LNG as a cost-effective and environmentally friendly solution for short-sea shipping

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Investment option analysis of the alternatives that shipowners have, to accommodate the already existing and upcoming regulations in North European ECA

Master Thesis

M.Sc. Economics and Business

Specialization: Urban, Port and Transport Economics (UPTE)

Erasmus University Rotterdam

Erasmus School of Economics (ESE)

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Acknowledgments

This Master Thesis brings my MSc studies at the Erasmus University of Rotterdam to an end. A lot of knowledge has been acquired during that time which helped me develop not only on a professional level, but on a personal level too. Urban, Port and Transport Economics is a very interesting field and highly relevant to anyone interested in contemporary global logistics.

I would like to thank my family for their continuous support during all the years of my studies, as without them I would have never been given the opportunity to accomplish what I have. Next, I would like to thank my friends for being who they are and helping me develop to the person I am today. Finally, I would like to thank my professor and supervisor Dr. Bart Kuipers, for all the valuable feedback and guidance that he provided with his experience and expertise on the researched subject.

Konstantinos Kokkinos,

Rotterdam, February 2018

Abstract

The objective of this thesis is to evaluate the use of LNG as a cost-effective and environmentally friendly solution for the ship-owners to accommodate the already existing and implemented regulations, as well as those upcoming, concerning the air emissions of the shipping industry. The method used to evaluate the economic feasibility of LNG and its most common alternatives, namely MGO and HFO, is the development of pricing scenarios for oil and natural gas and the calculation of the Net Present Value for each alternative. The input data were obtained from the literature and The Internet, when available, and other are based on own estimations and assumptions. This study concludes that LNG is not only a cleaner fuel than both HFO and MGO, but it is also the most cost-effective solution in most of the examined scenarios.

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Abbreviations

NO_x: Nitrogen Oxides

SO_x: Sulphur Oxides

PM: Particulate Matter

VOC: Volatile Organic Compounds

CO_2: Carbon dioxide

NMVOC: Non-Methane Volatile Organic Compounds

ECA: Emission Control Area

EEA: European Economic Area

EMEP: European Monitoring and Evaluation Programme

MEPC: Marine Environment Protection Committee

CFC: chlorofluorocarbons

HCFC: Hydrochlorofluorocarbons

UN: United Nations

LNG: Liquified Natural Gas

HFO: Heavy Fuel Oil

MGO: Marine Gasoil

GHG: Green House Gases

SCR: Selective Catalytic Reduction

EGR: Exhaust Gas Recirculation

EGCS: Exhaust Gas Cleaning System

IGC: International Code for the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk

IGF: International Code of Safety for Ships using Gases or other Low-flashpoint Fuels

SWTC: Standards of Training, Certification and Watchkeeping for Seafarers

MSC: Maritime Safety Committee

ISO: International Organization of Standardization

IRR: Internal Rate of Return

NPV: Net Present Value

Eq.: Equation

NBP: National Balancing Point

GTL: Gas-to-liquids

1. Introduction

This Master Thesis aims to evaluate LNG as a fuel for short-sea shipping in the North European Emission Control Area (ECA). ECAs are designated areas where specific, and regulated emissions limits apply. This evaluation will happen from the perspective of the ship-owners and will be examining two aspects. Namely, the economic feasibility and the environmental performance of LNG. Regarding the environmental performance, the Tier III emission limits will be the benchmark, as they are to be implemented in the near future, due to the emissions from ships becoming an increasingly important environmental concern. With regards to the economic feasibility, LNG will be compared to HFO and MGO, its two closest competitors. Both the capital and the operating costs will be considered, and the net present value will be used as the criterion for the most attractive investment option for the ship-owners.

This study starts out with an introductory chapter where the researched subject is introduced in detail, the scope of the research is defined, and the research question, along with the sub-questions, are presented. Furthermore, the necessary background concerning emissions and regulations is provided for the reader in order to create a clear overview of the situation. The second chapter is an introductory chapter as well and presents the approach that is used, and the main considerations that have been made to investigate and answer the research question. In addition, it explains the logic behind the selection of the used data and presents the sources where they were obtained from. The third chapter discusses what the available literature around this subject suggests. Specifically, on the one hand it examines in detail what LNG is and why it is relevant, while on the other hand discusses what the solutions alternative to LNG are, and how do they compare to LNG. In chapter four, the method, as well as the reasoning behind it, that is used to evaluate the economic feasibility of the LNG compared to the alternatives is explained. Scenarios for future prices of oil and natural gas are developed and the results are presented and analyzed. Finally, chapter five is the conclusion of the study.

1.1 Problem Definition

The growth in the world trade during the past decades has had a massive impact on the shipping industry ("Global shipping « World Ocean Review", 2010) as both global trade and consequently, global logistics are heavily relying on maritime transportation services.

Regarding the situation in European waters, European Environment Agency, (2013), estimates that in several areas the emissions from shipping can contribute up to 80 % in NO_x and SO_2 concentrations, up to 25 % in $PM_{2.5}$, up to 40 % in secondary Sulphur aerosol and up to 15 % in ozone (O_3). Thus, it becomes apparent that the sector’s impact on the environment is significant and regulatory bodies try to mitigate it by introducing contemporary regulations, enforcing this way more stringent limits for the industry’s emission levels. Consequently, stricter emission regulations pose a challenge for the shipping sector which needs to be addressed.

The objective of this thesis is to evaluate the use of LNG as a cost-effective and environmentally friendly solution for the ship-owners to accommodate the already existing and implemented regulations, as well as the upcoming regulations concerning the air emissions of the shipping industry. Although emission reduction is an important driver, the ship-owners should also take into consideration the viability of the business case when it comes to switching to LNG (PWC, 2013) as there are also other fuel alternatives which in combination with available abatement technologies could also be considered as viable investment options.

Thus, the question is whether the solution of investing in LNG, is a more attractive investment compared to the alternatives. This question is particularly relevant at this point as the Tier III controls for both the Baltic Sea and the North Sea will soon be put forward for adoption (“MEPC 70th session,” 2016). Consequently, LNG becomes a considerable option as main operating fuel for vessels that will be operating mainly or exclusively in this area. This is due to the potential of creating savings as a result of price differentials, even when considering a significant amount for such an investment.

The fact that this is a large topic which cannot be covered within the scope of an individual master thesis due to time and resource limitations is being acknowledged. Consequently, the aim is to contribute to this field by providing insight in one of the options that the ship-owners have to consider, when it comes to an investment decision, under the scope defined in the section further below.

1.2 Scope

The scope of this thesis will be limited to short sea operations. Arof, (2015), defines short sea shipping as “the movement of goods and people within coastal waters and inland waterways on routes that do not involve transit through oceans”; thus, shipping operations both inside and outside ECAs can be considered as short sea shipping.

