39	200	48
Other	Various	20.6%	4493	2654	11469

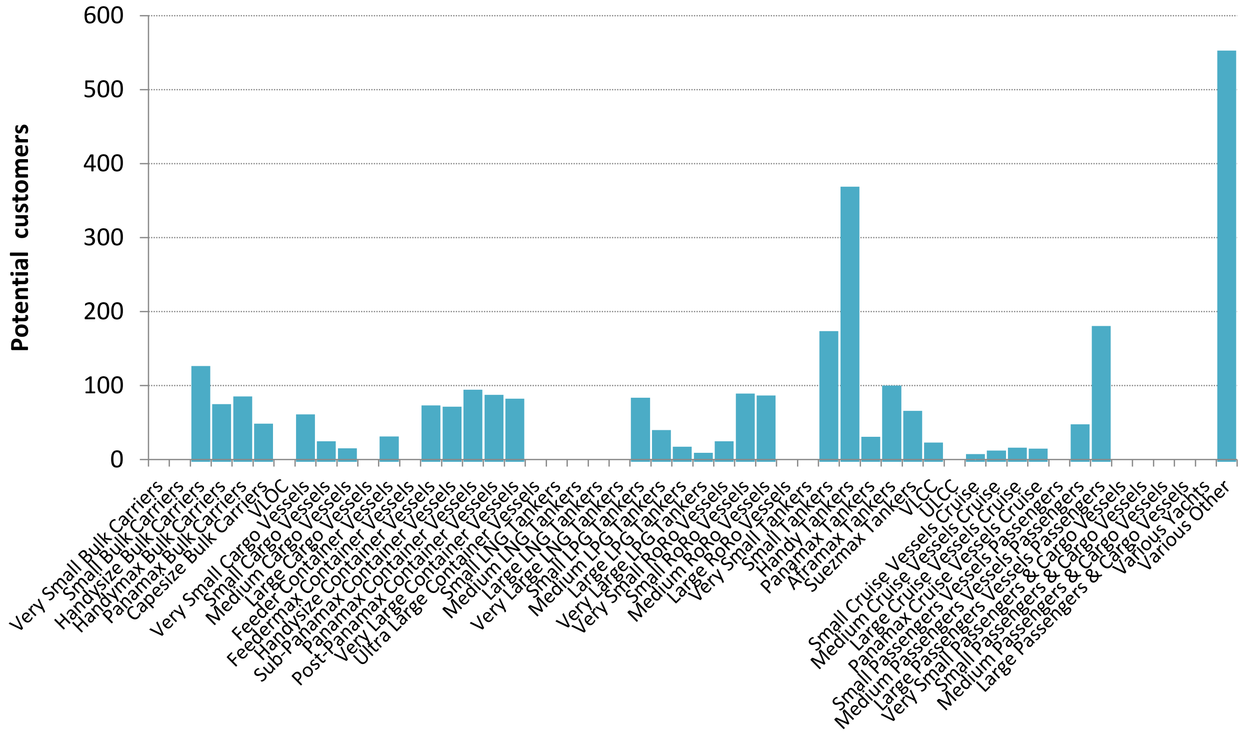

Figure 23: Potential LNG installations until 2022 obtained from a delivery forecast analysis.

3.2 Maritime traffic trend analysis

The previous analysis allows to know the most suitable vessels for an LNG system installation on the basis of the time spent in ECA zone, but the obtained results are also robust? Or could the time spent in ECA through different years affect the results?

For these reasons a second statistical analysis has been developed: the data cover three months of world ship traffic in three years: May 2008, May 2009 and May 2010.

Starting from the results of the previous analysis, it was decided to focus the analysis on 4 types of ship: tanker vessels, Ro-Ro vessels, bulk carrier vessels and cruise vessels. Analysed traffic data consist of 162,000 records and describe over 270,000 trips. The adopted methodology and the utilized software tools was the same of the previous analysis.

3.2.1 Results of the maritime traffic trend analysis

Table 18 shows the percentage of ships that spend a specific period of time in ECA zones: ships that spend most of their time sailing in ECA zones are very small bulk carriers, medium RoRo vessels, very small tankers and large cruise vessels. However, it is possible to observe that a large number of ships, such as small and medium sized vessels, spend more than 80% of their time in the current ECA zones.

Figure 24a shows the number of trips made by bulk carriers, Ro-Ro, tankers and cruise ships in the period considered: tankers recorded the highest number of trips (about 140,000) followed by Bulk Carriers (79,000) and Ro-Ro (28,000). Handysize tankers recorded the highest number of trips (52,000) among Tanker ships (Figure 24b). This confirm the results obtained in the previous analysis.

Table 18. Time spent in ECA zones by the vessels analysed in this study.

Vessel	Size	Percentage of vessels that spent time in ECA 1-2 zone:					
		> 80% of sailing time	60% - 80% of sailing time	40% - 60% of sailing time	20% - 40% of sailing time	20% - 5% of sailing time	< 5% of sailing time
Bulk Carriers	[DWT·10^3]						
Very Small Bulk Carriers	<5	28.4%	0.7%	0.5%	1.4%	0.7%	50.1%
Small Bulk Carriers	5-10	14.8%	0.3%	2.8%	1.4%	3.1%	58.3%
Handysize Bulk Carriers	10-40	11.6%	0.2%	1.4%	2.0%	5.0%	69.8%
Handymax Bulk Carriers	40-60	4.8%	0.1%	1.5%	1.2%	4.2%	81.1%
Panamax Bulk Carriers	60-80	5.7%	0.2%	1.5%	1.5%	6.0%	78.8%
Capesize Bulk Carriers	80-200	4.7%	0.2%	0.9%	0.9%	5.0%	81.1%
Very Large Ore Carrier	> 200	0.5%	0.0%	0.2%	0.1%	2.7%	84.2%
Ro-Ro (Roll on- Roll off)	[GRT·10^3]						
Very Small Ro-Ro Vessels	<5	31.2%	2.5%	2.2%	2.1%	1.4%	50.1%
Small Ro-Ro Vessels	5-20	36.7%	0.1%	2.0%	2.2%	2.8%	39.2%
Medium Ro-Ro Vessels	20-40	60.9%	0.1%	0.4%	1.6%	2.1%	22.6%
Large Ro-Ro Vessels	> 40	37.3%	0.1%	0.3%	5.7%	6.8%	42.6%
Tankers	[DWT·10^3]						
Very Small Tankers	<5	26.0%	0.2%	0.6%	0.7%	0.8%	59.3%
Small Tankers	5-10	22.2%	0.8%	0.7%	1.8%	2.1%	56.3%
Handy Tankers	10-60	18.5%	0.5%	1.5%	3.1%	6.4%	59.0%
Panamax Tankers	60-80	8.7%	0.1%	2.1%	3.4%	13.2%	68.6%
Aframax Tankers	80-120	18.2%	0.3%	2.3%	3.0%	10.6%	57.4%
Suezmax Tankers	120-200	19.0%	0.5%	3.6%	5.2%	7.6%	62.3%
Very Large Crude Carrier	200-320	1.8%	0.1%	1.2%	1.7%	2.3%	88.6%
Ultra Large Crude Carrier	> 320	3.5%	0.0%	4.7%	5.8%	3.5%	80.2%
Cruise	[GRT·10^3]						
Small Cruise Vessels	<10	16.4%	0.6%	0.8%	1.2%	1.6%	54.5%
Medium Cruise Vessels	10-60	19.1%	0.1%	4.2%	3.2%	2.3%	49.3%
Large Cruise Vessels	60-100	32.1%	2.6%	3.5%	15.9%	9.2%	23.0%
Panamax Cruise Vessels	> 100	16.3%	1.6%	3.3%	15.3%	11.0%	29.4%

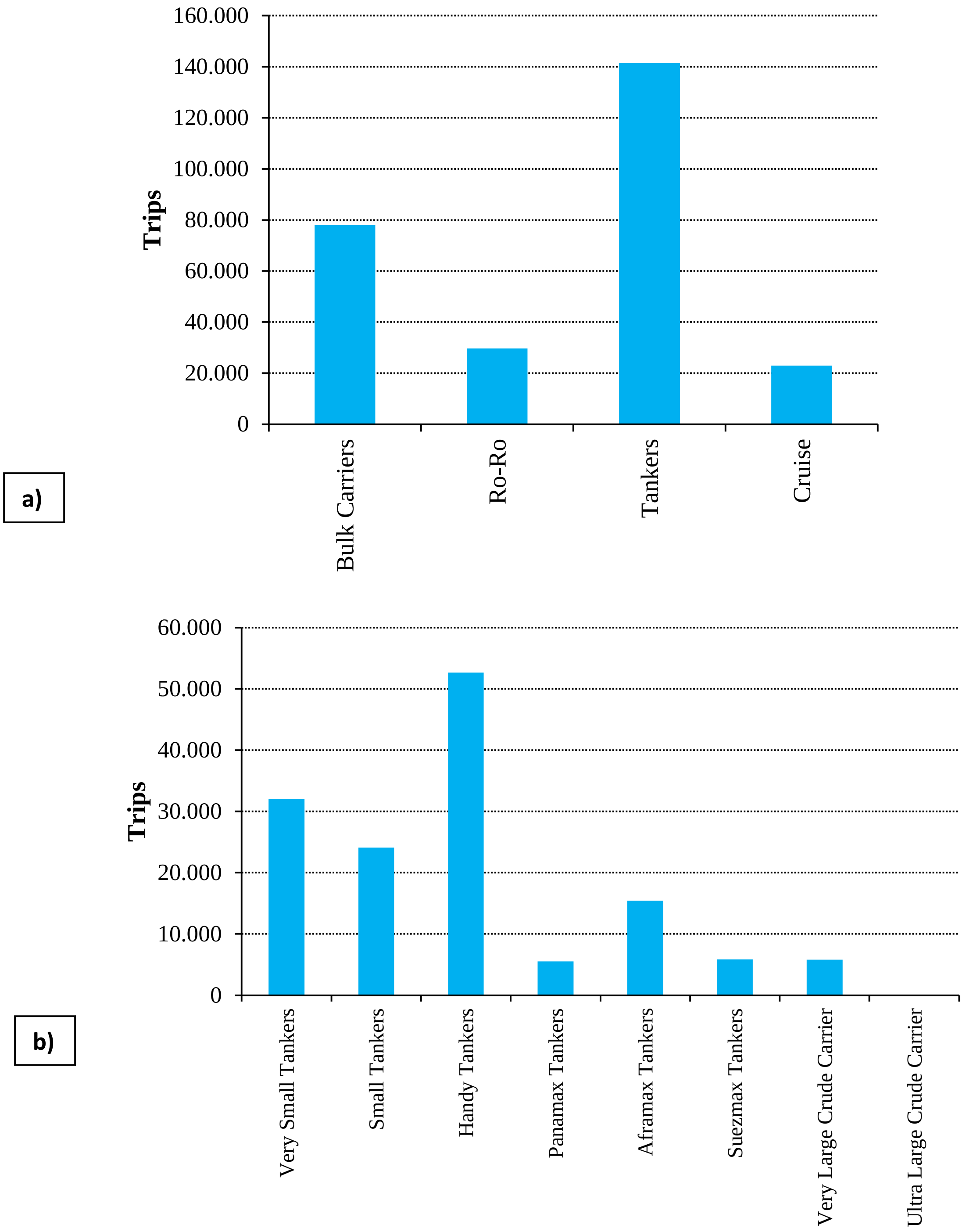

Figure 24. a) Number of trips for each vessel type; b) number of trips for each Tanker size.

Analysing the results through the three years, visible in Figure 25 and Figure 26, it is possible to note that the number of trips and days at sea does not show great variations. In particular tanker ships show an increasing trend. This result confirms also that tanker ships can be the most suitable vessel for the LNG propulsion, especially in the next future if the trend will not change.

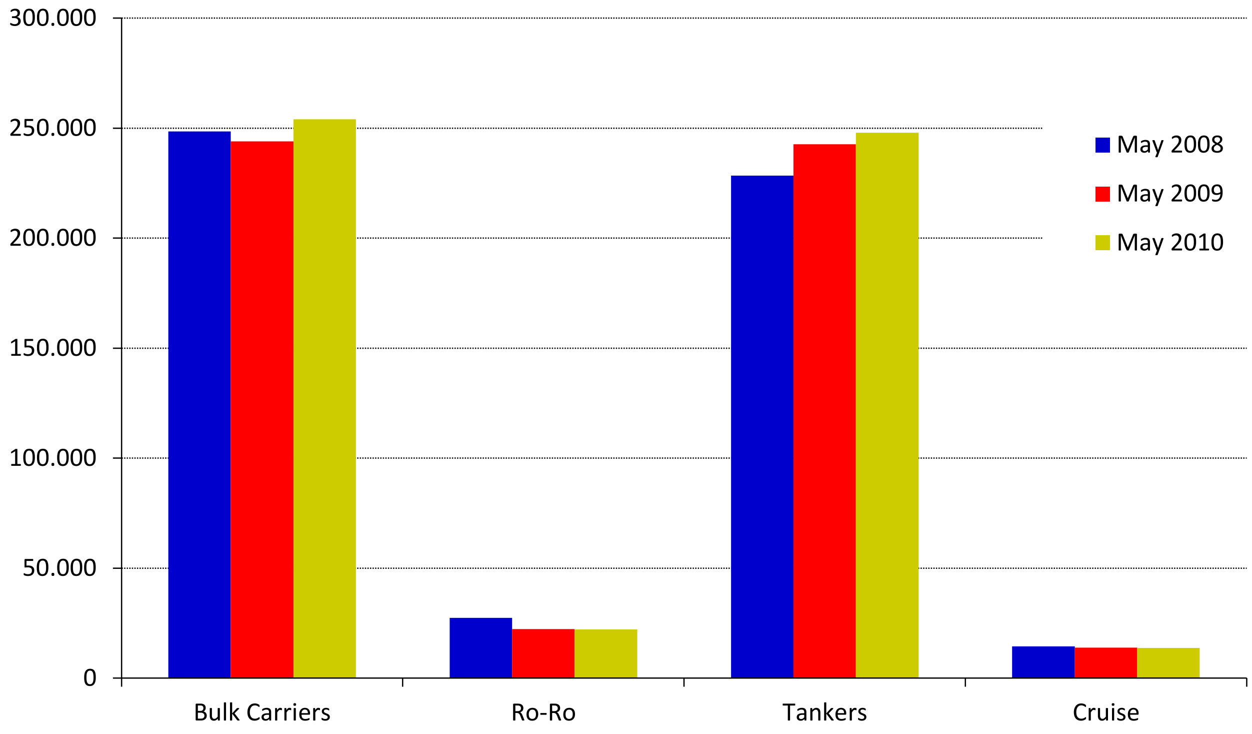

Figure 25. Days at sea in the considered years.

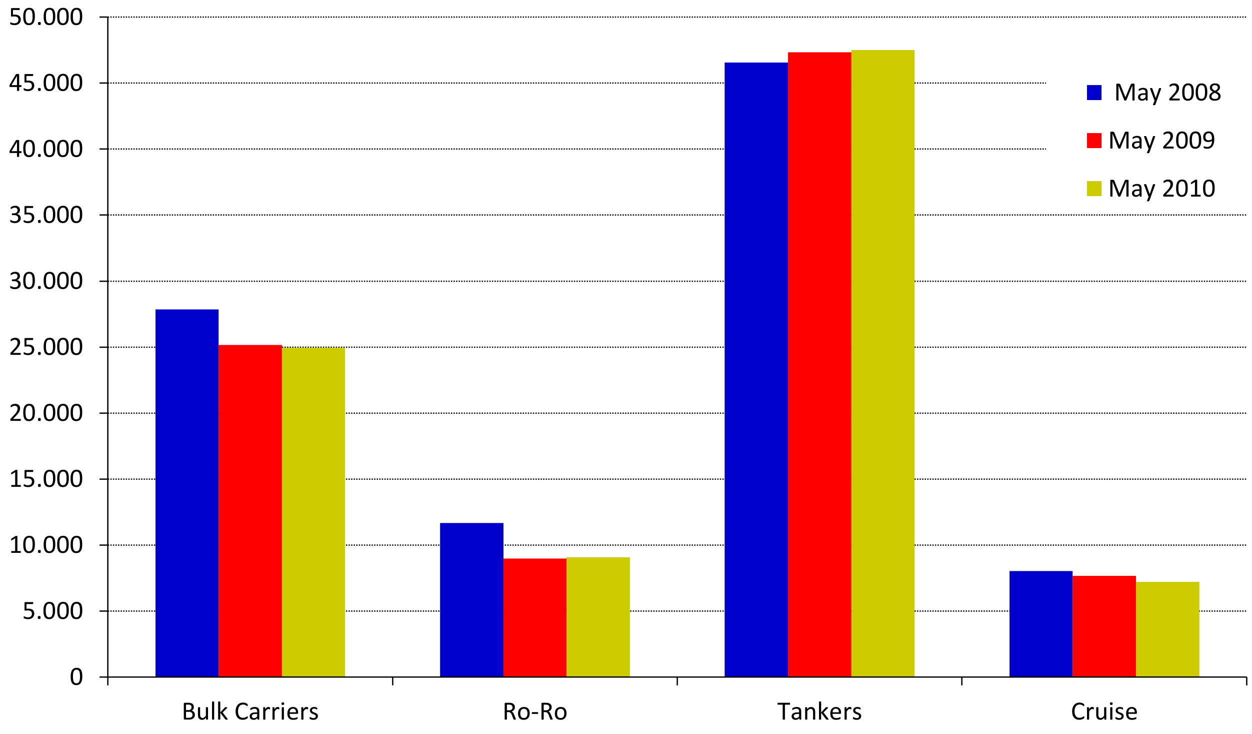

Figure 26. Number of trips in the considered years.

In Figure 27 the percentage of time spent in the current ECA zone for the examined ships confirm the result obtained in the previous analysis as well: in fact the difference between the percentages of time spent in the current ECA zone in the examined year generally is low.

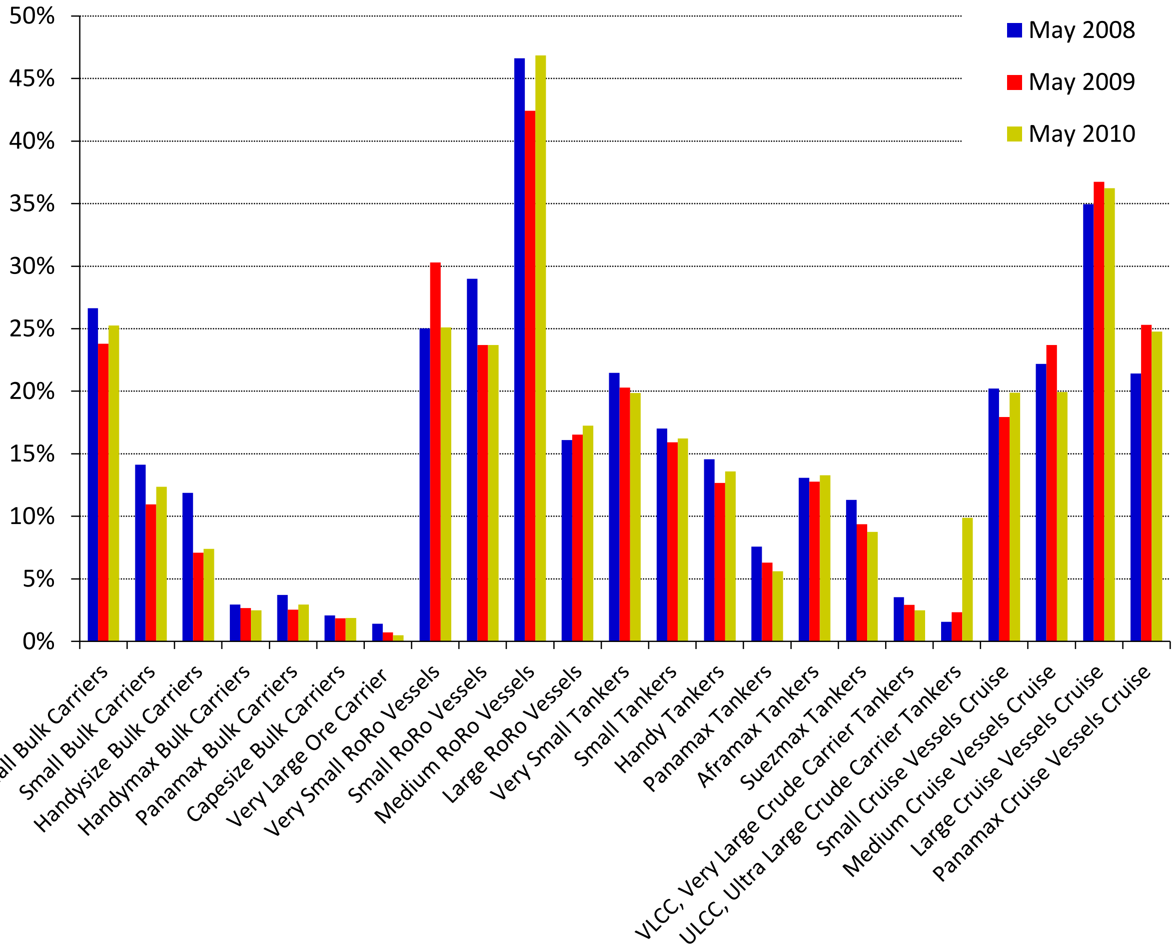

Figure 27. Percentage of time spent in ECA 1-2 (current ECA zones) in the three examined years.

A deeper analysis of the results on handysize tanker shows that this kind of ships spent most of their sailing time in ECA zone in the current ECA zone, especially in ECA 1 (Figure 28).

Figure 29 provide a fundamental information that allows to confirm that the handysize tanker is the most suitable vessel for the LNG propulsion: about 20% of ships spend in the current ECA zone more than 80% of their sailing time. Furthermore, about 12% of ships spend in the future ECA zone more than 80% of their sailing time. Then, the potential market for LNG propulsion is very wide and involve more than 30% of the handy tankers.

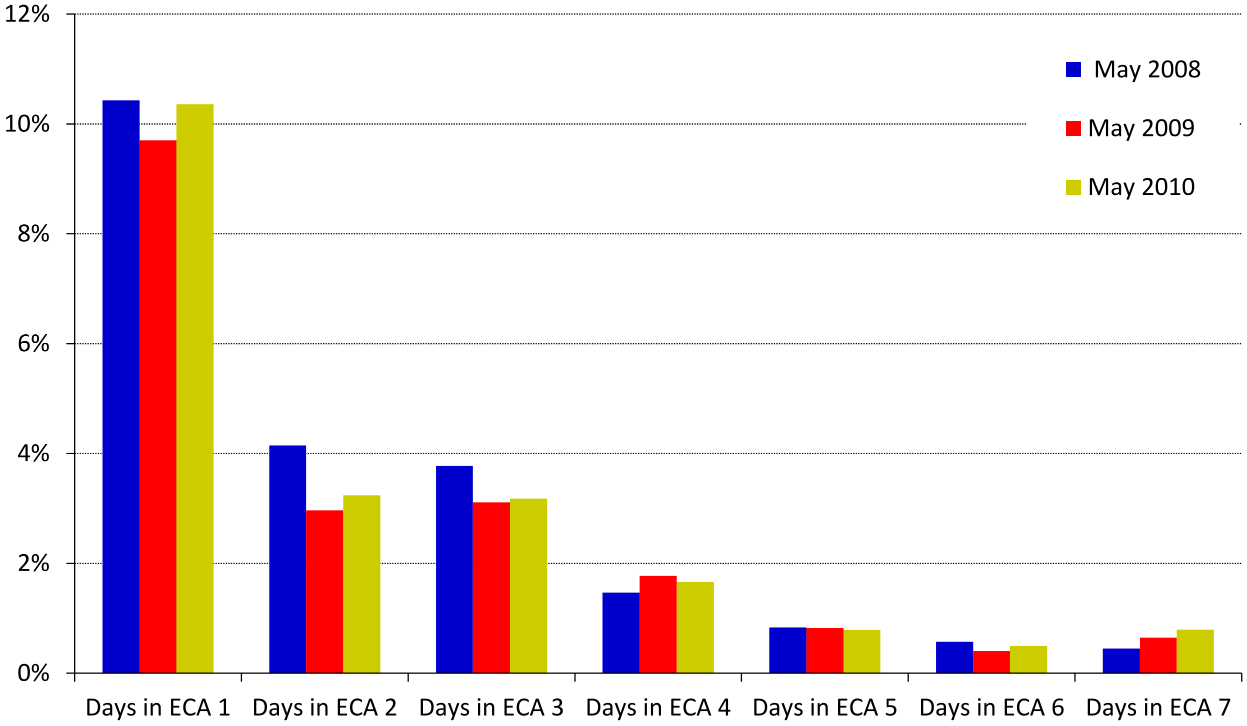

Figure 28. Time spent in ECA zone for Handy Tanker

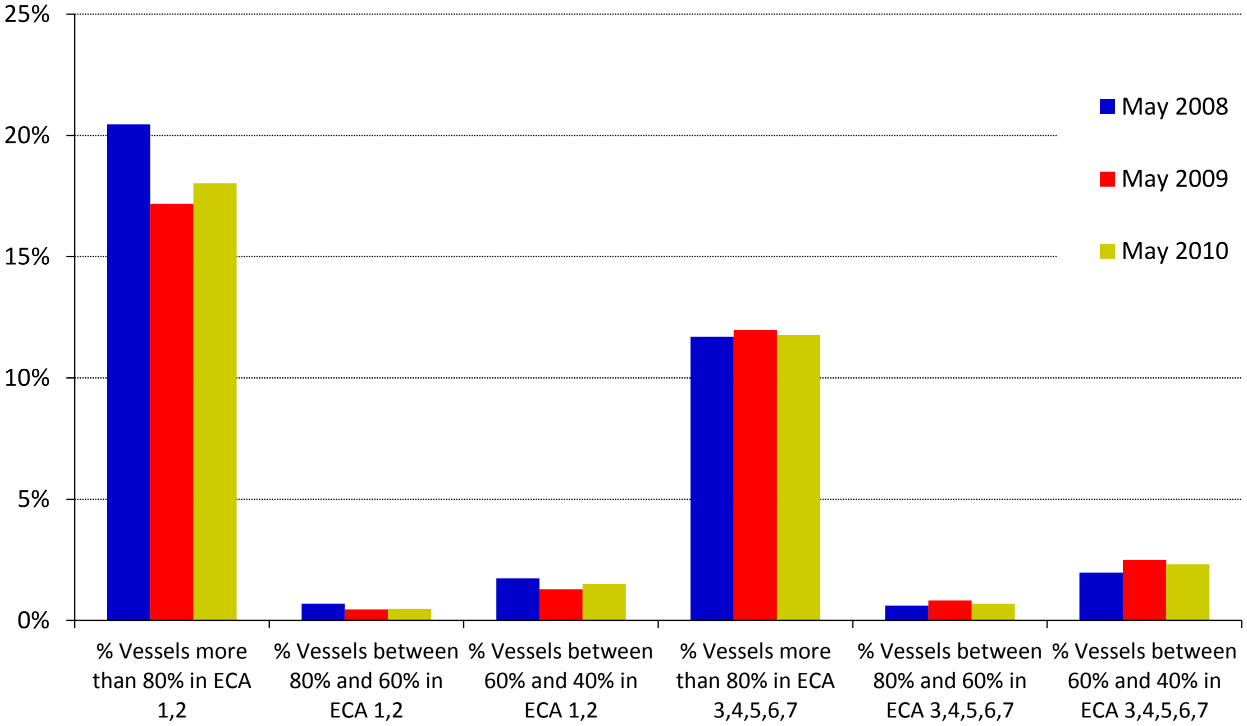

Figure 29. Time spent in ECA for Handy Tankers.

3.3 Conclusions

The world maritime traffic analysis is the starting point of the research. The obtained results show that the best ship type and sizes for the installation of an LNG propulsion system are handysize tanker, small and medium Ro-Ro, handysize bulk carrier and large Passenger ship, underlining the fact that there is a potential market for LNG fuelled-ships in particular in countries where policies for the reduction of CO_2 / gas emissions will be adopted. Among the highlighted ships, handysize tankers seem to be the best candidates since spent a high percentage of sailing time in ECA zone and have a great number of trips. Furthermore, the trend analysis does not show significant variation of time spent in ECA and number of trips through the three years considered.

For these reasons in the next chapter a technical and economic analysis will be developed in a specific handysize tanker.

4 LNG UTILIZATION ON HANDYSIZE TANKERS

As the traffic analysis points to the fact that 18.5% of handysize tankers spent more than 80% of their sailing time in ECA zones and recorded the highest number of trips among tanker ships, an analysis was conducted on this specific kind of vessel.

In the first part of this chapter a gas system analysis during a ship round trip has been developed in order to obtain the gas pressure variation in the LNG tank, the Boil Off Gas (BOG) production and the NG properties during the whole ship trip.

In the second part of this chapter an energy analysis on the considered ship has been developed. As already mentioned, LNG allows a reduction of gas emissions and, at the same time, the application of new energy conversion technologies on ships. Furthermore, thanks to clean exhaust gases, that do not require after-treatment systems, LNG simplifies the use of recovery technologies. Several heat recovery technologies are described in the following paragraph as well as the introduction of an Organic Rankine Cycle (ORC). The aim of the energy analysis is to evaluate the overall energy efficiency of ships, CO_2 emissions and LNG consumption.

The study was conducted on a chemical cargo carrier, sailing on the route from Dubai (Saudi Arabia) to Hamburg (Germany): Table 19 describes the main characteristics of the analysed tanker, shown in Figure 30, while Table 22 describes its operating profile. The ship is equipped with a dual fuel propulsion engine coupled with a Power Take In / Power Take Off (PTI/PTO) [50], two dual fuel gen-sets [50] and two gas boilers for cargo heating.

In order to demonstrate the environmental and economic benefits of the LNG propulsion it has been assumed to use only LNG as fuel also outside the ECA zone. The LNG tank has been sized considering a round trip plus an allowance for a safety trip. Obviously, a safety margin has been considered in case of rough sea. Since the LNG tank has a volume of 3500 m^3, it has been decided to use a B-type tank installed below deck, because it is suitable for large volumes and can easily fit in the structure of the examined ship thanks to its prismatic shape.

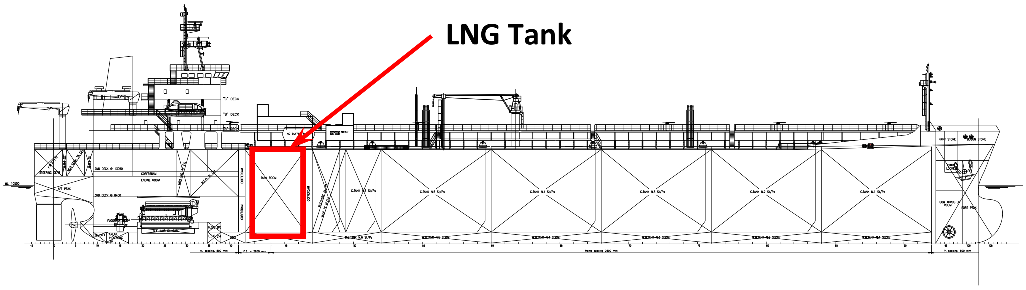

Figure 30. Position of the LNG tank in the examined ship.

Table 19. Main characteristics of the investigated vessel

Dead Weight Tonnage	33,000 DWT
Overall Length	176 m
Max Breadth	31 m
Main Deck Height	17 m
Design Draft	9 m
Main Engine	Dual fuel - 8,775 kW
Gen Set	Dual fuel - 2 x 1,014 kW
Boiler 1	1,500 kW
Boiler 2	12,000 kW
Fuel	Liquefied Natural Gas
LNG Tank	B-type, 3500 m^3

4.1 Analysis of the tank pressure and gas composition over time

4.1.1 LNG plant simulation model

In this paragraph, the behaviour of the gas mixture in the LNG tank of the ship has been simulated by means of commercial software, Aspen Plus Dynamics® 7.1.

The key thermodynamic property calculation performed in a simulation is phase equilibrium. The basic relationship for every component *i* in the vapour and liquid phases of a system at equilibrium is:

$$f_i^v = f_i^l \qquad (1)$$

Where:

f_i^v= Fugacity of component i in the vapor phase

f_i^l = Fugacity of component i in the liquid phase

Applied thermodynamics provides two methods for representing the fugacities from the phase equilibrium relationship in terms of measurable state variables, the equation-of-state method and the activity coefficient method.

In this analysis the activity coefficient method has been used and in particular the physical properties method adopted is Non Random Two Liquid (NRTL).

The NRTL model equation was described in detail for the first time by Renon and Prausnitz [57] who showed its application to a wide variety of mixtures for the calculation of the vapour-liquid and liquid-liquid equilibrium. The model is based on the molecular local composition concept which is expressed by the following equation:

$$x_{ji} = \frac{x_j \text{ exp } (-\alpha_{ji}\tau_{ji})}{\sum_{k=1}^{c} x_k \text{ exp } (-\alpha_{ki}\tau_{ki})} \qquad (2)$$

For the binary pair *ij*, x_{ji} is the local mole fraction of a central molecule *i* surrounded by molecules *j*, τ_{ij} and τ_{ji} are adjustable parameters, and α_{ji} (=α_{ij}) is third parameter that can be fixed or adjusted.

Table 20. Operating profile of the analysed ship.

	Distance [nm]	Speed [kn]	Time [h]	Fuel thermal power [kW]
Loading	0	0	24	10420
Waiting Dubai	0	0	2	1879
Manoeuvring Full Load	0	0	1	9476
Trip Full Load 15 kn	6321	15	421	24871
Trip Full Load 12 kn	346	12	29	19174
Waiting Suez Full Load	0	0	15	8914
Manoeuvring Suez Full Load	0	0	2	9476
Trip Full Load 9 kn	88	9	10	14594
Unloading	0	0	24	10420
Waiting Hamburg Port	0	0	12	1660
Manoeuvring Ballast	0	0	1	4649
Trip Ballast 15 kn	6321	15	421	15246
Trip B 12 kn	346	12	29	10321
Trip B 9 kn	88	9	10	6961
Waiting Suez Ballast	0	0	15	1879
Manoeuvring Suez Ballast	0	0	2	4649

Excess free energy for the liquid system is expressed wherein only binary molecular interactions are considered leading to the following expression for the excess free energy:

$$\frac{g^E}{RT} = \sum_{i=1}^{c} x_i \left[\sum_{j=1}^{c} x_{ji}\tau_{ji}\right] \qquad (3)$$

The expression for the activity coefficients is given by:

$$\ln \gamma_i = \frac{\sum_{j=1}^{c}(\tau_{ji} G_{ji} x_j)}{\sum_{j=1}^{c}(G_{ki} x_k)} + \sum_{j=1}^{c}\left[\frac{(x_j G_{ij})}{\sum_{k=1}^{c}(G_{kj} x_k)} + \left(\tau_{ij} - \frac{\sum_{k=1}^{c}(x_k \tau_{kj} G_{kj})}{\sum_{k=1}^{c}(G_{kj} x_k)}\right)\right] \qquad (4)$$

Where:

$$G_{ij} = \exp\left(-\alpha_{ji}\tau_{ji}\right) \qquad (5)$$

$$\tau_{ij} = \frac{(g_{ij} - g_{jj})}{RT} = \frac{A_{ij}}{T} \qquad (6)$$

$$\tau_{ji} = \frac{(g_{ji} - g_{ii})}{RT} = \frac{A_{ji}}{T} \qquad (7)$$

g_{ij}, g_{jj} and so on, are energies of interaction between molecule pairs. In the above equations $G_{ji} \neq G_{ij}$; $\tau_{ij} \neq \tau_{ji}$; $Gii = Gjj = 1$; $\tau_{ii} = \tau_{ji} = 0$; A_{ji} and A_{ij} are the interaction parameters between each pairs of molecule in Kelvin unit.

The parameter α_{ij} characterizes the tendency of species *j* and species *i* to be distributed in a non-random manner [58].

Then the fugacities can be calculated as

$$f_i^v = \varphi_i^v \, y_i \, p \qquad (8)$$

$$f_i^l = x_i \, \gamma_i \, f_i^{*,l} \qquad (9)$$

Where

$f_i^{*,l}$= Liquid fugacity of pure component *i* at mixture temperature

And the fugacity coefficient φ_i^v is calculated as:

$$\ln \varphi_i^v = -\frac{1}{RT}\int_{-\infty}^{V_v}\left[\left(\frac{\partial p}{\partial n_i}\right)_{T,V,n_{iej}} - \frac{RT}{V}\right] dV - \ln Z_m^v \qquad (10)$$

V= Total volume

n_i = Mole number of component *i*

p = pressure

Once calculated the physical properties, the software perform the mass and energy balances. For the numerical resolution with Aspen Plus Dynamics an Implicit Euler scheme with variable step size has been used as integrator, a Mixed Newton method as non-linear solver and MA 48 method as linear solver.

4.1.2 Cases studied

In order to identify the best solution in term of LNG plant design and layout to be adopted in the considered vessel the following case studies have been analysed:

1) Simulation of the pressure variation in the tank without gas extraction
2) Simulation of the BOG production maintaining a constant pressure in the tank
3) Simulation of the ship round trip

The examined B-type tank has a capacity of 3500 m^3 and a surface of 1570 m^2. The capacity has been calculated using the data of Table 20 and taking into account three trips: one round trip and a safety trip for the emergency. A 20% safety factor has been also introduced in order to consider also the rough sea condition. Regarding the tank insulation, it has been assumed to use polyurethane foam, with a thermal conductivity of 0.02 W/m K. Three different insulation thicknesses have been considered: 0.4, 0.2 and 0.13 m. The specific heat fluxes are 9.6, 19.1 and 28.6 W/m^2, while the thermal fluxes are 15, 30 and 45 kW respectively.

Furthermore three different gas compositions have been considered for the simulation; the composition of each gas mixture tested can be seen in Table 21.

Table 21. Gas compositions considered.

	Composition 1 [% molar]	**Composition 2** [% molar]	**Composition 3** [% molar]
Methane	89.90	95.00	88.00
Ethane	6.00	3.00	7.80
Propane	2.20	0.60	2.80
Butane	1.50	0.40	1.05
Nitrogen	0.40	1.00	0.35

4.1.2.1 Simulation of the pressure variation in the tank without gas extraction

In this case a failure of the LNG system or a ship stop has been simulated: there are no users for LNG and BOG and then it is important to know how much time is necessary before the tank pressure reaches the maximum pressure allowed and it is necessary to burn BOG into a Gas Combustion Unit (GCU). In this case, two extreme conditions have been simulated: the case of full tank, filled with 3200 m^3, and the case of almost empty tank, with only 350 m^3 of LNG.

Figure 31 and Figure 32 show the results of these simulations. It is possible to highlight that considering the full tank the pressure increase is very slow, due to the presence of a high amount of liquid and only a small volume of gas. The pressure is lower than the limit pressure for 250/380/760 hours, depending on the insulation. In case of empty tank the increase of pressure is faster and the limit pressure is overtaken in 40/60/115 hours respectively for the heat flux of 15/30/45 kW. It can be seen that the pressure variation is not linear with time and heat flux.