However, due to the stricter regulations imposed as well as to the considerable volume of traded goods, the area of focus will be the European ECA as the combined share of the North Sea and the Baltic Sea, in terms of the total EU short sea shipping tonnages, was equal to 48 % in 2015 ("Maritime transport statistics - short sea shipping of goods - Statistics Explained", 2017). Since the area of focus will be an ECA, the types of engines that will be considered in this study will not include the dual-fuel engines. The reason behind this consideration is the assumption that the vessels will be operating exclusively inside the ECA and, as the literature argues, dual-fuel engines are mostly suitable for vessels which spend only a portion of their operating time in ECAs (Koers & Vaart B.V., 2015; Herbert Engineering Corp., 2015; International Maritime Organization, 2016), so that they can burn other fuels the rest of the time. Hence, according to the assumption made above, a gas engine will not have to switch to a different fuel mode. Thus, taking into account the capital investment and the operational expenses of such a solution is out of the scope of this study.

The types of reference vessels that will be examined are selected in such a way that will allow this study to capture the cases which constitute the majority of the short sea traffic in the

European ECA. According to EUROSTAT data, liquid bulk represents the 45 % of the total short sea shipping of goods to and from main EU ports in 2015 while dry bulk and containers are following with 20 % and 15 % respectively ("Maritime transport statistics - short sea shipping of goods - Statistics Explained", 2017).

At this point it is important to clarify that when referring to regulations, this study is considering those that have already been adopted as well as those that will enter into force in 2020 (Global Sulphur cap) and 2021 (Tier III control limits in European ECAs). Moreover, since the limit concerning the SO_x and PM emissions inside ECAs is stricter than that outside ECAs, ships compliant with the former, will also be in compliance with the latter.

1.3 Research Question

The topic of this study can be summarized in the form of the following main question:

“Is LNG as bunker fuel a cost-effective and environmentally friendly solution for short-sea shipping?”

In order to provide a sufficient answer to the research topic, the main question has been broken down to the following set of sub-questions:

- What is the relevance of the LNG as marine fuel?
- Which are the alternative solutions?
- How do these alternatives solutions perform environmentally, compared to LNG?
- What is the current status of LNG in Europe and which are the potential challenges?
- Under which pricing scenarios would the investment in LNG be cost-effective compared to the alternatives?

1.4 Background

1.4.1 Overview of ships' emissions

Although from a global point of view ships are not the prevalent source of air pollution, given that they follow trade routes which are close to shore not only they contribute to the global air pollution, but also to the degradation of air quality in coastal regions (Jarlsby, 2008; Viana et al., 2014). According to Eyring et al. (2010), as multiple studies point out, approximately 70% of emissions produced by deep-sea vessels occur within 400 km of land and as modelling and measurements of those emissions confirm, even if they are emitted at sea, they are transported in the atmosphere over several hundreds of kilometers and can still have negative effects not only on the air quality on land but also soils, rivers and lakes in those areas (Han, 2010). Jarlsby (2008), classifies the impact of the emissions from shipping in two broad categories. The first, concerns pollution with local and regional effects associated with the release of air pollutants from diesel engines such as Sulphur oxides (SO_x), Nitrogen oxides (NO_x), particulates (PM) and volatile organic compounds (VOC). The second, concerns the climate change matter and is mainly associated with emissions of Carbon dioxide (CO_2) and, to some degree, methane (CH_4) as well as certain other gases.

Carbon Dioxide (CO_2)

Carbon dioxide is a gas which is naturally released in the atmosphere. The unnatural release of carbon dioxide happens when fossil fuels are combusted in engines (Baumgart & Olsen, 2010) and is considered as a significant greenhouse gas. Like the rest of the transportation modes which burn fossil fuels, ships also produce carbon dioxide emissions (Harrould-Kolieb, 2008). CO_2 emissions from the shipping industry account for approximately 2.2% of the global anthropogenic CO_2 emissions (IMO, 2015), contributing this way to the global climate change. Contrary to other pollutants emitted from ships, CO_2 remains in the atmosphere and continues to have a warming effect for a long time after its release (Eyring et al., 2010). Moreover, carbon dioxide is a major cause of ocean acidification (Harrould-Kolieb, 2008) which has an impact on the marine environment and subsequently to humans.

Nitrogen Oxides (NO_x)

Nitrogen oxides are formed in the atmosphere during the combustion of fuels such as oil, gas and coal, especially in high temperatures. NO_x emissions from combustion are mainly in the form of NO and NO_2 (EPA, 1999), they depend on both the engine and the type of fuel, and in general they are higher for heavy oils than they are for distillates (Jarlsby, 2008). Nitrogen oxides have a negative impact on the environment as they cause ground level ozone, fine particle pollution, they contribute to acid rain and eutrophication, which is a major issue especially in the Baltic sea area and can also have adverse effects on the human respiratory system ("Basic Information about NO2 | US EPA", 2016). The shipping sector has a significant contribution to this type of emissions as it is the source of 15% of those anthropogenic emissions on a global scale (IMO, 2015). However, NO_x emissions are regulated in designated areas which are close to shore and technologies have been developed to tackle this type of emissions.

Sulphur Oxides (SO_x)

Sulphur oxides refer to several types of Sulphur and oxygen combinations such as SO_2, SO_3 and certain others. Sulphur oxides are produced naturally during volcanic activity while the major source of unnatural production is from burning fossil fuels in power plants. Smaller sources include ships, locomotives and non-road vehicles ("Sulfur Dioxide Basics | US EPA", 2016). Sulphur oxides are a major air pollutant causing both environmental and health problems (Svensson, 2011). SO_x emissions are directly related on the fuel Sulphur content (R. Verbeek, M. Verbeek, 2015) and can negatively impact the respiratory system and contribute to acid rain which not only can harm trees, plants and generally sensitive ecosystems but buildings, infrastructure and cultural objects such as statues and monuments as well ("Sulfur Dioxide Basics | US EPA", 2016). Similar to NO_x, SO_x emissions have a significant contribution on a global scale as the shipping industry is responsible for approximately 13% of those anthropogenic emissions (IMO, 2015). Thus, they are heavily/strongly regulated and the use of alternative fuels as well as technologies that have been developed can assist in their effective reduction.

Particulates (PM)

Particulates, particulate matter or particle pollution is the most directly perceived form of pollution (Jarlsby, 2008) and refer to a mixture of solid particles and liquid droplets found in the air. Particulate matter can be divided into primary and secondary particulates and the main difference is that primary particulates are emitted directly into the atmosphere, while secondary particulates form reactions with other pollutants (Baumgart & Olsen, 2010). Some particles are visible to the naked eye while some others can only be detected using special equipment ("Particulate Matter (PM) Basics | US EPA", 2016). PM emissions from shipping have a considerable local impact on air quality and as epidemiological studies have shown, ambient concentrations of particulate matter are linked with negative health impacts such as asthma, heart attacks, hospital admissions and premature mortality (Eyring et al., 2010). PM emissions are generated through the combustion of fuels in main engines, auxiliary engines and boilers of sea-going vessels and same as with NO_x emissions, they depend on the fuel and are in general higher for heavy oils than for distillates (Sax & Alexis, 2007). Thus, the most effective measure to reduce PM emissions from ships is to lower the Sulphur content in marine fuels (Eyring et al., 2010).

Volatile Organic Compounds (VOC)

According to EPA (2015), VOCs are a large group of organic chemicals which are of interest mainly because they contribute to ozone formation, they are associated with airborne particulate matter and are known to be harmful to human health. VOCs are emitted from a variety of sources; however, in the shipping industry VOC emissions are released during the loading, unloading and transportation of liquid cargo such as gasoline, other petroleum products, organic chemicals and crude oil (Rudd & Hill, 2001). This type of emissions is mainly relevant to tankers.

Ozone-Depleting Substances (ODS)

Defined as ODS are the chlorofluorocarbons (CFC), halons and the Hydrochlorofluorocarbons (HCFC). Although HCFCs were introduced as an intermediate replacement for CFCs, they are still classed as ODS and as part of a world-wide movement, the production and use of all these materials is being phased out under the provisions of the Montreal Protocol (Chopra, 2017). As the name of those emissions suggests, they have the potential to destroy the stratospheric ozone which protects humans, plants and animals from the sun's harmful radiation effects ("Ozone-depleting substances (ODS) – regulation 12," 2016).

When considering the situation in Northern Europe, which is also the focus of this study, the sector's environmental impact is considerable. As European Environment Agency (2013) mentions, based on the EMEP source-receptor data, emissions released in the North Sea area are contributing to the Sulphur deposition in countries such as Denmark and The Netherlands about 13% and 25% respectively as well as to the Nitrogen deposition in countries such as Belgium for 13%, Denmark The Netherlands and Norway for 17% while for Sweden and the UK for approximately 11%.

Figure 1 below, presents a rather clear view of the relative contribution of different European sea areas, to the deposition of oxidized Sulphur and oxidized Nitrogen in EEA countries in 2010.

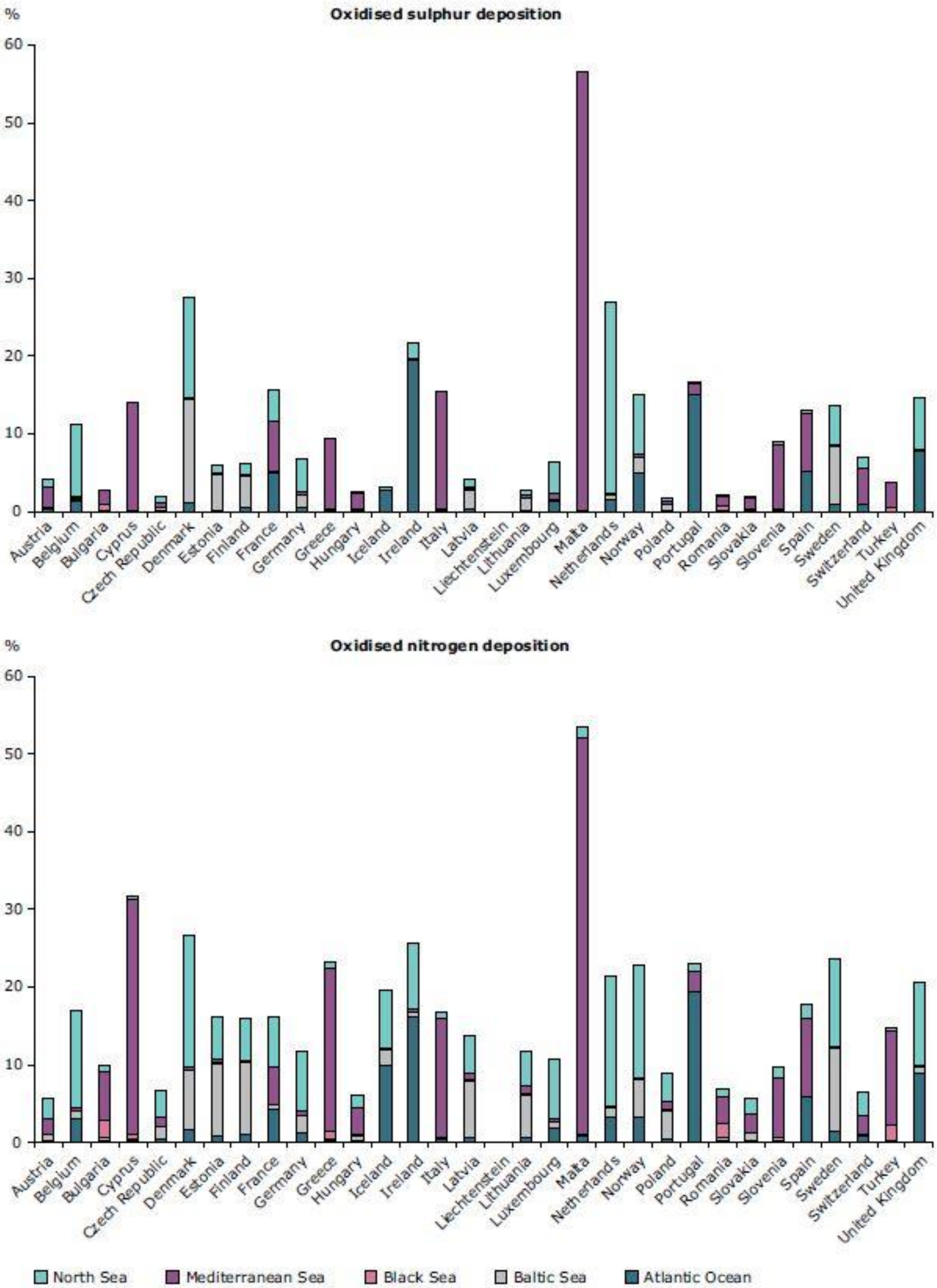


Figure 1. - The percentage contribution of emissions released from ships in various European seas to the national oxidized nitrogen and oxidized Sulphur deposition in EEA countries

Source: EEA, 2013

1.4.2 Regulations

Over the last century, the shipping industry and the maritime states have been progressively developing a regulatory system addressing all aspects of the shipping business (Stopford, 2008). Although shipping is more efficient and environmentally friendly compared to other modes of transportation, namely road transport and air freight, the local air pollution from the shipping traffic has attracted more attention the last decade, and the industry is facing an increasing number of rules and regulations as well as voluntary appeals from international, national and local legislators (Eyring et al., 2010). The reason for this, as explained previously in this study, is that emissions from ships' exhausts into the atmosphere can be harmful to the environment, to human health and can contribute to global warming of the planet.

The challenge in this situation is the international nature of the shipping industry and the fact that a supreme legislative body which can form a set of laws internationally applicable, does not exist. Instead, the regulatory system involves six principal participants in this process of making a set of international rules (Stopford, 2008):

- ***Classification societies:*** This is the shipping industry's own system for regulating the technical and operational standards of the vessels.

- ***The United Nations:*** This is the international organization which sets the broad framework of maritime law.

- ***Flag States:*** The state under which each ship is registered. Flag states have the responsibility of regulating every aspect of the commercial and operational performance of the registered ships. In addition, international laws are developed by the involvement of flag states in conventions or treaties.

- ***Coastal States:*** The state in whose waters a ship is trading. Ships are subject to the laws of the coastal states.

- ***International Maritime Organization (IMO):*** The UN agency responsible for the safety and security of shipping and the prevention of pollution by ships.
- ***International Labor Organization (ILO):*** Responsible for regulations governing crew on ships.