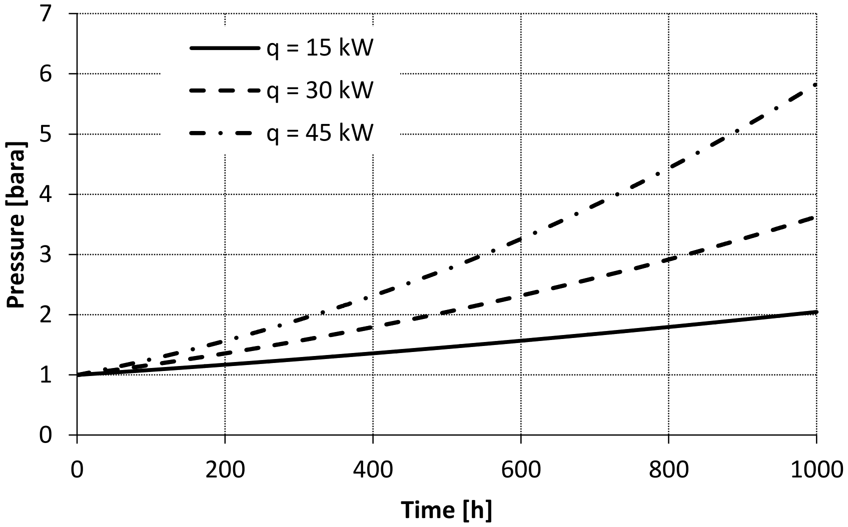

Figure 31. Pressure increase in case of full tank.

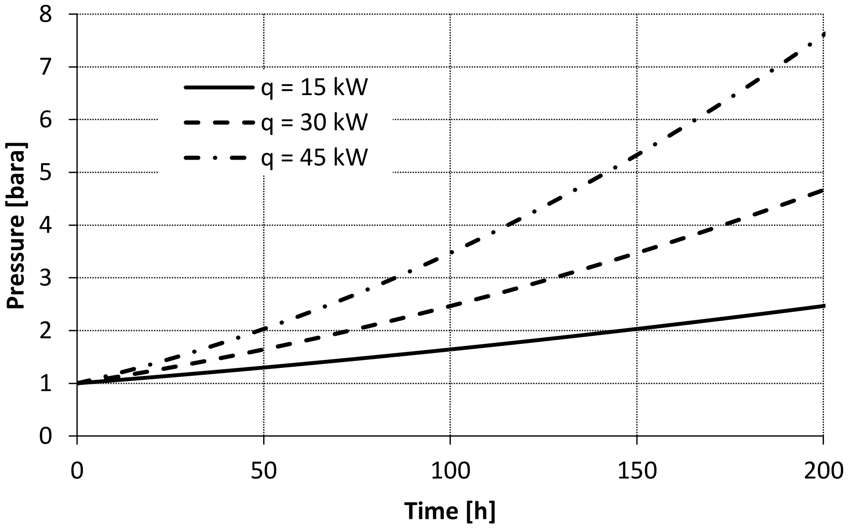

Figure 32. Pressure increase in case of empty tank.

4.1.2.2 Simulation of the BOG production maintaining a constant pressure in the tank

In this case a tank where only the BOG is extracted in order to maintain the tank at the atmospheric pressure has been simulated. In fact it is crucial to know the BOG flow rate in order to design the LNG system. In this case also the two opposite conditions have been simulated: the tank filled with 3200 m^3 and the case of almost empty tank, with only 350 m^3 of LNG.

Figure 33 and Figure 34 show the BOG production in case of full and empty tank respectively: it is possible to note that the BOG production is not constant but shows a little increase during the trip. For the heat flux of 45 kW the BOG flow decrease in the last part of the graph due to the low amount of liquid in the tank that contains an high percentage of high boiling point gases like propane and butane.

Figure 35 and Figure 36 show respectively BOG LHV and power variation with time: during the trip the lower heating value (LHV) of the BOG shows an increase of about 10%, and also the power of the BOG flow increases due to the increase of the flow rate and LHV. At the beginning these variations are faster in case of high thermal flux then both the BOG LHV and power became almost constant.

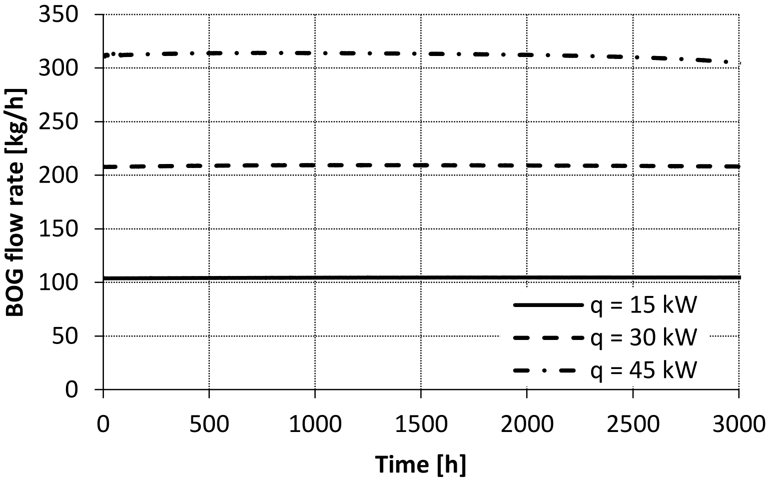

Figure 33. BOG production in case of full tank.

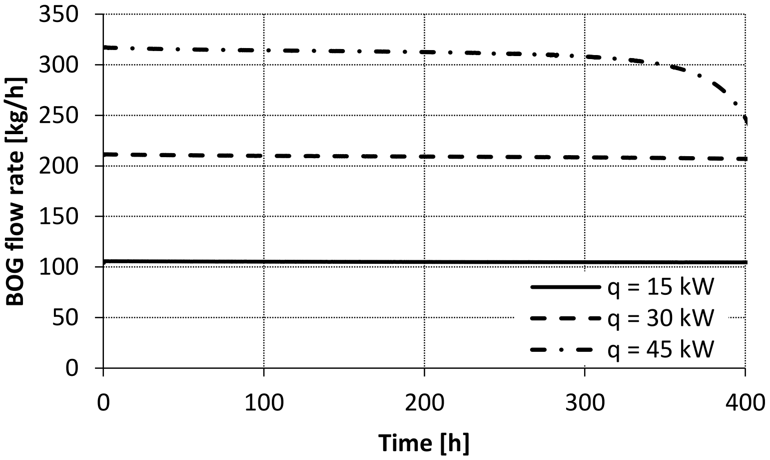

Figure 34. BOG production in case of empty tank.

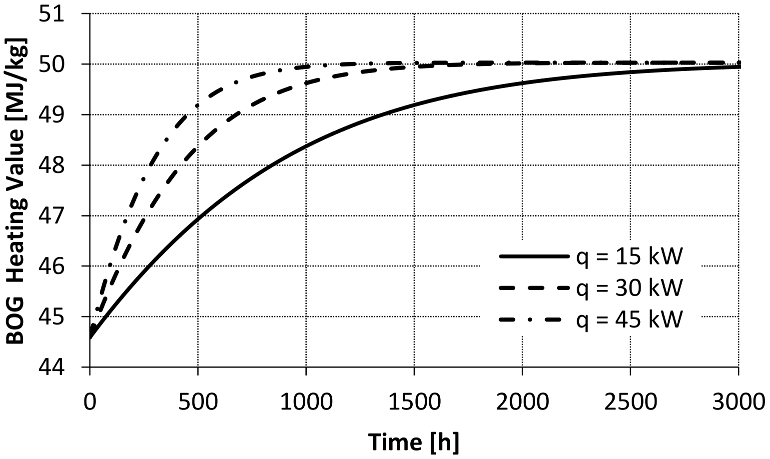

Figure 35. BOG lower heating value in case of full tank.

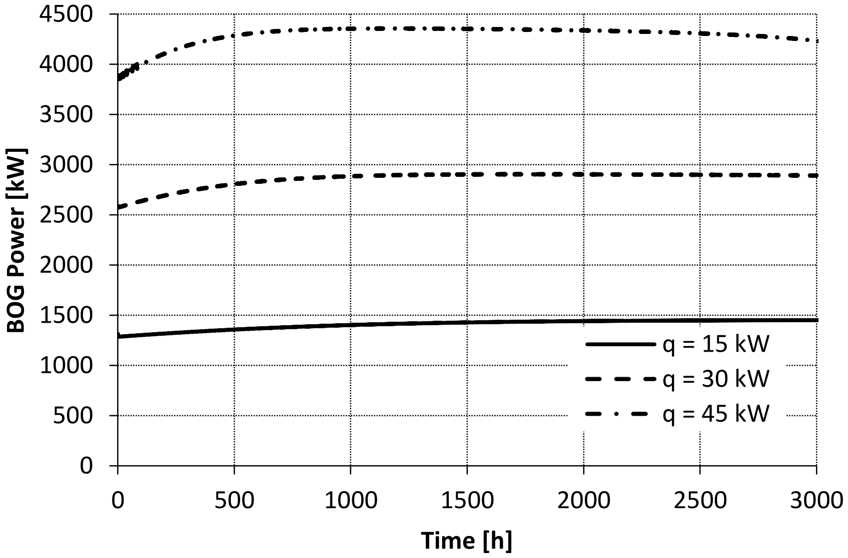

Figure 36. BOG power in case of full tank.

4.1.2.3 *Simulation of the ship round trip*

In this case a round trip from Hamburg to Dubai of the considered vessel has been simulated. The fuel power profile during the trip is shown in Table 20. During the trip the fuel thermal power is extracted both from the BOG and the liquid gas (Figure 37). The control strategy is aimed to maintain 1 bara in the fuel tank. To maintain the pre-set pressure a gas compressor could be used. Otherwise, an innovative solution could be the use of a fuel cell auxiliary generator: in fact, this kind of generator requires a very low gas feeding pressure, 0.025 barg, and then is a feasible solution to replace at the same time the compressor and the auxiliary generator [48].

The round trip has been simulated for the three gas compositions and for a tank insulation with a thermal flux of 15 kW. Only for the first gas composition the three different insulations of the LNG tank have been tested. These simulations are useful to design all the components of the gas system and avoid engine knocking problem.

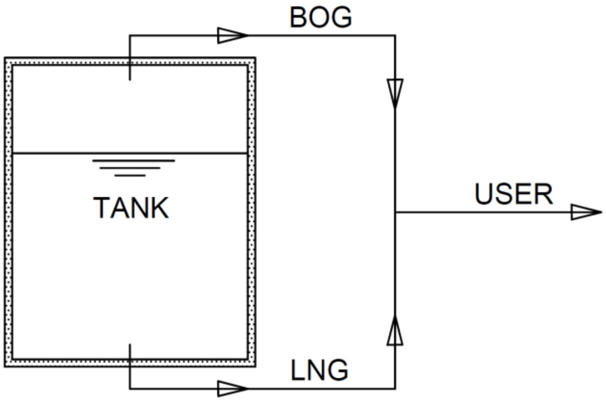

Figure 37. Scheme of the streams of the LNG system.

Figure 38, Figure 39 and Figure 40 show the LHV variation of the three different gas flows analysed in case of different gas composition: it can be noted that the LHV of all the streams increases due to the evaporation of nitrogen which happens mainly at the begging of the trip. This behaviour is particularly marked for the BOG stream. In particular, for the composition 2, that has the higher nitrogen percentage, LHV increase for the BOG is more than 20%. The short periods of lower value shown in Figure 40 are caused by the use of BOG only during low power requirement phases.

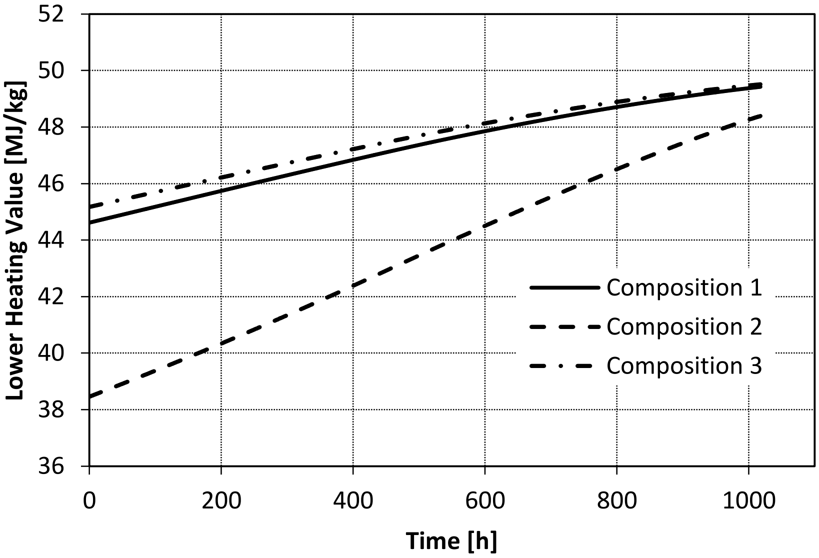

Figure 38. BOG lower heating value for different gas composition.

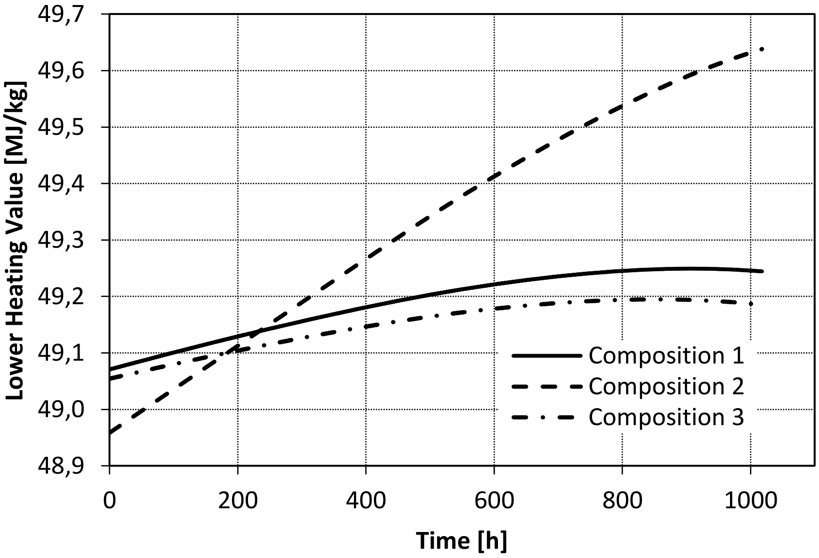

Figure 39. LNG lower heating value for different gas composition.

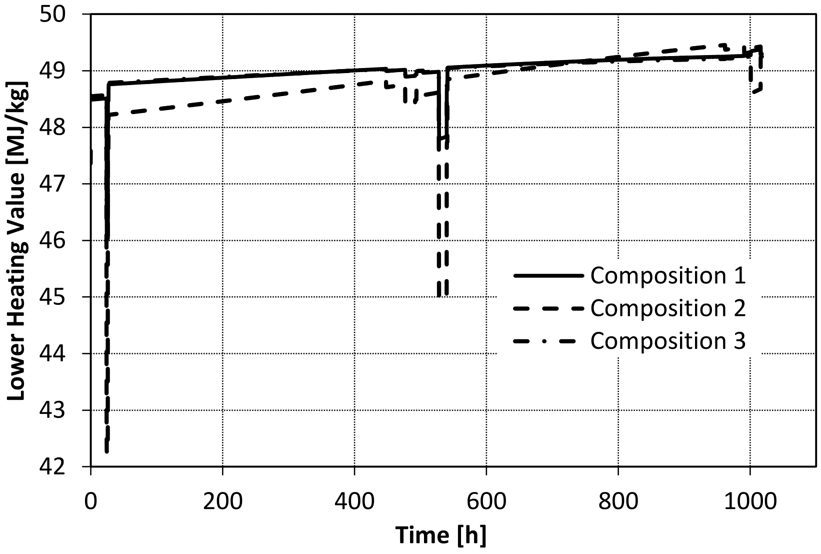

Figure 40. "User" gas lower heating value for different gas composition.

The Methane Number (MN) of the three flows for the considered gas mixture is shown in Figure 41, Figure 42 and Figure 43. It is possible to highlight that the MN of the BOG stream increases during the trip due to the evaporation of the nitrogen, in particular for the composition 2, while the MN of the LNG decreases during the trip due to the decrease of methane percentage in the liquid mixture. Regarding the combination of BOG and LNG flows (Figure 43), gas composition 2 shown the higher MN, more than 85 for almost all the trip, with short periods of higher value when only BOG is utilized. It also shows a growing trend. The other analysed compositions show a lower MN, about 75 with short periods of higher value when BOG is used, and a decreasing trend.

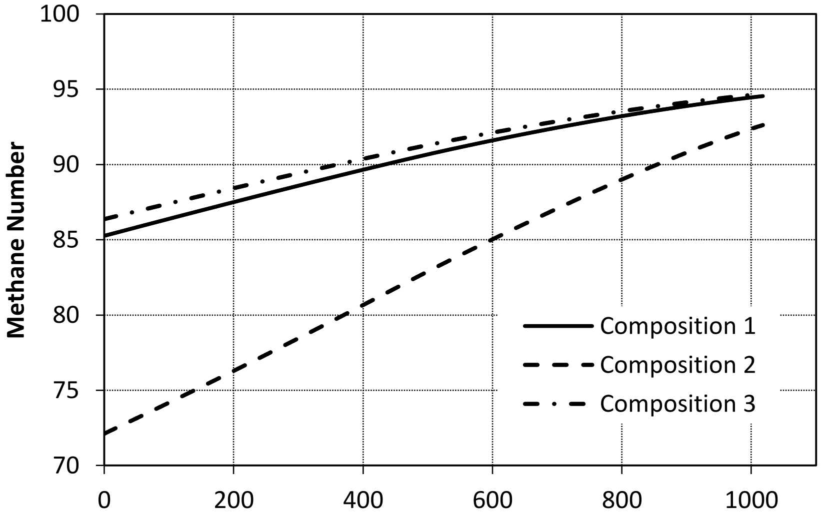

Figure 41. BOG Methane Number for different gas composition.

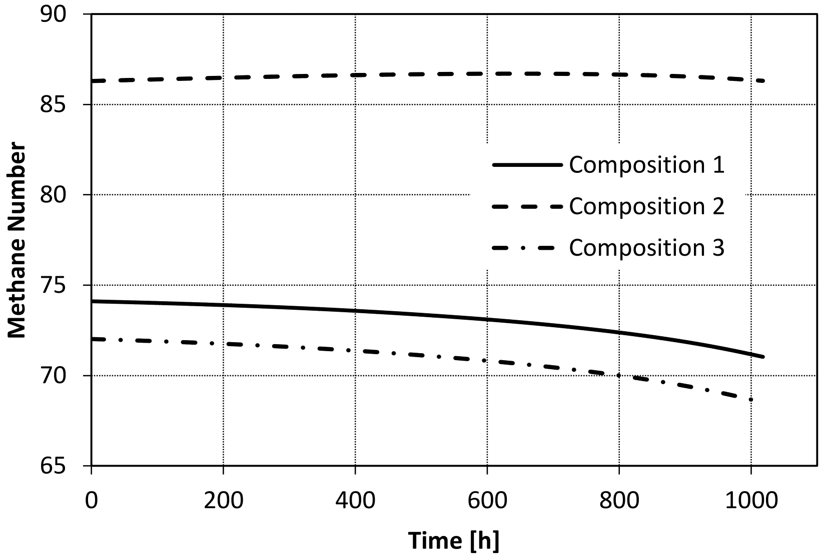

Figure 42. LNG Methane Number for different gas composition.

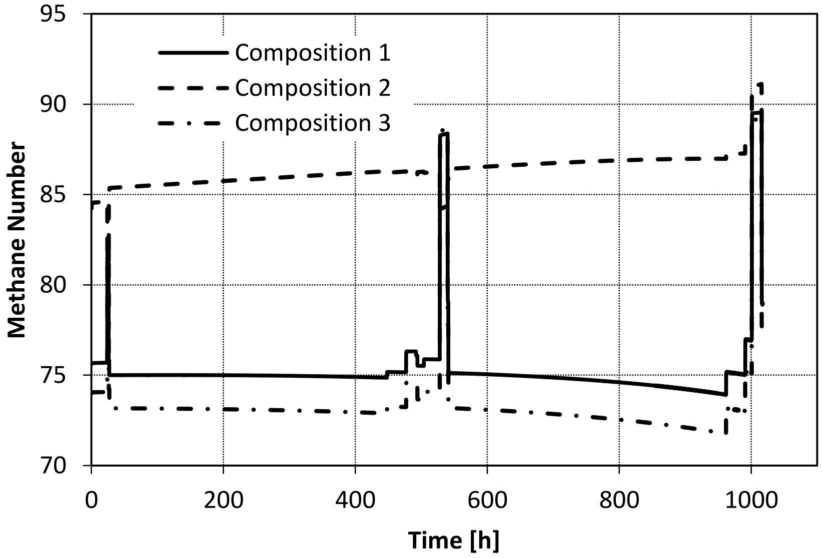

Figure 43. User Methane Number for different gas composition.

Figure 44 shows the gas mass flow rate during the trip for the different gas compositions: there are only little variations due to the variation of the LHV during the trip.

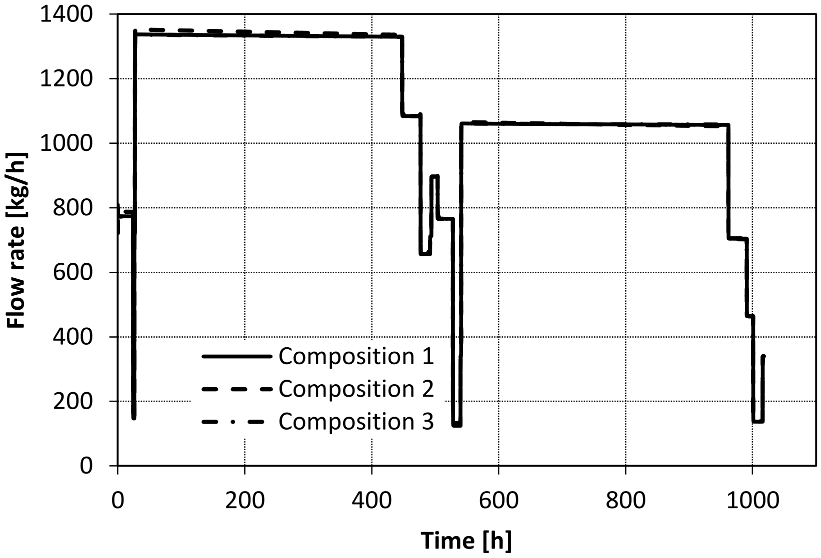

Figure 44. Gas flow for different gas composition.

Figure 45, Figure 46 and Figure 47 show the three streams LHV variation with time considering gas composition 1 and different tank insulation:

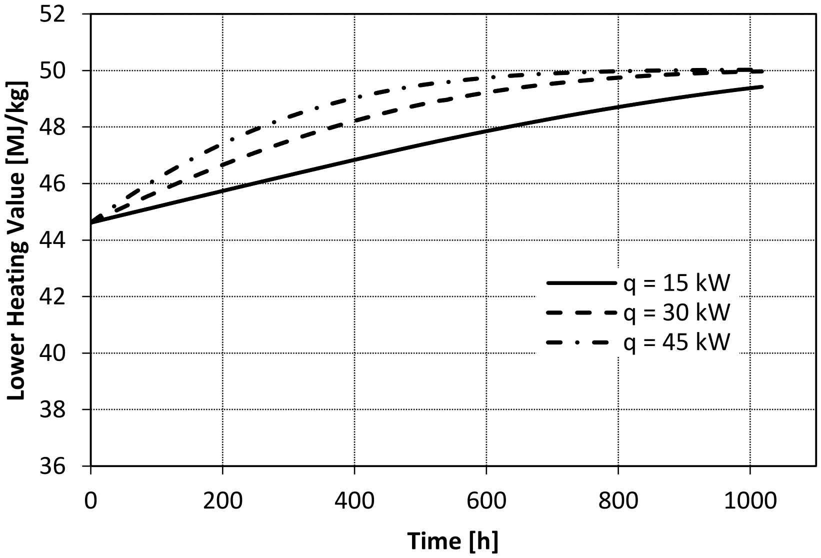

Figure 45. BOG lower heating value for different tank insulations.

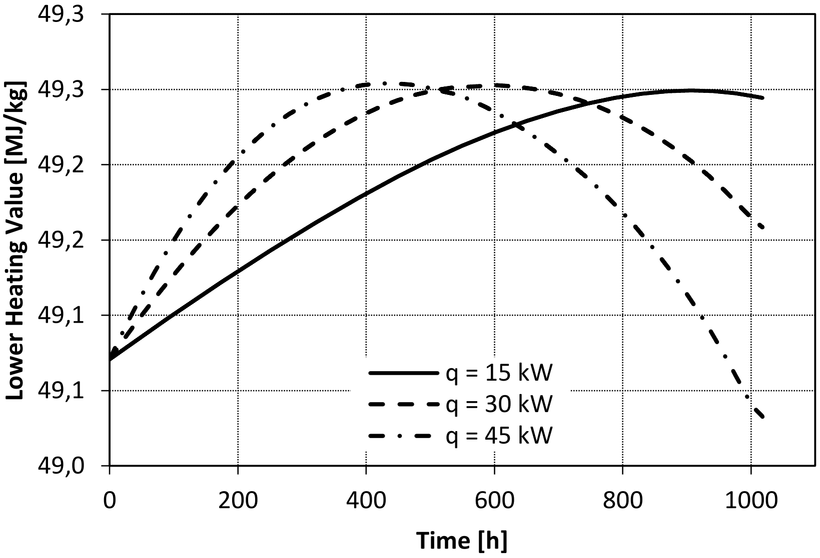

Figure 46. LNG lower heating value for different tank insulations.

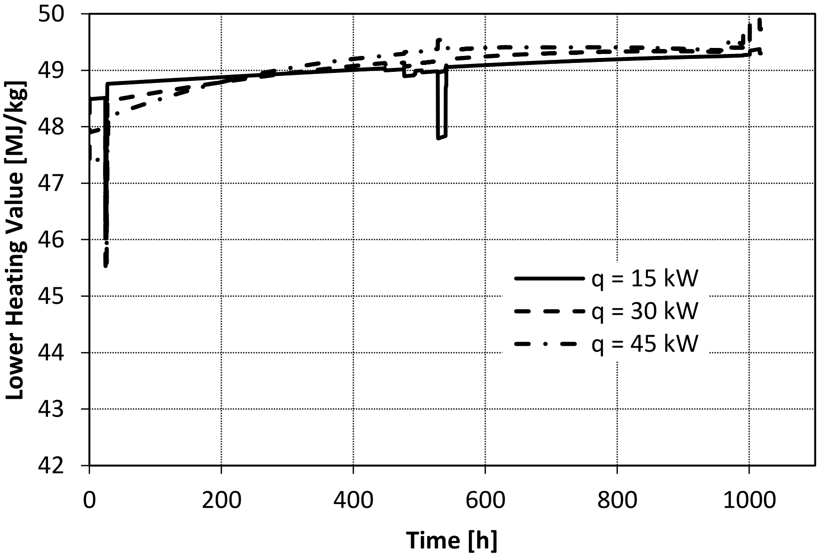

Figure 47. "User" stream lower heating value for different tank insulations.

BOG flow LHV follows the behaviour described in 4.1.2.2 , whereas LNG LHV shows a little variation with a parabolic trend. This can be explained as, in the first phase, the nitrogen evaporates and the value increases while in the second phase the value decreases due to the decrease of methane percentage in the liquid. The mixture of the BOG and LNG shows a slight increase during the trip with short period variation when only BOG is used. Figure 48, Figure 49 and Figure 50 show the MN of the three streams: the MN of the BOG flow shows an increasing trend, from 85 at the beginning to 95 at the end of the trip, and it increase faster as the thermal flux is higher. The LNG MN, on the contrary, has a decreasing trend especially for higher thermal losses: in fact the MN in case of a heat flux of 15 kW varies from 74 to 71 while in the case of 45 kW thermal flux, it decreases from 74 to 62 due to the higher evaporation ratio of methane.

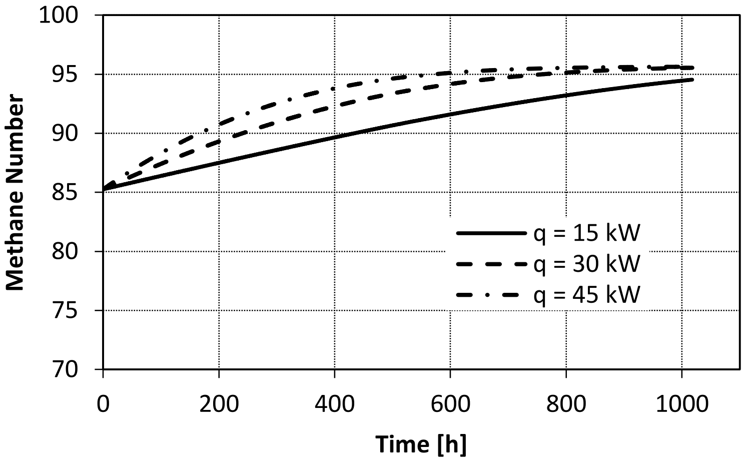

Figure 48 BOG Methane Number for different tank insulations.

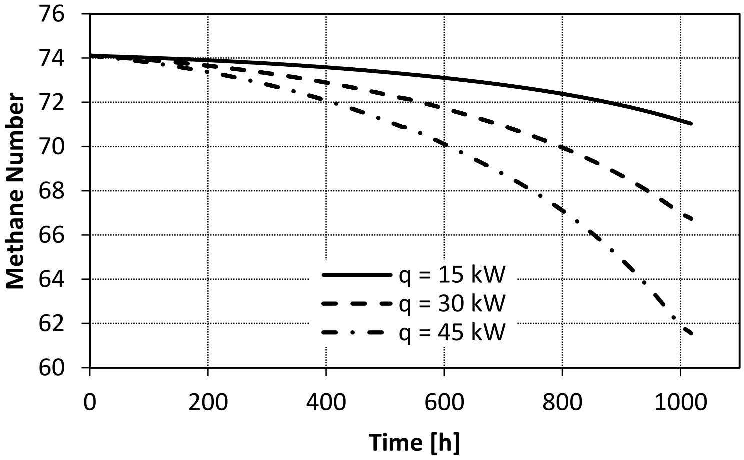

Figure 49. LNG Methane Number for different tank insulations.

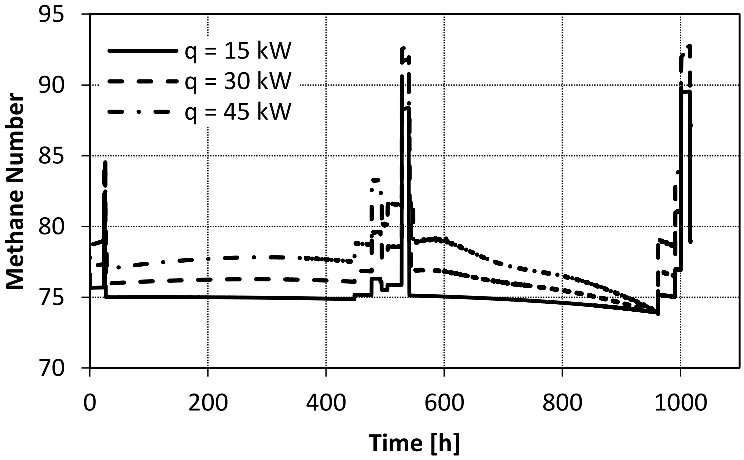

Figure 50. "User" stream Methane Number for different tank insulations.

Analysing the graph of the MN of the user stream that feed the engines, it is possible to see that there is a difference of about two points between the different insulations. This is due to the mixing of the BOG and LNG flow which have different characteristics.

Figure 51 shows the pressure in the tank during the trip: it is possible to highlight that only in case of the lower thermal flux the pressure is always atmospheric while in the other cases the pressure increase up to 1.1 bara due to unutilized BOG.

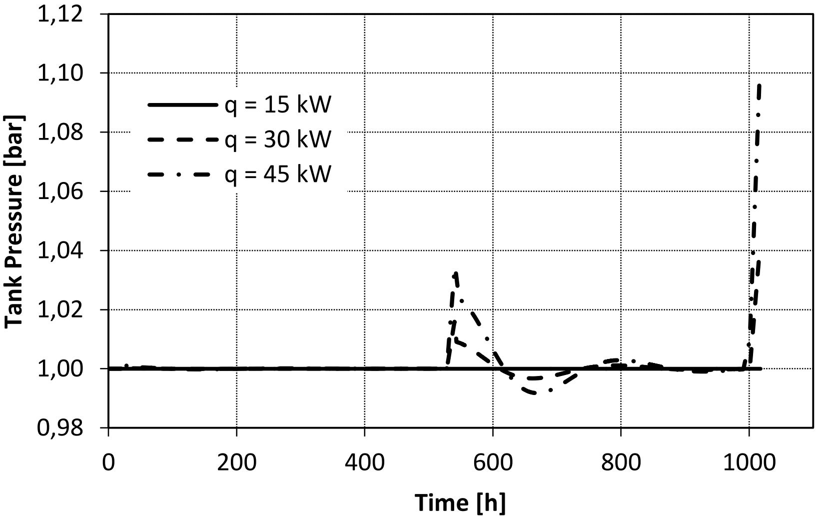

Figure 51. Tank pressure during the trip for different insulations.

4.1.3 Conclusions

In this paragraph an analysis on the considered vessel during its trip has been carried out in order to obtain tank pressure variation, BOG production, gas composition and its characteristics, such as heating value and Methane Number. Different cases have been considered: the first case, that simulates a condition where the gas fuel system is not used, shows that the tank pressure increase is faster as the quantity of LNG in the tank is small. Furthermore, the pressure variation is not linear with time and heat flux. These results are very important because they allow to know how much time is available before reaching the maximum allowable pressure and then provide useful information in order to withstand safety rules.

The second case, that considers an extraction of boil off gas in order to maintain a constant pressure in the tank, allows to determine the BOG flow rate, that is a crucial parameter for the design of the overall gas system and in particular of the GCU. The results show that the flow rate is not constant, but increases as the liquid in the tank decreases. Furthermore, during the design phase, the variation of the power content of the BOG stream has to be taken into account as, for the considered conditions, it increases to about 10% due to the LHV increase. In the third case a round trip of the ship has been simulated considering three different gas compositions and three different tank insulations. Results show different behaviours of the analysed gas mixtures. Nitrogen content at the beginning of trip influences the BOG proprieties, in particular Methane Number, while in the liquid mixture it is important to have a percentage of methane as high as possible in order to have a gas with a high MN. If BOG and LNG are mixed, the gas feed to users has more homogeneous proprieties since the MN and LHV of the BOG increase during the trip while in the LNG they decrease. The results of the simulation with different tank insulations show that there is a change in gas properties despite initial gas composition is the same. The mixing of the two streams balances the properties in this case also. Furthermore, different insulation thickness influences the pressure in the tank during the trip which is a fundamental parameter when an atmospheric tank is considered. The results of this study highlight that, for the design of the overall gas system, the right choice of the tank insulation is fundamental: this parameter, in fact, influences BOG production, and then the pressure in the tank, and the gas properties during the trip. The correct choice of the insulation therefore requires an iterative design, taking into account the consumption during the trip and the ship operating profile, in order to “fit” the energy requirements of the ship: using all the vapour fraction produced it is possible to maintain the pressure into the pre-set limits. Together with the right tank insulation a control strategy for the different flows has to be developed: in fact, a variable tank pressure control strategy could reduce the difference of gas quality during the trip mixing the right percentage of BOG and LNG maintaining the pressure into the limits. This will allow to avoid issues caused by low Methane Number and heating value and to maintain the correct pressure in the tank.

4.2 Energy analysis

After the analysis on the gas system, an energy analysis on the ship has been developed in order to improve the ship efficiency: Table 22 describes its operating profile highlighting the energy requirements.

Table 22. Operational profile of the analysed ship.

Navigation condition	Covered distance [n mile]	Time [h]	Total energy requirement [MWh]
Loading	0	24	167.1
Waiting Dubai	0	2	1.9
Manoeuvring Full Load	0	1	8.4
Trip Full Load 15 kn	6,321	421	6,316.0
Trip Full Load 12 kn	346	29	344.6
Waiting Suez Full Load	0	15	107.1
Manoeuvring Suez Full Load	0	2	16.9
Trip Full Load 9 kn	88	10	94.7
Unloading	0	24	167.1
Waiting Hamburg Port	0	12	9.6
Manoeuvring Ballast	0	1	4.1
Trip Ballast 15 kn	6,321	421	3,122.2
Trip Ballast 12 kn	346	29	139.2
Trip Ballast 9 kn	88	10	31.3
Waiting Suez Ballast	0	15	14.0
Manoeuvring Suez Ballast	0	2	4.5
Total for round trip	**13,510**	**1,018**	**10,602.7**
Yearly total (8 trips)	**108,080**	**8,144**	**84,821.2**

During cargo trips, from Dubai to Hamburg, products are supposed to be maintained warm at 65°C, while during ballast trips only the fuel tank (a small amount of diesel fuel that is necessary for engine pilot injection) has to be kept warm. The analysis encompasses a possible absence of the recuperative boiler. In this case, LNG- fuelled boilers provide cargo and fuel tank heating entirely. Their efficiency is assumed to be equal to 88%. Table 23 shows ship propulsive power, auxiliary power and cargo heating power requirements: this study does not take into account pilot fuel consumption because it represents about 1% of LNG consumption. The thermal power needed during navigation depends on speed, as the amount of LNG in the evaporator changes.

Data of Table 23 were used to calculate ship system efficiency, CO_2 emissions and LNG consumption.

Table 23. Vessel power requirements during the analysed navigation conditions.

Phase	Mechanical Power [kW]	Electrical Power [kW]	Thermal Power [kW]
Navigation - Full Load 15 kn	7,363	752	6,949
Navigation - Full Load 12 kn	4,400	752	6,844
Navigation - Full Load 9 kn	2,200	752	6,759
Navigation - Ballast Trip 15 kn	6,000	752	694
Navigation - Ballast Trip 12 kn	3,500	752	603
Navigation - Ballast Trip 9 kn	1,930	752	541
Manoeuvring Full Load	2,018	1,782	4,645
Manoeuvring Ballast	1,930	1,782	386
Waiting Full Load	0	489	6,654
Waiting Ballast	0	489	447
Harbour Cargo Handling	0	2,123	4,838
Harbour	0	470	331

The system's efficiency was calculated using the following formula:

$$\eta = \frac{\sum_{i=1}^{np} P_i \cdot t_i}{FC \cdot LHV} \qquad (11)$$

P is the ship power requirement, *t* is the navigation time, *FC* is the fuel consumption, *LHV* is the lower heating value of fuel, assumed to be 48 MJ/kg, and *np* is the number of investigated navigation conditions that are indicated by the subscript *i*.

CO_2 emissions were calculated as follows: $CO_2 = FC \cdot C_F$; C_F is an *emission factor* described by the following relation: C_F = (kg CO_2) / (kg fuel). For natural gas, it was assumed that C_F = 2.75 according to IMO papers [51]. Propulsion engine, generator and boiler efficiency values were obtained from the manufacturer's data sheets [50,52]. The main engine and gen-set specific fuel consumption variations with loads were taken into account.

Figure 52 shows the main engine cooling circuit layout: engine cooling system encompasses both a High Temperature (HT) and a Low Temperature (LT) circuit. HT cooling circuit water goes through cylinder jackets, cylinder heads and the first stage of air-cooler; water in the LT circuit cools the second stage of the air-cooler and the lubricant oil. Different heat recovery solutions were evaluated:

- Case 1: no heat recovery;
- Case 2: heat recovery by a recovery boiler;
- Case 3: integration of an Organic Rankine Cycle;
- Case 4: integration of an Organic Rankine Cycle and heat recovery from ORC condenser.

Heat recovered from the main engine's LT cooling circuit is always used for LNG evaporation purposes.