Although all six participants have an important role to play in the development of maritime regulations, this study is focusing in those regulations dealing with environmental issues and the air pollution emissions from ships. Thus, IMO is the most relevant actor.

The International Maritime Organization (IMO)

IMO (originally named Inter-Governmental Maritime Consultative Organization, or IMCO) is an agency of the UN which was formally established by an international convention in Geneva in 1948, became active in 1958, and currently groups 172 Member States and 3 Associate Members. IMO’s most important responsibility was, and remains, safety; however, a new problem emerged – pollution ("History of IMO", 2016). IMO’s main international convention regarding the prevention of pollution of the marine environment by ships from operational and accidental purposes is “The International Convention for the Prevention of Pollution from Ships”, known as MARPOL 73/78, which includes six Annexes (Han, 2010).

MARPOL 73/78 Annex VI

MARPOL Annex VI (entitled “Regulations for the Prevention of Air Pollution from Ships”), which was adopted in 1997 and entered into force in 2005, is the most important with regards to emissions to air. This Annex not only limits SO_x and NO_x emissions, interdicts deliberate emissions of ODS, regulates shipboard incineration and the emissions of VOC from tankers but it also defines certain sea areas as special with regards to the level of protection (Cullinane & Bergqvist, 2014; Han, 2010).

In addition, MARPOL Annex VI was revised by the Marine Environment Protection Committee (MEPC). The revised version was adopted in 2008 and entered into force in 2010 with the aim of further reducing the emission limits and introducing emission control areas (ECA) where stricter regulations would apply with regards to PM as well as SO_x and NO_x ("Air Pollution", 2016)

Emission Control Areas (ECA)

As mentioned above, there are certain sea areas which due to reasons such as traffic density, spatial characteristics and their ecological condition are defined as “special areas”. Under MARPOL, these areas, which were eventually named Emission Control Areas (ECA), are provided with a higher level of protection and require the adoption of special obligatory methods for the prevention of sea pollution (“Special areas under MARPOL,” 2016).

The established emission control areas designated under regulation 13 (NO_x emission control) and regulation 14 (SO_x and PM emission control) of MARPOL Annex VI are (“Sulphur oxides (SOx) – regulation 14,” 2016) :

- The Baltic Sea area as defined in MARPOL Annex I and where only SO_x emissions control applies;
- The North Sea area as defined in MARPOL Annex V and where SO_x emissions control applies;
- The North America area as defined in Appendix VII of MARPOL Annex VI and where PM, SO_x and NO_x emissions controls apply. This area entered into effect as of August 1st, 2012;
- The United States Caribbean Sea area as defined in Appendix VII of MARPOL Annex VI and where PM, SO_x and NO_x emissions controls apply. This area entered into effect as of January 1st, 2014.

The above mentioned ECAs are visible in Figure 2.

Figure 2. – Emission Control Areas

Source: DNV GL, 2014

Sulphur oxides (SO_x) – Regulation 14

SO_x and PM emission controls described by Regulation 14 apply to all fuel and combustion equipment, including main and auxiliary engines, as well as other devices onboard. The Sulphur emission is regulated by the amount of Sulphur contained in the fuel and is measured as percentage of weight. These controls separate between those applicable inside ECA and those outside such areas and are mainly achieved with the use of fuels with reduced maximum Sulphur content or other abatement technologies which will be analyzed later in this study. The regulation has been subject of gradual development through the years and in October 2016 it was decided that the global Sulphur cap of 0.50% m/m will come into effect on January 1st, 2020 ("Sulphur oxides (SOx) – regulation 14," 2016)

Outside an ECA established to limit SO_x and particulate matter emissions	Inside an ECA established to limit SO_x and particulate matter emissions
4.50% m/m prior to 1 January 2012	1.50% m/m prior to 1 July 2010
3.50% m/m on and after 1 January 2012	1.00% m/m on and after 1 July 2010
0.50% m/m on and after 1 January 2020	0.10% m/m on and after 1 January 2015

Table 1 – MARPOL Annex VI SO_x emission limits

Source: "Sulphur oxides (SOx) – regulation 14," 2016

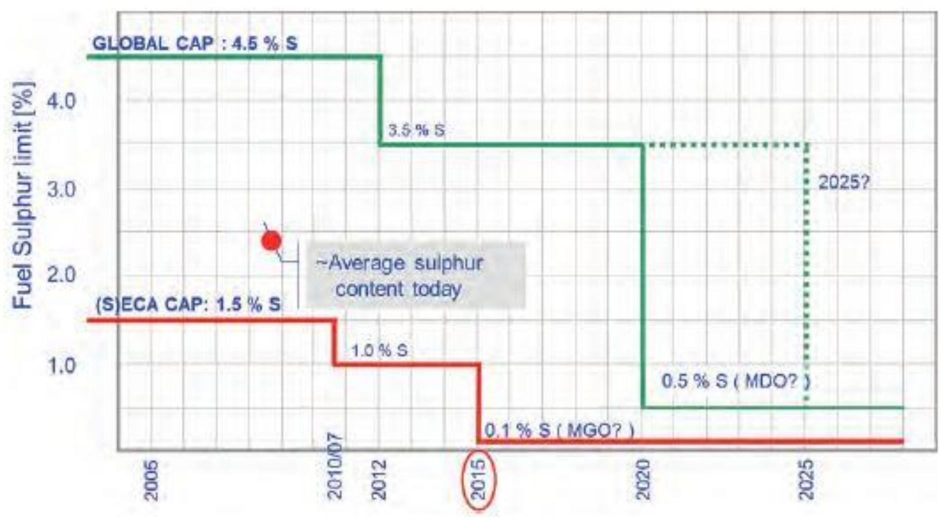


Figure 3. – MARPOL Annex VI SO_x emission limits

Source: International Maritime Organization, 2016

Nitrogen oxides (NO_x) – Regulation 13

The NO_x emission controls described by Regulation 13 apply to installed engines of over 130 kW output power other than those used exclusively for emergency purposes regardless of the tonnage of the ship. The nitrogen emission is described as total weighted cycle emission limit, and is dependent on the engine's rated speed which is categorized as a product of rounds per minute. The allowed NO_x emissions are decided in respect of the engine's rated speed by grams per kWh. Different levels of control apply based on the vessel's construction date and under each Tier the limit value depends on the engine's rated speed. The Tier III controls apply only inside nitrogen emission-controlled areas while outside those areas the Tier II controls apply ("Nitrogen oxides (NOx) – Regulation 13", 2016).

At this point it is important to mention that although the Tier III controls apply only within the North American and US Caribbean Sea ECAs, during the 71st session of MEPC in mid-2017, the draft amendments to formally designate both the Baltic Sea and the North Sea areas as NO_x ECAs under Regulation 13 will be put forward for adoption. Both areas will enter into effect on January 2021; thus, all vessels with marine diesel engines installed on or after January 1st of 2017 will have to comply with Tier III NO_x emission limits when operating within those areas ("MEPC 70th session," 2016).