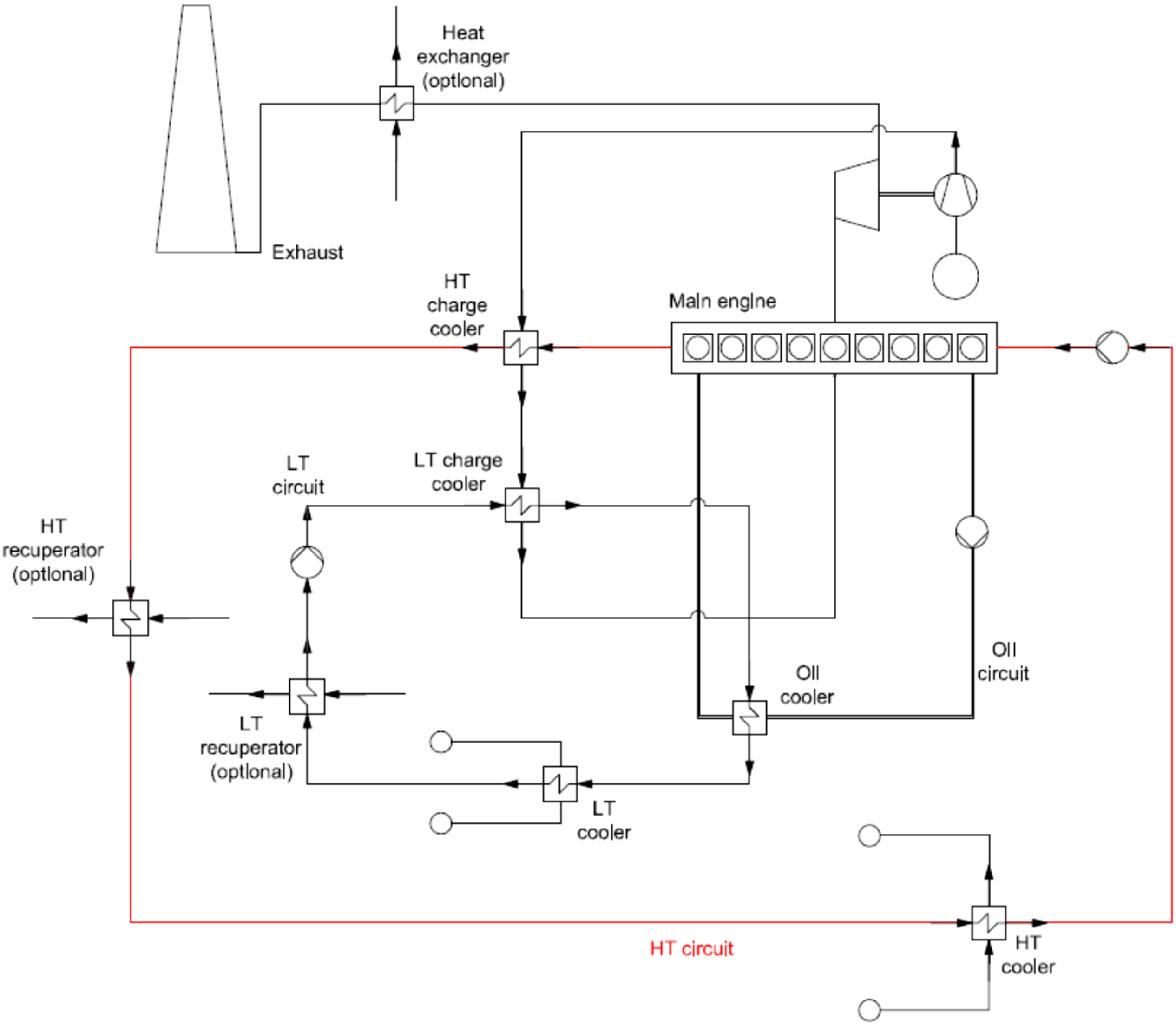

Figure 52. Simplified layout of the cooling and exhaust circuit of the propulsion engine. High Temperature (HT), Low Temperature (LT) circuits and optional exchanger for heat recovery and ORC plant.

A software tool has been developed to evaluate efficiency, CO_2 emissions and LNG consumption for all the above-mentioned cases. The heat recoveries from the engine has been calculated on the bases of the load, developing a series of fitting curves for the exhaust gas flow, temperature and cooling circuits heat fluxes based on the manufacturers experimental data. As for the ORC simulations, the manufacturer simulation software has been used.

Case 1: no heat recovery

This analysis took into account only heat recovered from the main engine's LT cooling system, which is used for LNG evaporation purposes. This applies also to tankers that do not need to heat the cargo. In Figure 53 can be seen the layout of the system: the heat recovered is used to heat the water/glycol circuit of the LNG evaporator.

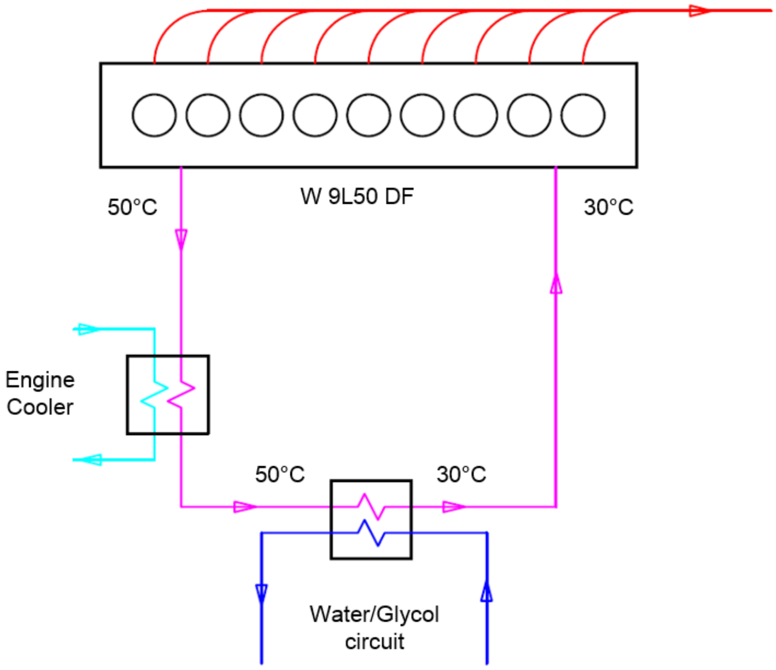

Figure 53. Heat recovery from the Low Temperature (LT) cooling system.

Case 2: heat recovery by a recovery boiler

This solution is widely used in Tankers. In this case, a commercial heat recovery boiler was taken into account and the exhaust gas temperature at the funnel was assumed to be equal to 120°C. Furthermore, the possibility of recovering heat from the HT main engine cooling system was assumed. The total amount of recovered heat is used for cargo heating purposes.

A simplified layout of the proposed solution can be seen in Figure 54. The values of flow rates, temperatures and thermal powers are referred to the full load navigation at 15 knots.

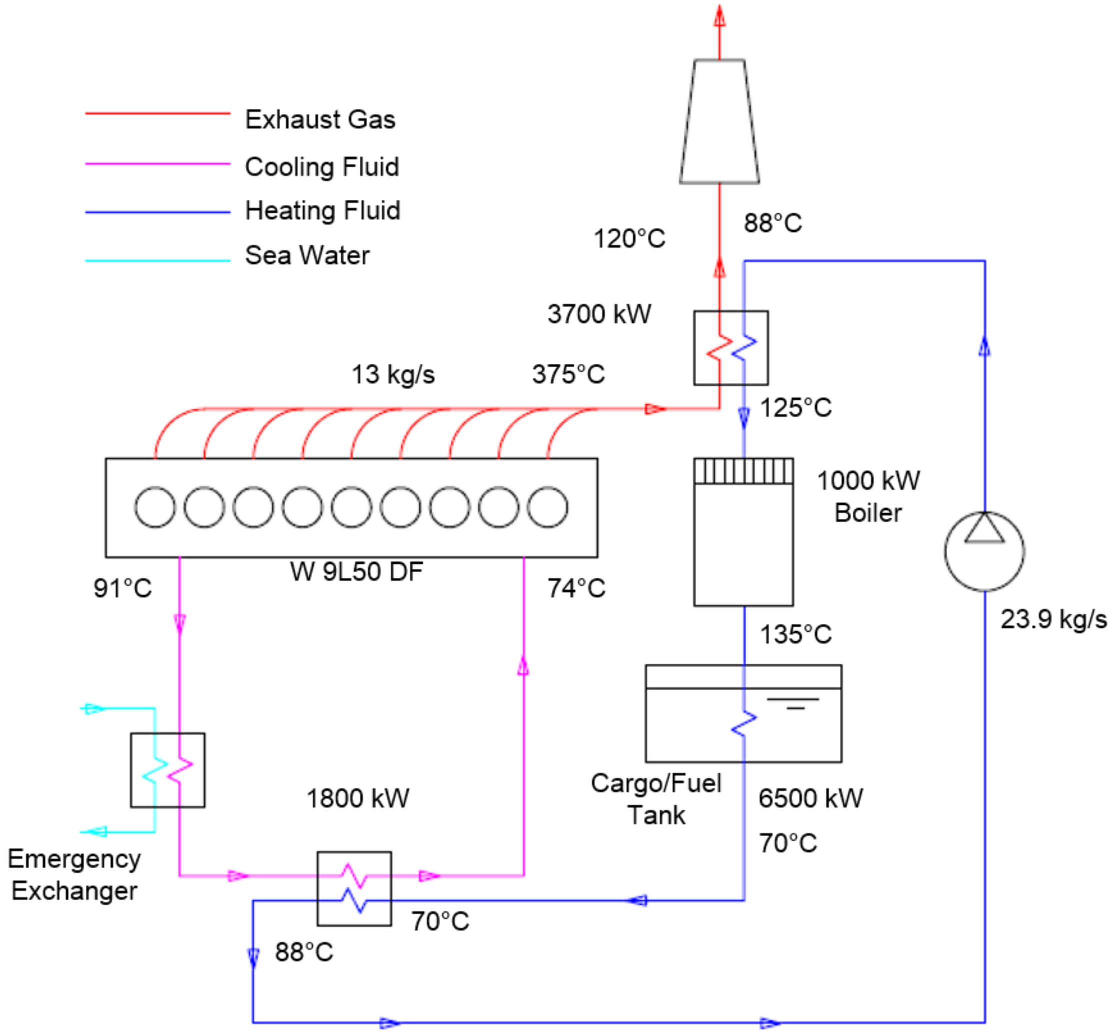

Figure 54. Simplified layout of the system configuration with heat recovery.

Case 3: integration of an Organic Rankine Cycle (ORC)

An Organic Rankine Cycle is similar to a steam Rankine cycle with the exception of the working fluid, being an organic mixture. By comparison with water, an organic mixture fluid has some favourable characteristics such as larger molecular mass, lower critical temperature, lower critical pressure, lower condensation entropy and lower solidification temperature [53]. These characteristics allow heat recovery from low temperature sources. The thermal power of engine exhaust gases can be usefully utilized in an ORC system which produces electrical energy and reduces gen-sets and main engine load through the Power Take In. A commercial ORC plant was analysed for this work. The ORC plant Turboden 7 [54] was selected as the available exhaust heat power was known. This ORC plant has a maximum power of 700 kWe. The exhaust gas temperature at the funnel was estimated to be equal to 120°C. Furthermore, heat recovery from the HT main engine cooling system was assumed.

In Figure 55 can be seen a simplified layout and the values of flow rates, temperatures and thermal/electric powers are referred to the full load navigation at 15 knots.

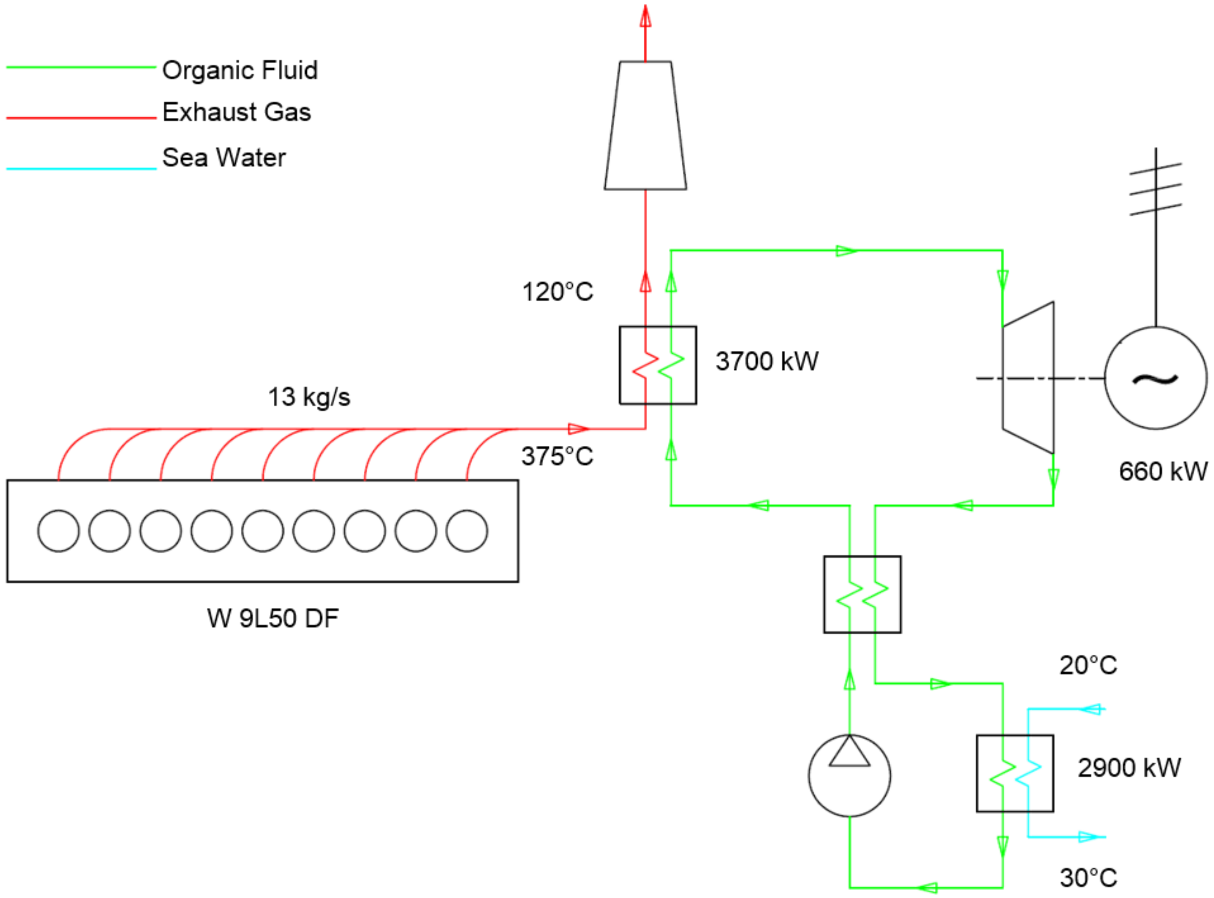

Figure 55. Simplified layout of the system configuration with ORC.

Case 4: integration of an ORC and heat recovery from ORC condenser

With respect to the previous case, heat was also recovered from the ORC condenser. For this reason ORC condenser pressure was assumed to be higher than in Case 3. As a consequence, condenser temperature increases up to 100°C. This leads to cargo heating by means of hot water (90°C). Nevertheless, a lower recovered electrical power has to be taken into account. Moreover, it is possible to suppose that, during the ballast trip, the ORC condenser pressure can be reduced to recover the maximum amount of electrical energy, as there is no need for cargo heating. The minimum exhaust gas temperature at the funnel was set at 120°C. Heat from main engine's HT cooling system was also used for cargo heating. This is a feasible solution for a tanker ship but is difficult to apply due to the required volume and the complex piping system.

In Figure 56 can be seen a simplified layout and the values of flow rates, temperatures and thermal/electric powers are referred to the full load navigation at 15 knots.

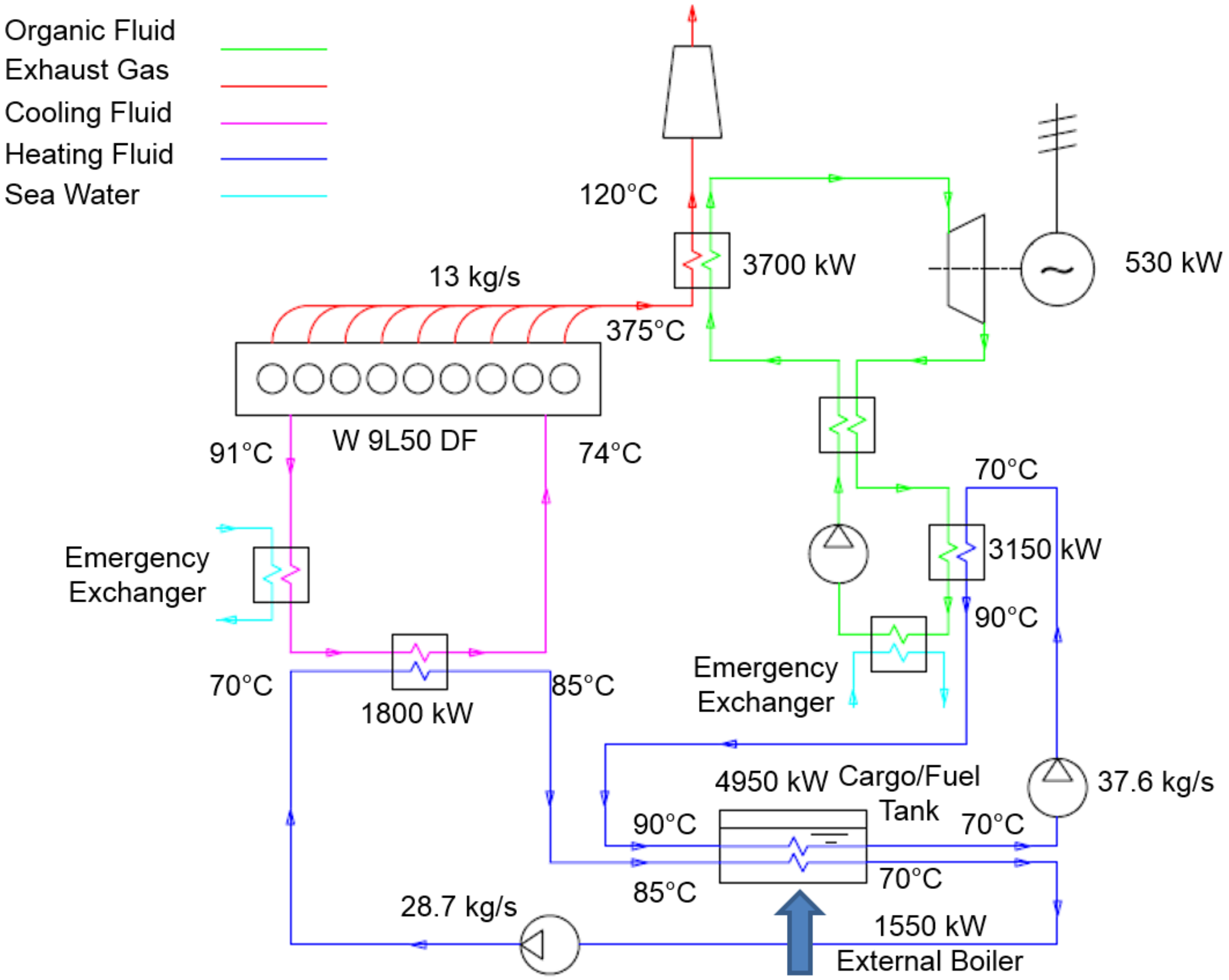

Figure 56. Simplified layout of the system configuration with ORC and heat recovery.

4.2.1 Efficiency improvements and environmental benefits

Table 24 presents recovered power and heat as a function of the adopted heat recovering solution and considered navigation conditions.

As expected, recovered heat and electric power decrease as engine load decreases. Figure 57 shows the effects of the adopted solution in terms of: a) energy efficiency, b) carbon dioxide emissions and c) LNG consumption for each examined power plant solution. It should be noted that the total efficiency includes the energy both for propulsion and for cargo heating purposes. Mechanical efficiency was defined as the ratio of mechanical and electrical power over fuel power content.

When recovery is not taken into account (Case 1) the round trip efficiency is equal to 56.7%, and mechanical efficiency to 47%, CO_2 emissions amount to 30,846 ton/yy while LNG consumption amounts to 11,217 ton/yy. In Case 2, the mechanical efficiency reaches the same value as in Case 1, whereas total efficiency increases to 68.6%. In Case 3, the use of an ORC plant is foreseen, the mechanical efficiency increases to 51.4%, but the total efficiency is lower as most of the thermal power flows out from the ORC condenser and is not recovered for cargo heating.

Table 24. Recovered heat and power as a function of adopted heat recovering solution and considered navigation conditions.

Navigation condition	Exhaust gas temp. [°C]	Exhaust gas flow [kg/s]	Boiler HR [kW]	ORC el. power [kW]	ORC+HR el. power [kW]	ORC+HR th. power [kW]	HT th. power [kW]	LT th. power [kW]
Full L. 15 kn	375	13.2	3,698	675	533	3,143	1,805	1,094
Ballast 15 kn	383	10.9	3,144	574	574	-	1,402	811
Full L. 12 kn	400	8.3	2,545	464	367	2,164	997	536
Ballast 12 kn	412	6.6	2,132	389	389	-	800	409
Full L. 9 kn	434	3.7	1,282	234	185	1,090	557	260
Ballast 9 kn	439	3.0	1,051	192	192	-	512	234

In Case 4, the highest total efficiency (72.2%) is recorded when the ORC condenser pressure is increased to allow heat recovery at a higher temperature level which is able to match the cargo heating requirements, while the mechanical efficiency (50.6%) is similar to Case 3. This value corresponds to an increase of about 5% compared to the typical Tanker ship reproduced in Case 2. As mentioned above, it was assumed that the cargo has to be maintained warm for the whole of the sailing time. Otherwise, fuel saving amounts to about 9%.

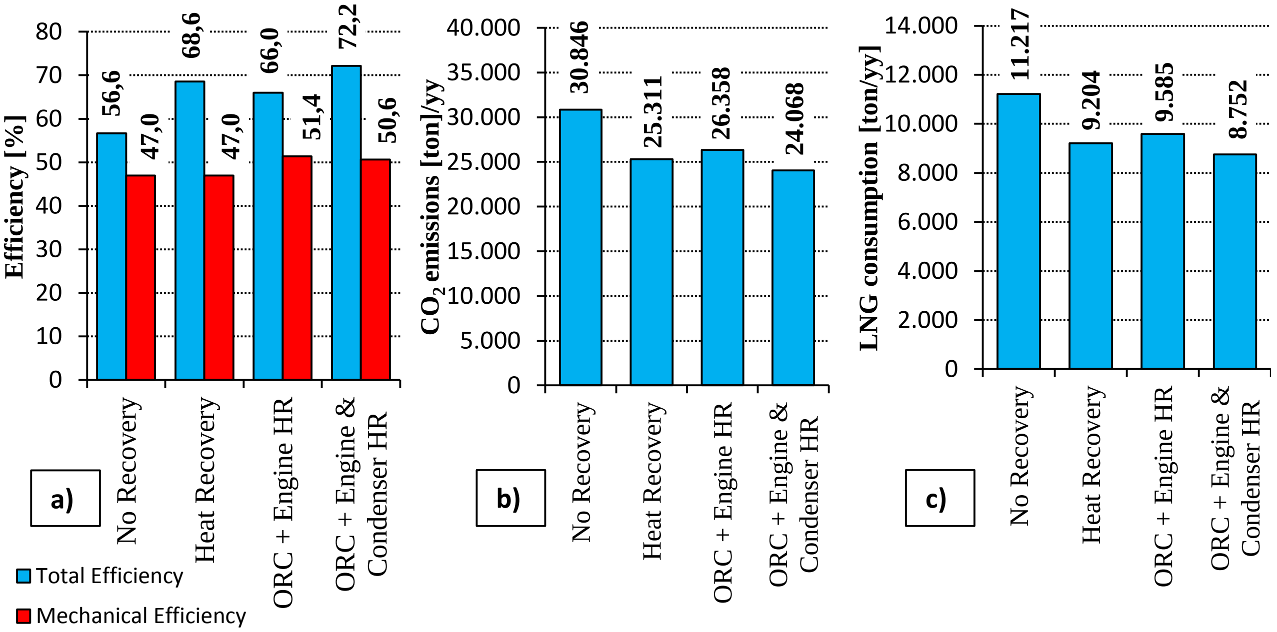

Figure 57. a) Energy efficiency, b) Carbon dioxide emissions and c) LNG consumption for each power plant solution examined.

Nevertheless, it must be noted that Case 1 has a better environmental performance than the same model of ship fuelled by HFO, with no recovery. In fact, assuming a lower heating value of 40.8 MJ/kg, a conversion factor of 3.1144 (kg CO_2) / (kg fuel) [51] and the same energy efficiency, HFO fuel consumption would come to 13,196 ton/yy and CO_2 emissions would be 41,099 ton/yy: thanks to LNG, it is possible to achieve a 25% CO_2 emission reduction in addition to a decrease of sulphur and nitrogen oxides.

4.2.2 Economic considerations

In order to evaluate the feasibility of the proposed solutions, it is necessary consider some economic aspects of the selected vessel. In fact, in the maritime industry an investment with a payback period higher than 5 years usually it is not suitable. Then, the installation costs of the propulsive system should be taken into account. They can be estimated to amount to about 13 million euro compared to about 3 million needed for the installation of a traditional diesel solution [55]. Nonetheless, taking into account installation costs, fuel costs (400 €/ton for LNG, 760 €/ton for MDO and 528 €/ton for HFO, with an estimated annual increase of 2.5% in the fuel price [56]), maintenance costs (2.5 €/kWh for LNG, 3.5 €/kWh for MDO/HFO [55]) and economic costs (interest rate equal to 5%, economic lifespan of 5 years, no residual value) it is possible to obtain a payback period of about three years for the selected vessel and relative route and a money saving of 30 million euro during the 20-year life span of the ship. Furthermore, a possible future variation of LNG prices was taken into account as well: if LNG prices increase to HFO price levels, the payback period will increase to 5 years, while an additional increase of the LNG price to 120% of the HFO price will increase the payback period to 8 years. In the case of retro-fitting existing ships, the cost estimate is more difficult to calculate since the LNG system installation, and in particular the fuel tank installation, might require structural modifications to the ship: nevertheless this is a viable option as in the above-mentioned case of the Bit Viking tanker.

Following the analysis of the proposed solutions for energy saving, it is possible to estimate installation costs in about 200 k€ for Case 1, 1,650 k€ for Case 2, 1,670 k€ for Case 3 and 1,700 k€ for Case 4 and the payback period is respectively 3, 51, 31 and 21 months. Nevertheless, a comparison between Case 2, a typical tanker with heat recovery, and Case 4 shows a possible annual saving of 180 k€.

If a carbon tax were applied, the above-mentioned economic benefits would be obviously higher.

4.2.3 Conclusions

The use of LNG for ship propulsion reduces NO_x, SO_x and CO_2 emissions compared to common heavy fuel oils. The energy analysis carried out on a handysize Tanker demonstrates that there are several possibilities for improving ship efficiency. Results show that the ship can reach a total efficiency of 72.2% when an ORC power plant is integrated with the propulsion system. The investigated solution brings a saving of about 5% in annual fuel consumption in comparison with a simple main engine heat recovery for cargo heating. The economic analysis shows that the payback period for an LNG system installation is equal to 3 years and only a strong rise in LNG price can increase the payback period to 5-8 years.

5 NATURAL GAS UTILIZATION ON CRUISE SHIPS

5.1 Cruise ship conversion

After the analysis on the tanker, a cruise ship has been examined since this type of ship spend an high percentage of time in ECA zone, as seen in the statistical analysis, and a clean image is very important for market reasons. Then, for this analysis, a typical cruise ship has been considered with a length of 220 m, 13 decks and a tonnage of 53,000 GT, able to host about 1,700 passengers and 600 crew members.

The ship is equipped with 4 propulsion diesel engines and 4 diesel gen-sets. Two options for the engines fuel have been considered: in the first case the engines are fuelled only with diesel oil and in the second case the engines can use both natural gas and diesel oil (dual fuel engine, compression ignition). The main specifications of the engines, chosen in the Wärtsilä product range [50] are shown in Table 25.

Table 25. Comparison between diesel engines and gas engines [50].

	Case 1: Diesel Engines			*Case 2:* Dual-Fuel Engines		
	Model	Power	Energy consumption (100% MCR)	Model	Power	Energy consumption (100% MCR)
Propulsive engines	W 8L38	5800 kW	7814 kJ/kWh	W 6L50DF	5700 kW	7300 kJ/kWh
Gen-sets	W 8L32	4400 kW	7857 kJ/kWh	W 9L34DF	3890 kW	7710 kJ/kWh

A typical one week Mediterranean Sea cruise sailing profile has been considered, the electric and propulsion power demand profile is shown in Figure 58. Knowing the engine specific fuel consumption [50] and the ship power demand it is possible to size both the HFO tank (Case 1) and the LNG tank (Case 2) and quantify the environmental benefit.

The fuel tanks, in both cases, have been sized considering the fuel required to cover three cruises. In normal conditions every two cruises the ship has to bunker, while an allowance for a third trip is introduced for emergency cases. Furthermore, a 20% safety margin was assumed for taking into account the fuel consumption increase in case of rough sea. Considering a HFO lower heating value of 42,700 kJ/kg and a density of 1,010 kg/m^3, the required volume for HFO volume is about 1,130 m^3, while, assuming a LNG lower heating value of 49,620 kJ/kg, a density of 422 kg/m^3 and C-type tanks filling limit (98%), the required volume for the LNG is about 2,350 m^3. In add to LNG, diesel fuel oil volume, used as pilot fuel, has been calculated: assuming a lower heating value of 42,700 kJ/kg and a density of 860 kg/m^3, the required volume is about 23 m^3. It is possible to highlight that the required LNG volume is about twice than that required for the diesel tanks.

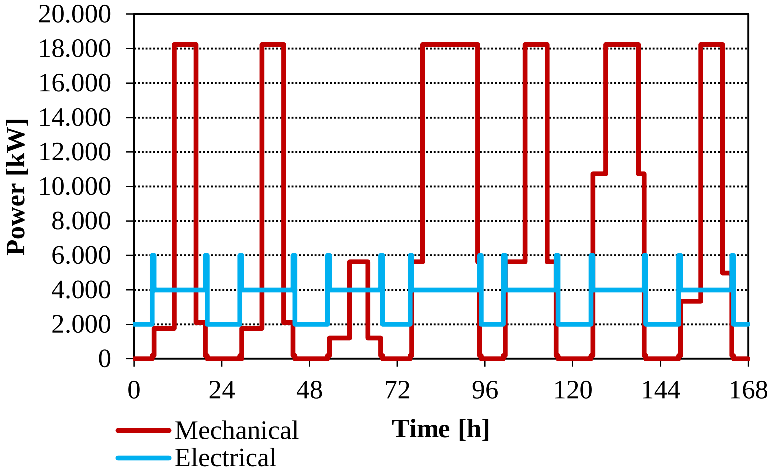

Figure 58. Power demand profile of the considered ship during a cruise.

As for the LNG tank, since the typical maximum size of the C-type tanks it is less than 1,000 m^3, it has been decided to use four tanks with a volume of 600 m^3 each vertically mounted. Each tank has an inner diameter of 5.5 m, is 27.5 m long and has hemispherical heads. Two different insulations have been considered: using different materials and thicknesses the heat flux for each tank has been calculated, obtaining a thermal loss equal to 1.23 and 8.94 kW respectively in case of 150 mm vacuum perlite and 200 mm polyurethane foam. In both cases the maximum allowable pressure has been assumed equal to 9 barg.

The use of different tank insulations allows two different strategies for fuel utilization:

- Plant 1: in this case, as the heat flux is lower, it is possible to use only the liquid phase for feeding engines, as the tank pressure does not exceed design limit during the sailing.
- Plant 2: in this case the higher heat flux raises the pressure in the tank over the design limit and therefore it is necessary to use both the BOG and the liquid to feed the engines.

In both cases, since the engines need a gas feeding pressure higher than 5 barg, the pressure in the tank is maintained constant through a pressure build up circuit: this circuit extracts, vaporizes and re-introduces the gas into the tank increasing the pressure. The tank pressure has been set equal to 5.5 barg and, in case of Plant 2, the control strategy for BOG using is to maintain the pressure equal to 5.8 barg: under this pressure only LNG is used. The four LNG tanks are connected, in order to maintain the same pressure, and natural gas is extracted simultaneously from all the tanks.

At the beginning of the first trip the LNG composition is: methane 89.9%, ethane 6%, propane 2.2%, butane 1.5% and nitrogen 0.4%. Every two trips the ship has to refuel: the bunkering flow rate has been assumed equal to 30 ton/h for each tank and the gas composition has been assumed equal to the initial gas composition. The LNG inlet temperature has been set equal to -162°C, since ship can be refuelled from a gas terminal where LNG is maintained at atmospheric pressure in full refrigerated conditions.

5.2 Simulations and results

As explained in the previous chapter, one critical parameter to consider during the design phase of a LNG system is the pressure increase in the tanks: in fact, in case of failure of the LNG system (no gas utilization), the pressure in the tanks increase and then the installation of a Gas Combustion Unit (GCU) could be necessary in order to burn the BOG and then maintain the pressure in the tanks below the design limit. According to the IGF rules, a relief valve is always installed but it has to be used only in emergency conditions, as methane is a powerful greenhouse gas. For this reason, an in-tank pressure profile analysis has been carried out: two different filling ratios have been considered, the full tank (98% filling) and the empty tank (20% filling). In all of the examined cases the starting pressure has been set equal to 5.5 barg. Results show that in case of Plant 1 (Figure 59a), for both filling ratios, the pressure does not exceed the limit of 9 barg in 15 days (360 h): then, in compliance with maritime rules [59], which impose a 15 day period without exceeding the limit pressure, it is not necessary to install a GCU. While, when considering Plant 2, a GCU is necessary, as the pressure exceeds the limit before 15 days, in particular, in case of empty tank, the pressure reaches the limit only in 4 days (96 h). Furthermore, in order to size the GCU, an evaluation of the BOG flow rate has been carried out: the analysis has been developed only for one tank, since the four tanks are identical, maintaining a constant pressure of 6 barg. Results show that BOG production for a single tank of Plant 1 is about 10 kg/h, while for Plant 2 it is about 70 kg/h: in both cases the BOG production has a little increase as the liquid level decreases. Then, Plant 2 requires a GCU able to burn at least 300 kg/h, in order to maintain a constant pressure in case of LNG system/engines failure.

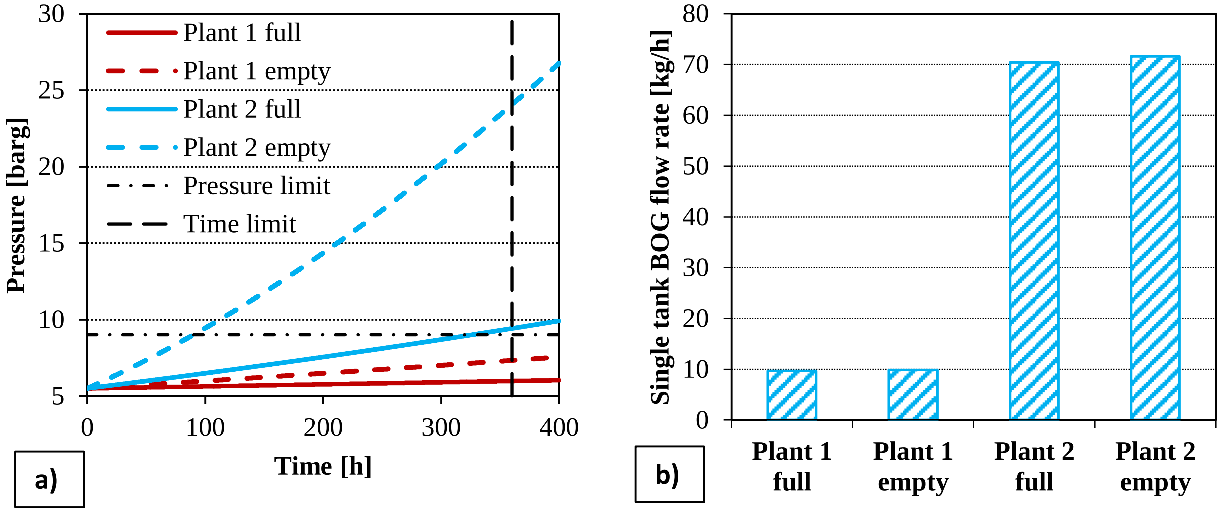

Figure 59. a) Tank pressure variation and b) Boil Off Gas production for the two different plants in case of full and empty tank.

As mentioned, this analysis has been focused, in particular, on Methane Number and heating value changes during a long operating period in order to avoid engines knocking. Figure 60 shows the Methane Number profile over time and it is possible to highlight that the variation is smaller than one point in case of Plant 1, whereas, in Plant 2, the MN variation is about 20 points, as BOG is used and its composition strongly changes over time.

Figure 61 shows the Methane Number profile during the firsts two cruises *a)* and the lasts two cruises *b)* (20 cruises period), where it is possible to see that the Methane Number decreases below the limit value of 70 in case of Plant 2, while in Plant 1 it remains greater than 70. In both cases it is possible to highlight a MN reduction during the firsts cruises. Figure 61 *c)* and *d)* show the BOG percentage and the MN during the firsts and lasts two cruises: it is possible to note that in case of Plant 2 there are frequent changes in the MN as, when the power required is lower, the quantity of BOG used is higher in order to maintain the pressure in the tank below the set limit. As for the heating value, the profile (Figure 62) shows a similar behaviour: in case of Plant 1 its value is almost constant, with a little decrease during the early cruises, while in Plant 2 the heating value variation is greater since BOG is used.

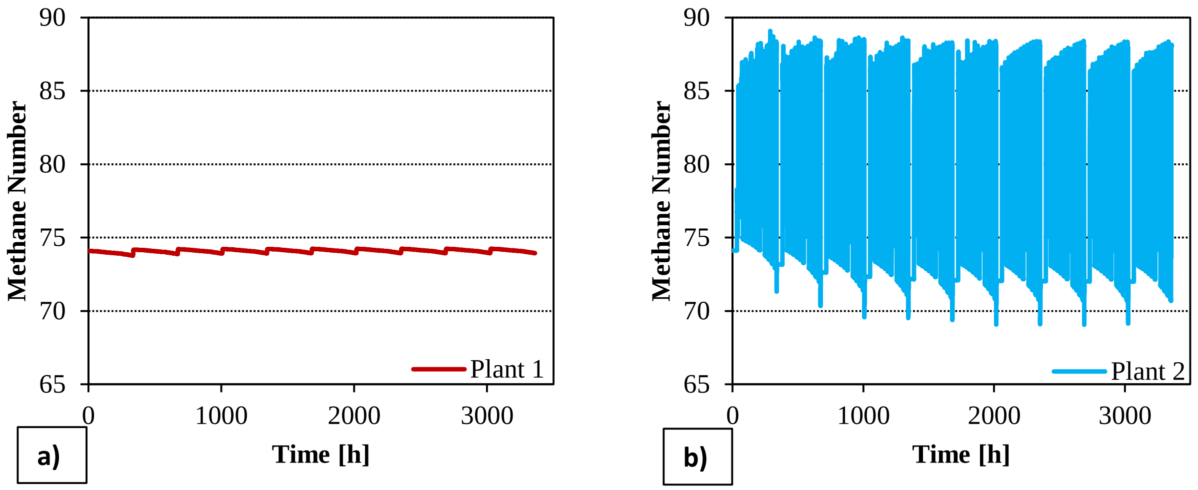

Figure 60. Methane Number variation during a 20 cruise period for a) Plant 1 and b) Plant 2.