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

Table 2 – MARPOL Annex VI NO_x emission limits

Source: "Sulphur oxides (SOx) – regulation 14," 2016

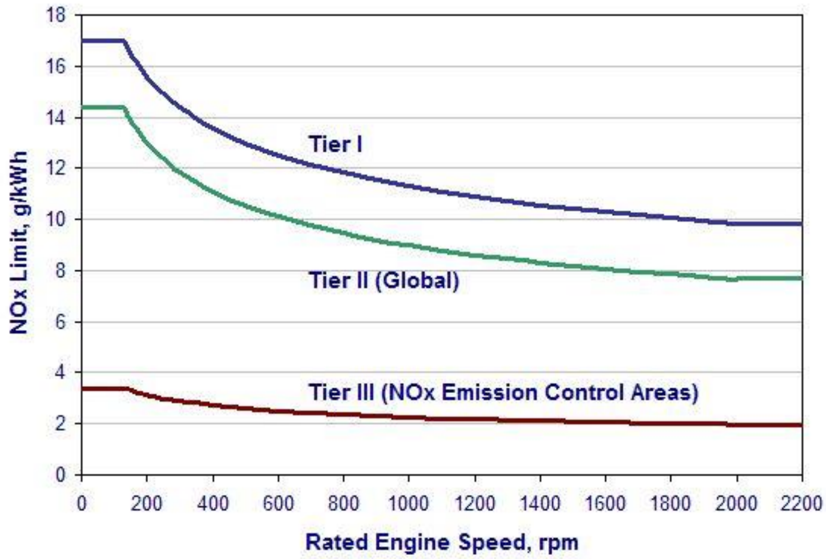


Figure 4. – MARPOL Annex VI NO_x emission limits

Source: International Maritime Organization, 2016

The above-mentioned regulations are relevant with regards to marine bunker fuel and provide a stimulus to considering LNG as a clean fuel for ships and as an alternative to the currently used bunker fuels, especially in consideration to short sea shipping.

2. Methodology

2.1 Research Approach

To answer the questions presented in the above section, this study will make use of collected data, scientific literature, general and industry reports, relevant thesis studies as well as news articles since this is an emerging topic and developments are ongoing.

Regarding the analysis, cases for new-builds only will be considered. The reasoning behind this is twofold. First, the literature argues that retrofitting a ship that it currently utilizes oil for propulsion is challenging from both a technical and an economical perspective (Koers & Vaart B.V., 2015; Wang & Notteboom, 2014**;** International Maritime Organization, 2016). Second, R. Verbeek, M. Verbeek (2015), define a retrofit system as “an engine originally produced as a diesel engine which is converted to LNG dual-fuel”. However, since the area of operations will be limited to the North European ECA, a dual-fuel solution does not seem attractive.

The alternative bunker fuels that will be considered in this study along with LNG will be Heavy Fuel Oil (HFO) and Marine Gasoil (MGO). The LNG bunker price will be estimated, and pricing scenarios will be developed. MGO will be used as the base case for comparison since it is the alternative for which the lowest amount of capital investments is required in order to be compliant with the Tier III control limits.

As far as the theoretical framework of the analysis is concerned, Net Present Value (NPV) analysis is the method that will be used to estimate the return on the investment, after accounting for the initial capital investment costs. With regards to the required input factors, many of them were acquired through publicly available studies and reports, others though are based on assumptions. Nonetheless, costs are not the single factor on which the ship owners’ decision will be based on (DNV GL, 2015) as the current situation in Northern Europe in terms of LNG bunker availability is also important and will be examined.

The investment costs of the infrastructure that is necessary to make the supply of bunker LNG available, are not considered in the analysis. The reasons behind this decision are several.

First of all, the focus is on the shipowners’ costs perspective and how they will accommodate the environmental regulations with regards to their operations. Suppliers of bunker fuel do not face this challenge. Although the infrastructure costs are considered a part of the whole picture, it is not costs that the shipowners will have to bear, at least directly.

Second, broadening the scope enough to include the suppliers’ perspective would require significantly more work as it would be necessary to examine costs on several steps of the downstream supply chain and for a combination of alternative paths that the gas could potentially follow. Following such an approach for a specific port could be possible given the data, but for a number of ports that are currently constructing, or have planned to construct, bunkering facilities would probably require so many assumptions that would degrade the value of the results.

Nevertheless, the costs of the infrastructure and supply are being accounted for, from the shipowners’ perspective, in the bunker price as it is the additional costs on top of the natural gas price. The value that is being considered (2 $/MMBtu) was provided by the literature. It is interesting that although this value was provided by some sources, one of those mentioned that this would be the cost of supply in a situation where the infrastructure would be already developed. Nonetheless, additional sources that would confirm that, were not found.

Third, it is already possible for vessels to bunker LNG in Norther Europe with the existing infrastructure that some ports have in place. Meaning, that LNG vessels could be built and operate with the current infrastructure. Assuming that since the supply chain for the provision of bunker LNG which is not currently fully developed would require higher costs for the supply of the fuel, increasing the costs of supply as part of the total bunker price, to partly account for this kind of investment costs that would carry-over to the customers (ship-owners), could represent these additional costs.

Though, this would require a sensitivity analysis or additional scenarios where instead of keeping the supply costs constant and adjusting the fuel prices, as has been done, calculations for different states of the infrastructure should be made, given specific fuel prices. For minor changes the results would be approximately the same, apart from the cases where the NPV of LNG is considerably close with the NPV of HFO. In such cases the results would be different.

An important assumption which could also be considered as one of the limitations of this study concerns the ship-owners' approach on the emission taxes. For reasons of simplicity it is assumed that the ship-owners are willing to make investments in order to be fully compliant with the upcoming regulations. Practically, this means that cases where they could decide to make investments on a lesser extent and compromise with paying emission taxes instead, on the base of achieving lower total costs, will not be taken into account.

2.2 Data

Since this study is trying to assess investment options, it becomes apparent that costs data are particularly relevant; especially since the capital investment and the net cash flow, which in this case translate to capital and operating costs, are required input factors for the calculation of NPV for the different scenarios.

The sources where those data could be obtained from are either direct contact with engine manufacturers, the Internet, or available literature, including industry and associated organizations' reports. Since there is no available contact in an engine manufacturing company and despite the considerable effort that was put in searching the Internet with no fruitful results, literature is the preferred source mainly due to availability reasons.

Although the majority of the literature around this subject would not get into extensive details regarding costs, generic cost data could be found in a number of cases. Good examples are Jarlsby, 2008; Germanischer Loyd, 2013**;** Nielsen, & Schack, 2012; Herbert Engineering Corp., 2015; Jiang, Kronbak & Christensen, 2014; Faber et al., 2015; MEPC, 2016. Though, the problem with the majority of the sources was that they would usually focus on very specific cases, which sometimes could also represent a part of the initial investment or an operational aspect, for which they would provide rough estimates of costs. That kind of data were not found particularly useful in terms of calculations in a broader scope, as they could not be combined; mainly, due to differences in geographical markets, periods of reference or vessel types and sizes.