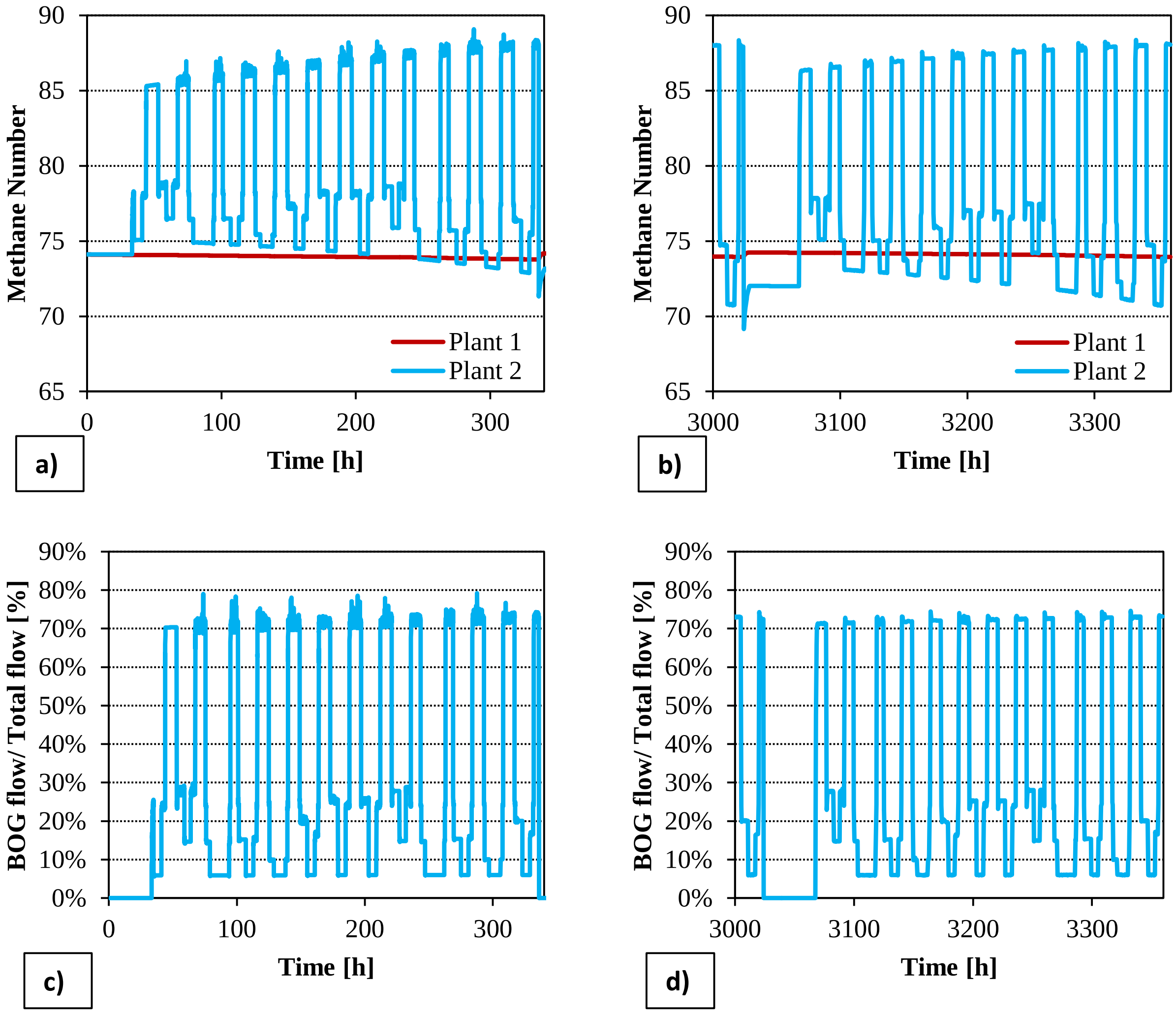

Figure 61. Detail of the Methane Number profile during a) the firsts two cruises and b) the lasts two cruises (20 cruises period) and BOG percentage profile during c) the firsts two cruises and d) the lasts two cruises for Plant 1(Plant 2 does not use BOG). It is possible to note that in case of Plant 2 there are frequent changes in the MN as, when the power required is lower, the quantity of BOG used is higher in order to maintain the pressure in the tank below the set limit.

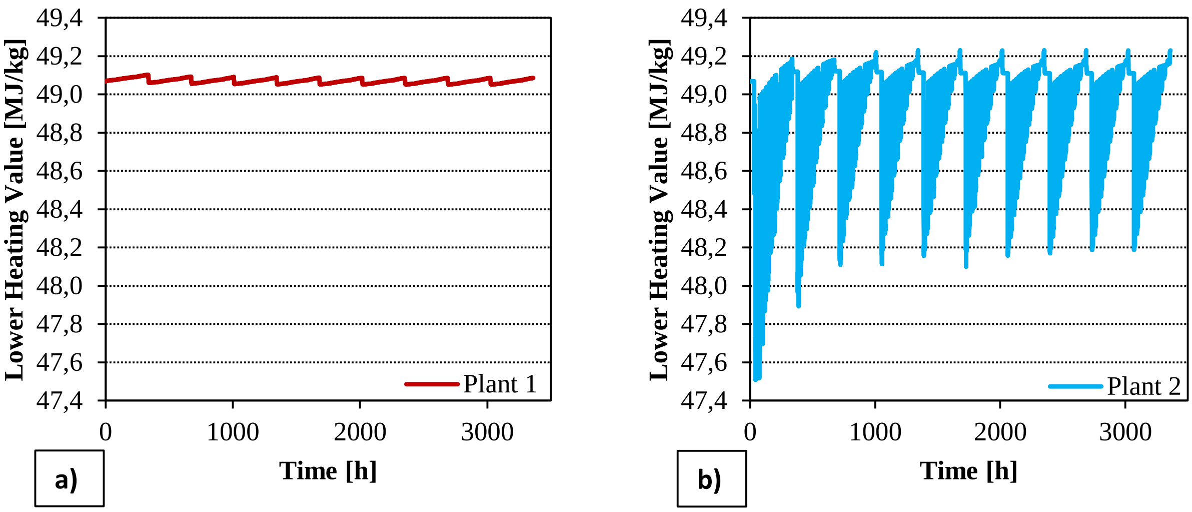

Figure 62. Lower heating value variation during a 20 cruise period for a) Plant 1 and b) Plant 2.

5.3 Economic analysis and environmental benefits

In order to evaluate the feasibility of the proposed solution, a preliminary economic analysis has been carried out. In Table 26 the installation cost of three different propulsive systems in compliance with current rules, fuel cost [60] (considering an increasing of 2.5% every year of the fuel price) and maintenance cost are shown. As for the economic costs, it has been assumed an interest rate of 5%, an economic lifespan of 5 years, and no residual value. Therefore, assuming 45 cruise/year, it is possible to obtain an LNG plant payback period, respectively for MDO and HFO, of about two and three years for the selected vessel and reference route. The obtained money saving is 170 M€ for MDO and 90 M€ for HFO during a 20 year ship life. Furthermore, it has been taken into account a possible future variation of LNG price: if LNG price reaches HFO price the payback period, respect HFO solution, will increase to 4 years, while an additional increase of LNG price up to 120% of HFO price will increase the payback period to 5 years.

In case of retro-fitting of existing ships, the cost estimation is more difficult, since the LNG system installation, and in particular fuel tank installation, could require structural modifications to the ship: nevertheless this is a viable option as in the case of the tanker Bit Viking [35].

Environmental benefits have been also quantified: CO_2 emissions have been calculated as: $CO_2 = FC \cdot C_F$, where FC is the fuel consumption during a cruise and C_F is an emission factor described by the following relation: $C_F = (kg\ CO_2) / (kg\ fuel)$. C_F has been assumed equal to 2.75 for natural gas, 3.1144 for HFO and 3.206 for MDO [51]. On these bases, the CO_2 emissions for each cruise has been quantified in 760 tons for LNG, taking into account also the MDO pilot fuel, and 984 for HFO: using LNG it is possible to achieve a 23% CO_2 emission reduction. The reduction of sulphur is almost complete and nitrogen oxides reduction depends on the engine model, but on average, it is about 85%.

Table 26. Installation, fuel and maintenance costs for the analysed solutions.

	MDO	HFO	LNG
Installation [M€]	10.5	15.5	27
Fuel [€/ton]	766	490	400
Maintenance [€/MWh]	3.5	3.5	2.5

5.4 Conclusions

The LNG plant installation on a cruise ship highlighted that the gas tank requires twice the volume of a traditional diesel oil tank, whereas the comparison between two different tank insulations showed that a reduction in the heat loss allows not to install a Gas Combustion Unit, while the solution with a lower insulation requires a GCU able to burn at least 300 kg/h of BOG in case of LNG system failure. Furthermore, in case of Plant 2, to reduce MN fluctuations and avoid knocking problems, a control strategy for BOG use has to be implemented.

The economic analysis shows that the payback period, for an LNG system installation, is 3 years, and only a strong increase of LNG price can raise the payback period up to 4-5 years.

6 CONCLUSIONS

In this thesis an analysis on the use of natural gas on ship has been carried out. In the first part of the work the emission caused by ship and the current regulation has been examined: the analysis demonstrates that the emission caused by ships are growing, especially in small areas with an high traffic. For these reasons, IMO and European Union scheduled an emission reduction program for the next years.

A literature analysis on the current available solutions to meet the gas emission limits has been developed: amongst the possible solution in compliance with current and future limits, natural gas seems to be one of the most promising technologies. In fact, natural gas can strongly reduce the emissions of CO_2, NO_X and SO_X, currently it is a cheap fuel and wide reserves are available.

The state of the art of the gas engine technologies, LNG tank types and plant solutions has been analysed, focusing in particular on the advantages and drawbacks of the different solutions.

After the literature analysis, a world maritime traffic statistical analysis has been developed. In fact, the first objective of the study was the identification of the most suitable vessels for the LNG adoption: the traffic analysis has pointed out that a potential market for the LNG ships exists, in particular for tanker ships, that show an high time spent in ECA zone, a big number of trips and especially a growing trend of the number of trips. In fact, considering the current and the future ECA zone and the ships that spend more than 60% of their time in these areas, more than 30% of the tankers could be LNG fuelled, obtaining significant environmental benefits.

As consequence of the results obtained in the traffic analysis, a specific LNG fuelled handysize tanker has been examined. The analysis on the selected tanker points out that one of the most critical components of the LNG plant is the tank: a correct choice of the insulation is fundamental because it influences the design of the whole LNG system and the engines performance. Further analysis has to be carried out in order to develop a control strategy able to maintain a constant pressure and a more homogeneous gas mixture during the sailing period.

The analysis demonstrates that the use of LNG for ship propulsion allows reducing NO_x, SO_x and CO_2 emissions respect to the currently adopted heavy fuel oils and complying with current and future maritime emissions rules. Thanks to the proposed energy recovery solutions a further reduction of the emissions and operating costs can be achieved: in fact, the integration of the ORC plant with heat recovery brings a saving of about 5% in annual fuel consumption in comparison with a simple main engine heat recovery for cargo heating.

The economic analysis shows that the payback period of the LNG plant can be three years demonstrating the economic benefits of the LNG solution, especially if the LNG use is coupled to energy recovery systems. Furthermore, taking into account that usually 5 years is considered an acceptable payback period in maritime industry, the sensitivity analysis shows that the LNG plant installation has a low economic risk: in fact, only a strong increase of the LNG price (120% of HFO price) can increase the payback period to 8 years.

After the analysis developed for the tanker, a specific cruise ship LNG conversion has been examined. The LNG system simulation shows again that the correct choice of the tank insulation is a crucial parameter: in fact the use of Gas Combustion Unit can be not necessary with the right insulation. In this case also a further analysis to develop a control strategy is necessary. In particular, a variable pressure control strategy could reduce the variation of the gas properties during the trip.

An economic analysis has been carried out also: the results show that the payback period, for an LNG system installation, is three years, and only a strong increase of LNG price can raise the payback period up to 4-5 years, whereas the environmental benefit can be quantified with a CO_2 emission reduction of 23%: in this case also the economic and environmental benefits has been demonstrated.

Concluding, it is possible to highlight that the use of natural gas for ship propulsion allows environmental benefits and a reduction of the operating cost but some improvements are necessary, like the reduction of the space requirements and installation costs of the system, the improvement of the engine performance at partial load and the reduction of the methane slip. Furthermore the lack in the standard has to be solved as soon as possible.

But the main issues in the LNG utilization is the availability of bunkering points. This is one of the classic chicken-egg problems that could be overcome, for example, introducing a proper incentives policy. Norway is the prove: this country has demonstrated that small scale LNG production and distribution is competitive as fuel for ships, and the adoption of an incentive policy allowed a large diffusion of LNG fuelled ship. For these reasons, further investigation on the LNG distribution network and incentives policy are necessary, in order to suggest the best places for the LNG bunkering points and define a proper incentives strategy for LNG ships.

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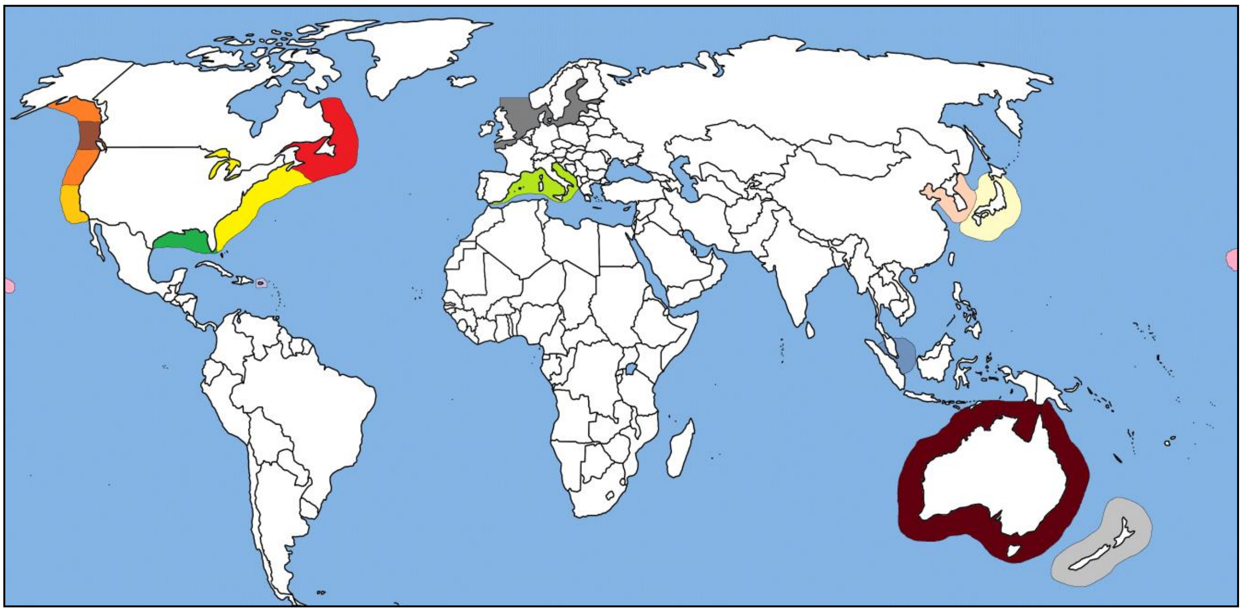
ANNEX 1: RESULTS OF THE TRAFFIC ANALYSIS



ECA Zone	ECA Area	ECA Zone N. rif	Extension (miles)	Color
Not in ECA zone	0	0	0	⬜
US East Coast / Lakes	2	1	Multiple Values	🟨
US West Coast Nord	2	2	200	🟧
US West Coast Sud	2	7	200	🟧
Hawaii	2	3	200	🟥
Gulf of Mexico	2	4	200	🟩
Puerto Rico	2	5	200	🟥
North Sea / Baltic Sea	1	6	Multiple Values	⬛
East Canada	2	8	Multiple Values	🟥
West Canada	2	9	200	🟫
Mediterraneo	3	10	Multiple Values	🟩
Singapore	4	11	200	🟦
Nuova Zelanda	5	12	200	⬜
Australia	5	13	200	🟫
Giappone	6	14	200	🟨
Korea	7	15	200	⬜

Vessel Category	Vessel Size	Number of Trips	Days at Sea	Days in ECA 1	Days in ECA 2	Days in ECA 3	Days in ECA 4	Days in ECA 5	Days in ECA 6	Days in ECA 7
Bulk Carriers	Very Small	931	2057	465	23	166	15	27	92	63
Bulk Carriers	Small	1039	3058	309	48	248	61	30	108	73
Bulk Carriers	Handysize	13200	92110	3133	3600	1669	758	876	783	409
Bulk Carriers	Handymax	7178	63236	809	1095	432	773	581	572	297
Bulk Carriers	Panamax	6237	60346	1156	1173	741	520	769	388	289
Bulk Carriers	Capesize	4041	37843	579	202	136	426	1524	602	185
Bulk Carriers	VLOC, Very Large Ore Carrier	541	5163	59	15	16	62	154	162	41
Cargo Vessels	Very Small	32510	115365	22375	332	6696	1219	153	2160	2245
Cargo Vessels	Small	21633	113775	7488	1571	3627	1216	317	1586	1250
Cargo Vessels	Large	869	6216	198	269	100	48	32	45	37
Container Vessels	Feeder	2256	5421	576	60	248	192	2	256	189
Container Vessels	Feedermax	5513	11693	2373	101	511	340	74	424	227
Container Vessels	Handysize	7698	22124	918	333	631	722	174	347	196
Container Vessels	Sub-Panamax	3882	15457	500	321	269	306	257	73	51
Container Vessels	Panamax	1894	8091	188	190	102	152	124	65	48
Container Vessels	Post-Panamax	5022	21093	488	698	347	305	106	195	159
Container Vessels	Very Large	961	4822	258	33	64	93	0	5	17
LNG Tankers	Large	1061	8051	29	85	57	69	44	194	93
LPG Tankers	Small	1662	4391	771	16	367	133	27	124	128
LPG Tankers	Medium	1268	5346	452	58	294	84	37	24	35
LPG Tankers	Large	613	4019	120	98	42	32	8	38	14
LPG Tankers	Very Large	358	2291	17	50	33	32	9	32	12
RoRo Vessels	Very Small	1074	2833	298	170	226	35	0	19	15
RoRo Vessels	Small	3589	11335	1991	202	751	97	60	273	66
RoRo Vessels	Medium	1949	6630	1113	163	430	34	64	115	50
RoRo Vessels	Large	1971	11167	479	377	157	96	111	240	115
Tankers	Very Small	7003	18077	2636	20	872	688	3	467	604
Tankers	Small	5149	17229	1831	146	810	672	70	218	267
Tankers	Handy	12686	65590	5365	2063	1873	1191	310	213	286
Tankers	Panamax	1702	10930	327	398	64	119	17	37	44
Tankers	Aframax	4371	23245	1490	757	848	489	261	111	110
Tankers	Suezmax	1940	13012	449	693	221	79	18	12	8
Tankers	VLCC, Very Large Crude Carrier	2144	22490	111	774	12	171	0	141	88
Cruise	Small Cruise Vessels	688	1658	153	74	145	33	13	12	2
Cruise	Medium Cruise Vessels	954	1785	171	69	220	21	6	27	19
Cruise	Large Cruise Vessels	481	823	66	153	102	0	7	3	0
Cruise	Panamax Cruise Vessels	203	347	15	45	61	0	0	0	0
Passengers	Small Passengers Vessels	267	364	64	13	30	12	3	1	1
Passengers	Medium Passengers Vessels	122	193	28	1	27	10	0	1	0
Passengers & Cargo	Very Small Passengers & Cargo Vessels	659	1111	88	31	449	2	5	11	5
Passengers & Cargo	Small Passengers & Cargo Vessels	2021	2705	750	14	1515	3	16	45	36
Yachts	Various	698	2727	278	253	328	11	19	1	1
Other	Various	21852	21893	10118	3264	1191	4936	539	832	885
Grand Total		192303	850322	71172	20075	27255	16271	6847	11073	8666
Percentages				8.4%	2.4%	3.2%	1.9%	0.8%	1.3%	1.0%