Nonetheless, the report from the *North European LNG Infrastructure Project,* commissioned by the Danish Maritime Authority (DMA), provided estimates of specific cost data[1] regarding the investment alternatives. Those data are based on the input of the engine manufacturing companies MAN Diesel & Turbo and Wartsila and can be considered as adequate for the scope of this study in terms of variety and detail. Not only they include estimates of an assortment of different alternatives, including those under examination, but they are also focused on short-sea types of vessels. In addition, it is interesting that this dataset provides costs estimates as a function of the engine power. This aspect is particularly relevant to this study, since more than one reference vessels are examined, as it allows for a higher level of accuracy in terms of cost calculations. A shortcoming, which can also be considered as one of the important limitations of this study, is the fact that this report was published in 2012. In order to tackle this issue, the data of 2012 are corrected for inflation with an adjustment ratio of 0.956[2].

As far as operating costs are concerned, the *North European LNG Infrastructure Project* report provided estimates regarding the costs of each abatement technology alternative as well. However, the operating costs will be heavily depended on the fuel prices as the maintenance costs for the different fuel options are considered to be comparable (The Danish Maritime Authority, 2011; Jónsdóttir, 2013). The fuel prices data were obtained from "Rotterdam Bunker Prices", (2017a, 2017b) and "CO1 Commodity Quote - Generic 1st 'CO' Future", (2017).

[1] Capital costs are a function of the main and auxiliary engine power (€ / kW) while the operational costs are a function of the main engine power and the operating hours per year (€ / kWh).
[2] Appendix 1

3. Literature review

After examining the regulations regarding the air emissions from the shipping industry, it becomes apparent that the situation has changed, and more changes are yet to come in the near future. The requirements regarding the emission control limits dictate a shift in the way that ships used to operate until now with regards to bunker fuels and air emissions abatement technologies. Nevertheless, numerous publications have been providing solutions that could be adopted by the ship-owners in order to be compliant with the current and upcoming regulations.

With regards to the fuel alternatives that could be used in the ECA's, the majority of the available literature (Lindstad, Eskeland, Psaraftis, Sandaas & Strømman, 2015; Nielsen, & Schack, 2012; Germanischer Loyd, 2013; Brynolf, Magnusson, Fridell & Andersson, 2014; Bengtsson, Andersson & Fridell, 2011; Trafikanalys, 2016; Jiang, Kronbak & Christensen, 2014 among others) is converging towards MGO and HFO, with the addition of abatement technologies, or LNG. Specifically, in order to accommodate the current regulations for the European ECA, which covers the limits of the upcoming Global Sulphur Cap as well, Jiang, Kronbak & Christensen (2014), are referring to:

1. High Sulphur fuel oil along with Sulphur scrubbers' installation
2. Switch to marine gas oil (MGO)
3. Alternative fuels, which in our case is LNG

While for compliance with the IMO NO_x Tier III limits, (MEPC, 2016**;** "Upcoming environmental regulations for emissions to air – IMO NOx Tier III - DNV GL", 2015) are referring to:

1. Selective catalytic reduction (SCR) systems
2. Exhaust gas recirculation (EGR)
3. Alternative Fuels, which in our case is LNG

3.1 HFO and Sulphur Scrubbers

Heavy fuel oils is a generic term which along with a number of other names is used to delineate an array of products based on the residues from various refinery conversion and distillation processes (Hombravella, Kılıçaslan, Péralès & Rüß, 2011). The quality among different types of heavy fuel oils varies, and viscosity is one of the main characteristics that differentiates one from another. With regards to marine applications, IFO 180 and IFO 380 (Intermediate Fuel Oil) are the most common heavy fuel oils (Trafikanalys, 2016). Technically though, those fuels are a blend of residual and distillate fuels (The Danish Maritime Authority, 2011).

HFO has an average Sulphur content of 2.5 % and is used by the majority of the diesel fueled engines (Brynolf, Magnusson, Fridell & Andersson, 2014; International Maritime Organization, 2016). Apart from the high-Sulphur HFO though, there is also HFO with less than 1 % Sulphur content, known as low-Sulphur heavy fuel oil (LSHFO), which could be either the result of desulphurization during the refinement process or, in some cases, product of low-Sulphur crude oil (Trafikanalys, 2016). To be able and use HFO with high Sulphur content (or more than 0.1 %) while operating inside an ECA the use of abatement technologies is required. Specifically, Sulphur scrubbers (Jiang, Kronbak & Christensen, 2014), which clear away the Sulphur from the exhaust by utilizing water (Trafikanalys, 2016).

There are two different types of scrubber; the wet and the dry scrubber. According to Hombravella, Kılıçaslan, Péralès & Rüß (2011), the dry scrubber, contrary to the wet scrubber, does not use seawater during the exhaust gas cleaning process but chemicals instead. On the other hand, the wet scrubber can be open loop where seawater is used and returned to the sea, closed loop where fresh water with chemicals is used in a closed system, or hybrid that works in both modes, open loop for open sea and closed loop for ports and ECA's. Regardless the mode though, there is waste produced which need to be left in ports (Trafikanalys, 2016). It is important to mention that in areas, such as the Baltic sea, where the waters could be considered sensitive, the closed loop scrubbing solution might be necessary from an environmental perspective as in that case the amount of acidic scrubber water released in the environment is less

(Brynolf, Magnusson, Fridell & Andersson, 2014). Although scrubbers can achieve Sulphur emissions reduction of 98 %, the installation costs can be significant (Jiang, Kronbak & Christensen, 2014) and additional operational expenses occur as well (The Danish Maritime Authority, 2012; Hombravella, Kılıçaslan, Péralès & Rüß, 2011).

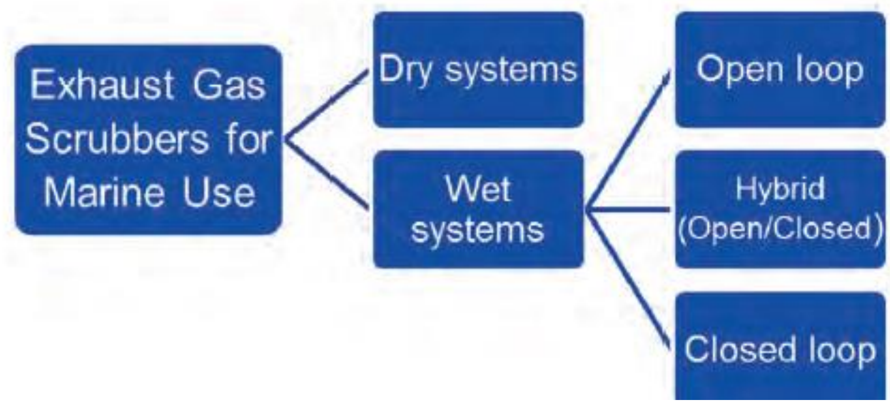


Figure 5. – Exhaust gas scrubber classification

Source: International Maritime Organization, 2016

3.2 MGO

As mentioned above, another compliance solution regarding the emission regulations as of 2015 is switching from HFO to a low Sulphur fuel such as marine gasoil (MGO) with a Sulphur content of 0.1 %. Contrary to HFO which is a residual fuel, MGO is a distillate fuel, meaning light, refined diesel fuel with a Sulphur content lower than 0.5 % (International Maritime Organization, 2016).

Regarding the decision to switch from HFO, a big benefit of MGO is the fact that none or slight investments and modifications are required to the main engine in order to be able to use it as main fuel. Most of the ships that are currently running on HFO, do not need retrofitting to be capable of burning MGO as well (Jiang, Kronbak & Christensen, 2014). Infrastructure for the bunkering of those fuels is the same as well (Bengtsson, Fridell & Andersson, 2013).

However, due to the lower viscosity of MGO compared to HFO, not only the installation of a fuel cooler system is required in order to chill the fuel and increase its viscosity to an acceptable level, but attention should be paid to the quality of lubricant oils as well. Nevertheless, the cost for such a modification is considered imperceptible (Nielsen & Schack, 2012). On the downside though, MGO is significantly more expensive than HFO.

Shipowners that will use MGO as fuel will be able to meet the required SO_x emission levels but NO_x levels will remain the same as with the use of HFO. In order to comply with the Tier III emission levels, the use of additional abatement technologies is required.

3.3 Selective Catalytic Reduction (SCR) systems

According to Brynolf, Magnusson, Fridell & Andersson (2014), Selective Catalytic Reduction (SCR) is the process of transforming the damaging NOx emissions into innoxious nitrogen gas (N2) and water, through a catalytic reaction which takes place over a base metal catalyst with the use of a reductant. Apart from the catalyst though, a SCR system consists of a reactor tank, a pump and a system which controls the dosage of the reduction agent as well (Kristensen, 2012).

Although there are two main types of SCR systems which are classified by the reductant used, ammonia-SCR and hydrocarbon-SCR, this study will not touch upon hydrocarbon-SCR systems as they are not able to perform on the same level that ammonia-SCR systems do (Hombravella, Kılıçaslan, Péralès & Rüß, 2011). For ammonia-SCR systems, the reducing agents that could be used are anhydrous ammonia, aqueous ammonia or urea (Hombravella, Kılıçaslan, Péralès & Rüß, 2011) with the latter being the most common despite the risk of ammonia emissions (ammonia slip), for which additional equipment such as oxidation catalysts might be added in some cases (Brynolf, Magnusson, Fridell & Andersson, 2014).

SCR systems have a high level of flexibility regarding the potential of cases where then can be used. This is particularly relevant regarding retrofit solutions, though the space required for the installation could be a challenge for already existing ships (Wang & Notteboom, 2014). As

Azzara, Rutherford & Wang (2014) point out, SCR systems have been used on existing engines not only from a variety of manufacturers but also on engines and boilers that burn a variety of fuels, either high-Sulphur residual fuel or low-Sulphur distillate fuel, including HFO and MGO on an equal share. Moreover, although most of the SCR applications have been on four-stroke engines, two-stroke engines are compatible as well with no limitations regarding the types of vessels (Kristensen, 2012).

Contemporary SCR systems are capable of reducing NO_x emissions by more than 90 % with slight or no fuel efficiency penalty (Azzara, Rutherford & Wang, 2014) but they are usually set up to operate slightly under the maximum capacity in order to mitigate the risk of the ammonia slip (Kristensen, 2012). Due to the performance of this technology and given the fact that it has already been applied on numerous vessels and have been proven satisfactory with regards to the Tier III emission limits (Brynolf, Magnusson, Fridell & Andersson, 2014), an array of countries and regulatory authorities have acknowledged it as one of the most promising abatement technologies regarding the control of NO_x emissions (Kristensen, 2012). Nevertheless, effectively combining the scrubber with the SCR technology is a method that is not yet fully optimized (Koers & Vaart B.V., 2015).

3.4 Exhaust gas recirculation (EGR)

Same as with SCR, Exhaust Gas Recirculation (EGR) is another abatement technology for complying with the Tier III NO_x emission limits. As far as marine applications are concerned, this technology is relatively new compared to SCR ("Upcoming environmental regulations for emissions to air – IMO NOx Tier III - DNV GL", 2015) and is mainly available for two-stroke engines (MEPC, 2016). Compared to SCR, the EGR method has a higher level of compatibility with exhaust gas cleaning systems (EGCS), such as a Sulphur scrubber, (Faber, 2016).

EGR is a technology integrated on the engine which limits the NO_x emissions by decreasing the combustion temperature (International Maritime Organization, 2016). As Kristensen (2012) explains, part of the exhaust gas is redirected from the exhaust gas receiver to a wet scrubber and then through a cooler and mist catcher to the EGR blower. The EGR blower lifts the pressure to the scavenge air pressure with the effect of replacing a minor part of the oxygen with CO_2. In some cases, EGR will drive the fuel consumption up as it leads to an increased level of specific fuel oil consumption, known as SFOC penalty.

The information for marine applications of EGR are not as abundant as for the other compliance options. Nevertheless, this technology is proven to successfully meet the Tier III requirements (Kristensen, 2012) and although new, is developing into a competitive option ("Upcoming environmental regulations for emissions to air – IMO NOx Tier III - DNV GL", 2015).

3.5 Liquified Natural Gas (LNG)

3.5.1 Natural gas and LNG

LNG, which is examined as the alternative fuel of choice in this study, is natural gas in its liquid form. Natural gas is produced by extracting, processing and eventually refining fossil gas (R. Verbeek, M. Verbeek, 2015). Compared to oil which is also a fossil fuel, the reserves of natural gas are larger and more widely spread (Jarlsby**, 2008;** PWC, 2013). In addition, they have shown a growing trend due to, among other factors, the development of extraction technologies which provide access to resources of which no productive use was being made before (Burel, Taccani & Zuliani, 2013). Its liquid form is obtained by cooling it down to approximately -162 °C, a process during which specific components of the gas, such as water, dust and acid gases, are removed (R. Verbeek, M. Verbeek, 2015).

The reasons why natural gas is liquified are storage and transportation as in its gaseous form, as opposed to its liquid form, its energy content is relatively low (PWC, 2013). This practically means that in order to transport a specific amount of energy from point A to point B, the volume required for natural gas is larger than the volume required for LNG, specifically 600:1.

Compared to diesel oil, LNG has almost two times its volume (Wang & Notteboom, 2014). At this point it is important to mention that before LNG can be used as fuel it needs to return to its gaseous state and on the appropriate pressure and temperature (Koers & Vaart B.V., 2015).

3.5.2 LNG as marine fuel

LNG has methane (CH_4) as its primary component and none of the rest of its components are either toxic or extremely polluting. In addition, its molecular structure which is simpler compared to other fuels, such as diesel oil, gives LNG the advantage of producing less CO_2 emissions when combusted (Jarlsby**, 2008**). NO_x emissions decrease considerably to a level below the Tier III limits eliminating the necessity of abatement technologies (International Maritime Organization, 2016). That, in combination with the fact that it does not contain Sulfur, meaning the SO_x and PM emissions are negligible, makes LNG a fuel cleaner than the alternatives examined in this study (Burel, Taccani & Zuliani, 2013). However, methane, a green-house gas (GHG) which tends to sustain considerable amounts of heat in the atmosphere, has relatively high emissions with regards to gas engines (methane slip); thus, considerable reductions on GHG emissions cannot be realized. Nevertheless, major engine manufacturers are able to accomplish GHG emission levels equal or better than those of the respective diesel engines (R. Verbeek, M. Verbeek, 2015). The emission factors for the three different fuel options can be seen in Table 3, below.