Vessel Category	Vessel Size	N. Vessels more than 80% in ECA 1,2	N. Vessels between 80% and 60% in ECA 1,2	N. Vessels between 60% and 40% in ECA 1,2	N. Vessels between 40% and 20% in ECA 1,2	N. Vessels between 20% and 5% in ECA 1,2	N. Vessels less than 5% in ECA 1,2	Average Trip in Days	Average vessel power (kW)
Bulk Carriers	Very Small	226	7	5	5	13	579	2	1463
Bulk Carriers	Small	125	11	22	22	21	674	2	2858
Bulk Carriers	Handysize	1263	68	289	378	645	9807	2	6632
Bulk Carriers	Handymax	322	16	153	124	290	5956	2	8182
Bulk Carriers	Panamax	336	35	187	119	426	4875	2	9571
Bulk Carriers	Capesize	146	3	33	37	214	3357	2	14012
Bulk Carriers	VLOC, Very Large Ore Carrier	8	0	1	5	24	453	1	17542
Cargo Vessels	Very Small	8385	310	523	555	534	20118	2	1277
Cargo Vessels	Small	2049	149	323	612	1064	15883	2	4489
Cargo Vessels	Large	107	4	26	44	79	535	1	10152
Container Vessels	Feeder	270	7	15	29	40	1633	2	3636
Container Vessels	Feedermax	1412	29	65	101	107	3145	2	6879
Container Vessels	Handysize	505	9	92	128	143	5902	2	12165
Container Vessels	Sub-Panamax	330	6	52	102	209	2818	1	21140
Container Vessels	Panamax	162	10	16	64	74	1402	1	27323
Container Vessels	Post-Panamax	623	46	13	222	259	3430	1	47875
Container Vessels	Very Large	168	0	8	32	65	648	1	67829
LNG Tankers	Large	8	1	10	10	33	950	2	20397
LPG Tankers	Small	390	12	25	37	20	918	2	2307
LPG Tankers	Medium	182	5	30	52	62	856	2	5118
LPG Tankers	Large	57	2	17	14	38	467	2	10748
LPG Tankers	Very Large	6	0	9	5	8	309	7	12856
RoRo Vessels	Very Small	176	12	24	20	24	721	2	1905
RoRo Vessels	Small	1115	20	54	99	95	1810	2	5403
RoRo Vessels	Medium	740	6	39	71	82	811	1	9921
RoRo Vessels	Large	415	2	24	79	117	1072	1	13641
Tankers	Very Small	1486	23	60	42	37	4579	2	1662
Tankers	Small	920	28	36	101	84	3369	2	2984
Tankers	Handy	2180	117	264	560	729	7694	2	7318
Tankers	Panamax	141	3	77	76	204	1146	2	10983
Tankers	Aframax	671	22	157	174	364	2708	2	12306
Tankers	Suezmax	312	21	124	83	94	1270	2	15644
Tankers	VLCC, Very Large Crude Carrier	73	3	27	46	65	1880	2	24445
Cruise	Small Cruise Vessels	81	2	5	11	6	500	2	1923
Cruise	Medium Cruise Vessels	123	0	40	33	19	589	1	6960
Cruise	Large Cruise Vessels	83	10	31	58	49	191	2	17356
Cruise	Panamax Cruise Vessels	23	3	6	28	31	77	1	17705
Passengers	Small Passengers Vessels	73	0	0	2	1	159	1	1129
Passengers	Medium Passengers Vessels	13	0	2	0	0	70	2	2926
Passengers & Cargo	Very Small Passengers & Cargo Vessels	91	2	6	6	5	394	1	3831
Passengers & Cargo	Small Passengers & Cargo Vessels	549	0	19	22	23	670	1	8564
Yachts	Various	138	4	50	13	18	420	0	1280
Other	Various	4493	178	185	238	308	12632	3	2408
Grand Total		31046	1186	3146	4473	6734	127773		
Percentages		16.1%	0.6%	1.6%	2.3%	3.5%	66.4%		

Vessel Category	Vessel Size	Number of Trips	% Days at Sea	% Days in ECA 1	% Days in ECA 2	% Days in ECA 3	% Days in ECA 4	% Days in ECA 5	% Days in ECA 6	% Days in ECA 7
Bulk Carriers	Very Small	931	0.2%	22.6%	1.1%	8.1%	0.7%	1.3%	4.5%	3.1%
Bulk Carriers	Small	1039	0.4%	10.1%	1.6%	8.1%	2.0%	1.0%	3.5%	2.4%
Bulk Carriers	Handysize	13200	10.8%	3.4%	3.9%	1.8%	0.8%	1.0%	0.8%	0.4%
Bulk Carriers	Handymax	7178	7.4%	1.3%	1.7%	0.7%	1.2%	0.9%	0.9%	0.5%
Bulk Carriers	Panamax	6237	7.1%	1.9%	1.9%	1.2%	0.9%	1.3%	0.6%	0.5%
Bulk Carriers	Capesize	4041	4.5%	1.5%	0.5%	0.4%	1.1%	4.0%	1.6%	0.5%
Bulk Carriers	VLOC, Very Large Ore Carrier	541	0.6%	1.1%	0.3%	0.3%	1.2%	3.0%	3.1%	0.8%
Cargo Vessels	Very Small	32510	13.6%	19.4%	0.3%	5.8%	1.1%	0.1%	1.9%	1.9%
Cargo Vessels	Small	21633	13.4%	6.6%	1.4%	3.2%	1.1%	0.3%	1.4%	1.1%
Cargo Vessels	Large	869	0.7%	3.2%	4.3%	1.6%	0.8%	0.5%	0.7%	0.6%
Container Vessels	Feeder	2256	0.6%	10.6%	1.1%	4.6%	3.6%	0.0%	4.7%	3.5%
Container Vessels	Feedermax	5513	1.4%	20.3%	0.9%	4.4%	2.9%	0.6%	3.6%	1.9%
Container Vessels	Handysize	7698	2.6%	4.2%	1.5%	2.9%	3.3%	0.8%	1.6%	0.9%
Container Vessels	Sub-Panamax	3882	1.8%	3.2%	2.1%	1.7%	2.0%	1.7%	0.5%	0.3%
Container Vessels	Panamax	1894	1.0%	2.3%	2.3%	1.3%	1.9%	1.5%	0.8%	0.6%
Container Vessels	Post-Panamax	5022	2.5%	2.3%	3.3%	1.6%	1.4%	0.5%	0.9%	0.8%
Container Vessels	Very Large	961	0.6%	5.4%	0.7%	1.3%	1.9%	0.0%	0.1%	0.3%
LNG Tankers	Large	1061	0.9%	0.4%	1.1%	0.7%	0.9%	0.6%	2.4%	1.2%
LPG Tankers	Small	1662	0.5%	17.6%	0.4%	8.3%	3.0%	0.6%	2.8%	2.9%
LPG Tankers	Medium	1268	0.6%	8.5%	1.1%	5.5%	1.6%	0.7%	0.5%	0.7%
LPG Tankers	Large	613	0.5%	3.0%	2.4%	1.1%	0.8%	0.2%	1.0%	0.3%
LPG Tankers	Very Large	358	0.3%	0.7%	2.2%	1.5%	1.4%	0.4%	1.4%	0.5%
RoRo Vessels	Very Small	1074	0.3%	10.5%	6.0%	8.0%	1.2%	0.0%	0.7%	0.5%
RoRo Vessels	Small	3589	1.3%	17.6%	1.8%	6.6%	0.9%	0.5%	2.4%	0.6%
RoRo Vessels	Medium	1949	0.8%	16.8%	2.5%	6.5%	0.5%	1.0%	1.7%	0.8%
RoRo Vessels	Large	1971	1.3%	4.3%	3.4%	1.4%	0.9%	1.0%	2.2%	1.0%
Tankers	Very Small	7003	2.1%	14.6%	0.1%	4.8%	3.8%	0.0%	2.6%	3.3%
Tankers	Small	5149	2.0%	10.6%	0.8%	4.7%	3.9%	0.4%	1.3%	1.6%
Tankers	Handy	12686	7.7%	8.2%	3.1%	2.9%	1.8%	0.5%	0.3%	0.4%
Tankers	Panamax	1702	1.3%	3.0%	3.6%	0.6%	1.1%	0.2%	0.3%	0.4%
Tankers	Aframax	4371	2.7%	6.4%	3.3%	3.6%	2.1%	1.1%	0.5%	0.5%
Tankers	Suezmax	1940	1.5%	3.4%	5.3%	1.7%	0.6%	0.1%	0.1%	0.1%
Tankers	VLCC, Very Large Crude Carrier	2144	2.6%	0.5%	3.4%	0.1%	0.8%	0.0%	0.6%	0.4%
Cruise	Small Cruise Vessels	688	0.2%	9.2%	4.4%	8.8%	2.0%	0.8%	0.7%	0.1%
Cruise	Medium Cruise Vessels	954	0.2%	9.6%	3.9%	12.3%	1.2%	0.4%	1.5%	1.1%
Cruise	Large Cruise Vessels	481	0.1%	8.0%	18.6%	12.4%	0.0%	0.8%	0.3%	0.0%
Cruise	Panamax Cruise Vessels	203	0.0%	4.3%	13.1%	17.5%	0.1%	0.0%	0.0%	0.0%
Passengers	Small Passengers Vessels	267	0.0%	17.5%	3.6%	8.2%	3.3%	0.8%	0.1%	0.1%
Passengers	Medium Passengers Vessels	122	0.0%	14.7%	0.4%	14.0%	5.3%	0.0%	0.5%	0.2%
Passengers & Cargo	Very Small Passengers & Cargo Vessels	659	0.1%	8.0%	2.8%	40.4%	0.2%	0.5%	1.0%	0.5%
Passengers & Cargo	Small Passengers & Cargo Vessels	2021	0.3%	27.7%	0.5%	56.0%	0.1%	0.6%	1.7%	1.3%
Yachts	Various	698	0.3%	10.2%	9.3%	12.0%	0.4%	0.7%	0.0%	0.0%
Other	Various	21852	2.6%	46.2%	14.9%	5.4%	22.5%	2.5%	3.8%	4.0%

Vessel Category	Vessel Size	% Vessels more than 80% in ECA 1,2	% Vessels between 80% and 60% in ECA 1,2	% Vessels between 60% and 40% in ECA 1,2	% Vessels between 40% and 20% in ECA 1,2	% Vessels between 20% and 5% in ECA 1,2	% Vessels less than 5% in ECA 1,2	Average Trip in Days	Average vessel power (kW)
Bulk Carriers	Very Small	24.3%	0.8%	0.5%	0.5%	1.4%	62.2%	2	1463
Bulk Carriers	Small	12.0%	1.1%	2.1%	2.1%	2.0%	64.9%	2	2858
Bulk Carriers	Handysize	9.6%	0.5%	2.2%	2.9%	4.9%	74.3%	2	6632
Bulk Carriers	Handymax	4.5%	0.2%	2.1%	1.7%	4.0%	83.0%	2	8182
Bulk Carriers	Panamax	5.4%	0.6%	3.0%	1.9%	6.8%	78.2%	2	9571
Bulk Carriers	Capesize	3.6%	0.1%	0.8%	0.9%	5.3%	83.1%	2	14012
Bulk Carriers	VLOC, Very Large Ore Carrier	1.5%	0.0%	0.2%	0.9%	4.4%	83.7%	1	17542
Cargo Vessels	Very Small	25.8%	1.0%	1.6%	1.7%	1.6%	61.9%	2	1277
Cargo Vessels	Small	9.5%	0.7%	1.5%	2.8%	4.9%	73.4%	2	4489
Cargo Vessels	Large	12.3%	0.5%	3.0%	5.1%	9.1%	61.6%	1	10152
Container Vessels	Feeder	12.0%	0.3%	0.7%	1.3%	1.8%	72.4%	2	3636
Container Vessels	Feedermax	25.6%	0.5%	1.2%	1.8%	1.9%	57.0%	2	6879
Container Vessels	Handysize	6.6%	0.1%	1.2%	1.7%	1.9%	76.7%	2	12165
Container Vessels	Sub-Panamax	8.5%	0.2%	1.3%	2.6%	5.4%	72.6%	1	21140
Container Vessels	Panamax	8.6%	0.5%	0.8%	3.4%	3.9%	74.0%	1	27323
Container Vessels	Post-Panamax	12.4%	0.9%	0.3%	4.4%	5.2%	68.3%	1	47875
Container Vessels	Very Large	17.5%	0.0%	0.8%	3.3%	6.8%	67.4%	1	67829
LNG Tankers	Large	0.8%	0.1%	0.9%	0.9%	3.1%	89.5%	2	20397
LPG Tankers	Small	23.5%	0.7%	1.5%	2.2%	1.2%	55.2%	2	2307
LPG Tankers	Medium	14.4%	0.4%	2.4%	4.1%	4.9%	67.5%	2	5118
LPG Tankers	Large	9.3%	0.3%	2.8%	2.3%	6.2%	76.2%	2	10748
LPG Tankers	Very Large	1.7%	0.0%	2.5%	1.4%	2.2%	86.3%	7	12856
RoRo Vessels	Very Small	16.4%	1.1%	2.2%	1.9%	2.2%	67.1%	2	1905
RoRo Vessels	Small	31.1%	0.6%	1.5%	2.8%	2.6%	50.4%	2	5403
RoRo Vessels	Medium	38.0%	0.3%	2.0%	3.6%	4.2%	41.6%	1	9921
RoRo Vessels	Large	21.1%	0.1%	1.2%	4.0%	5.9%	54.4%	1	13641
Tankers	Very Small	21.2%	0.3%	0.9%	0.6%	0.5%	65.4%	2	1662
Tankers	Small	17.9%	0.5%	0.7%	2.0%	1.6%	65.4%	2	2984
Tankers	Handy	17.2%	0.9%	2.1%	4.4%	5.7%	60.6%	2	7318
Tankers	Panamax	8.3%	0.2%	4.5%	4.5%	12.0%	67.3%	2	10983
Tankers	Aframax	15.4%	0.5%	3.6%	4.0%	8.3%	62.0%	2	12306
Tankers	Suezmax	16.1%	1.1%	6.4%	4.3%	4.8%	65.5%	2	15644
Tankers	VLCC, Very Large Crude Carrier	3.4%	0.1%	1.3%	2.1%	3.0%	87.7%	2	24445
Cruise	Small Cruise Vessels	11.8%	0.3%	0.7%	1.6%	0.9%	72.7%	2	1923
Cruise	Medium Cruise Vessels	12.9%	0.0%	4.2%	3.5%	2.0%	61.7%	1	6960
Cruise	Large Cruise Vessels	17.3%	2.1%	6.4%	12.1%	10.2%	39.7%	2	17356
Cruise	Panamax Cruise Vessels	11.3%	1.5%	3.0%	13.8%	15.3%	37.9%	1	17705
Passengers	Small Passengers Vessels	27.3%	0.0%	0.0%	0.7%	0.4%	59.6%	1	1129
Passengers	Medium Passengers Vessels	10.7%	0.0%	1.6%	0.0%	0.0%	57.4%	2	2926
Passengers & Cargo	Very Small Passengers & Cargo Vessels	13.8%	0.3%	0.9%	0.9%	0.8%	59.8%	1	3831
Passengers & Cargo	Small Passengers & Cargo Vessels	27.2%	0.0%	0.9%	1.1%	1.1%	33.2%	1	8564
Yachts	Various	19.8%	0.6%	7.2%	1.9%	2.6%	60.2%	0	1280
Other	Various	20.6%	0.8%	0.8%	1.1%	1.4%	57.8%	3	2408

VESSEL CATEGORY	**VESSEL SIZE**	**UNITS**	**FROM**	**TO**	**SPEED**
Bulk Carriers	Very Small	DWT	1	5000	11
Bulk Carriers	Small	DWT	5000	10000	13
Bulk Carriers	Handysize	DWT	10000	40000	14.5
Bulk Carriers	Handymax	DWT	40000	60000	14.5
Bulk Carriers	Panamax	DWT	60000	80000	14.5
Bulk Carriers	Capesize	DWT	80000	200000	14.5
Bulk Carriers	VLOC	DWT	200000		14.5
Cargo Vessels	Very Small	DWT	1	5000	11.5
Cargo Vessels	Small	DWT	5000	20000	14.5
Cargo Vessels	Medium	DWT	20000	40000	15.5
Cargo Vessels	Large	DWT	40000		15
Combination Carriers	Very Small	DWT	1	5000	12
Combination Carriers	Small	DWT	5000	10000	14
Combination Carriers	Handysize	DWT	10000	40000	14
Combination Carriers	Handymax	DWT	40000	60000	15
Combination Carriers	Panamax	DWT	60000	80000	14.5
Combination Carriers	Capesize	DWT	80000	200000	15
Combination Carriers	VLOC	DWT	200000		15
Container Vessels	Feeder	TEU	1	500	14
Container Vessels	Feedermax	TEU	500	1000	17
Container Vessels	Handysize	TEU	1000	2000	19.5
Container Vessels	Sub-Panamax	TEU	2000	3000	21.5
Container Vessels	Panamax	TEU	3000	4000	22.5
Container Vessels	Post-Panamax	TEU	4000	8000	24.5
Container Vessels	Very Large	TEU	8000	10000	25
Container Vessels	Ultra Large	TEU	10000		25.5
LNG Tankers	Small	DWT	1	10000	13
LNG Tankers	Medium	DWT	10000	50000	17
LNG Tankers	Large	DWT	50000	125000	19.5
LNG Tankers	Very Large	DWT	125000		19.5
LPG Tankers	Small	DWT	1	5000	12.5
LPG Tankers	Medium	DWT	5000	20000	15.5
LPG Tankers	Large	DWT	20000	50000	16.5
LPG Tankers	Very Large	DWT	50000		17
RoRo Vessels	Very Small	GRT	1	5000	13.5
RoRo Vessels	Small	GRT	5000	20000	17
RoRo Vessels	Medium	GRT	20000	40000	20
RoRo Vessels	Large	GRT	40000		21
Tankers	Very Small	DWT	1	5000	11.5
Tankers	Small	DWT	5000	10000	13
Tankers	Handy	DWT	10000	60000	14.5
Tankers	Panamax	DWT	60000	80000	14.5
Tankers	Aframax	DWT	80000	120000	15
Tankers	Suezmax	DWT	120000	200000	15.5
Tankers	VLCC	DWT	200000	320000	15.5
Tankers	ULCC	DWT	320000		15.5

VESSEL CATEGORY	VESSEL SIZE	UNITS	FROM	TO	SPEED
Cruise	Small Cruise	GRT	1	10000	16
Cruise	Medium Cruise	GRT	10000	60000	20
Cruise	Large Cruise	GRT	60000	100000	22
Cruise	Panamax Cruise	GRT	100000		22.5
Passengers	Small	GRT	1	2000	22.5
Passengers	Medium	GRT	2000	10000	20
Passengers	Large	GRT	10000		21.5
Passengers & Cargo	Very Small	GRT	1	10000	18
Passengers & Cargo	Small	GRT	10000	60000	21.5
Passengers & Cargo	Medium	GRT	60000	100000	22.5
Passengers & Cargo	Large	GRT	100000		23.5
Yachts	undefined	GRT	1		15