	HFO		MGO		LNG	
	Baseline	Changes with scrubbers	Baseline	Changes with SCR	Wartsila data	US EPA data
Sulphur content in the fuel (wt%)	1		0.1		≈ 0	
Emission factors (g / MJ)						
CO_2	78		74		57	
CO	0.13		0.13		0.28	0.24
CH_4	0.0005		0.0005		0.28	0.56
NO_x	1.6		1.5	0.23	0.17	0.36
NMVOC	0.06		0.06		-	0.1
N_2O	0.004		0.004		-	-
NH_3	0.0003		0.0003	0.00029	-	-
PM10	0.093	0.071	0.034		0.009	0.004
SO_2	0.5	0.05	0.05		0	0

Table 3 – Emission factors (g / MJ)

Source: Bengtsson, Andersson & Fridell (2011)

To utilize LNG as bunker fuel, a vessel should be able to operate on LNG, meaning that an LNG compatible engine and a cryogenic tank are required (PWC, 2013). The types of tanks defined by the IGC code are independent tanks (Type A, Type B, Type C) and membrane tanks with full secondary barrier. Nonetheless, those that are currently being used by all the LNG-powered vessels are cylindrical shaped, vacuum insulated, Type C tanks (International Maritime Organization, 2016). A drawback of those tanks is their sizeable dimensions which result in loss of cargo space, though, the amount of space lost depends on the type of the ship. Although for dry bulk and container vessels it could be up to 5 %, for liquid bulk vessels is negligible, even zero (R. Verbeek, M. Verbeek, 2015). The investment costs required are significant and represent a major fraction of the total investment costs of an LNG system. Nevertheless, Type C tanks are considered as the best option from a technical perspective and can be placed either on, or below the deck (Koers & Vaart B.V., 2015).

As far as the engines are concerned, major engine manufacturers such as Wartsila, Rolls Royce, Caterpillar and MAN have already developed and now provide both pure gas engines as well as two-stroke and four-stroke dual-fuel engines (DNV GL, 2015). R. Verbeek, M. Verbeek (2015), separate the engine technologies in two categories. The first, is the single fuel, spark ignition

(Otto cycle) engines which can accomplish emission levels below the Tier III limits without any use of abatement technologies. The power output of those engines ranges between 500 kW and 10,000 kW and the ignition source used is either an electric spark or pilot oil (International Maritime Organization, 2016). An acknowledged issue of gas engines is the methane slip, which is basically unburnt fuel, released into the atmosphere during combustion; though, according to DNV GL (2015), “it has been practically eliminated in modern two-stroke engines, and further reductions should be expected from four-stroke engines”. The second category is the dual fuel, compression ignition engines which can operate on both diesel and gas mode. Contemporary engines are capable of seamlessly switching from one mode to another, without any kind of operational interruption (International Maritime Organization, 2016). When operating on gas mode, a small quantity of diesel is still required to ignite the gas. Regarding the ECA regulations, these engines require the use of after-treatment technologies in order to achieve emission levels below the Tier III limits (R. Verbeek, M. Verbeek, 2015).

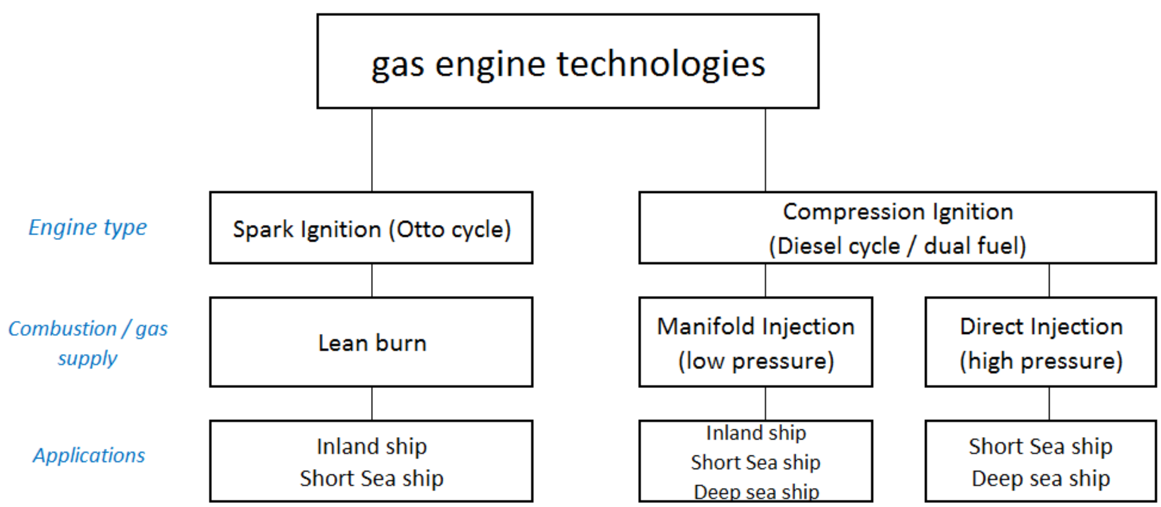


Figure 6. – Currently applied gas engine technology

Source: R. Verbeek, M. Verbeek, 2015

LNG as marine fuel is not new. It has been used for many years with excellent safety records by LNG carriers that utilized the boil-off gas as fuel for combustion, setting this way the foundation for the development of standards and guidelines concerning the use of LNG as fuel for combustion, on a broader range (International Maritime Organization, 2016). Besides LNG carriers, it is also being used by LNG-fueled vessels in Norway since the last decade, holding excellent safety records as well (Wang & Notteboom, 2014). With regards to the profile of the vessels that can be considered as most suitable for the adoption of LNG, the literature converges towards ship segments which spend a considerable amount of their operational time inside ECA's and operate mainly on short and fixed routes (Burel, Taccani & Zuliani, 2013; Koers & Vaart B.V., 2015; International Maritime Organization, 2016; Wang & Notteboom, 2014). Good examples are container and RoRo vessels as well as small and medium-sized tankers and bulk carriers.

3.5.3 LNG supply chain

There are several potential courses for LNG to follow on its way from the production of natural gas to the tanks on board a vessel (International Maritime Organization, 2016). Although Europe's demand for gas had always been met by domestic production and pipeline imports from countries such as Russia, over the last thirty years, roughly, a portion of this demand has been covered by imports of LNG from regions such as North Africa, Middle East and Australasia (PWC, 2013). Currently, around 77 % of the demand for LNG imports in EU is covered by Qatar, Algeria and Nigeria (Faber et al., 2015). The LNG supply chain includes all the intermediate stages that LNG goes through, from the extraction of natural gas to the consumption of LNG by the end users. Though, the whole process could be broken down into two distinct stages; the upstream supply chain and the downstream supply chain (The Danish Maritime Authority, 2012).

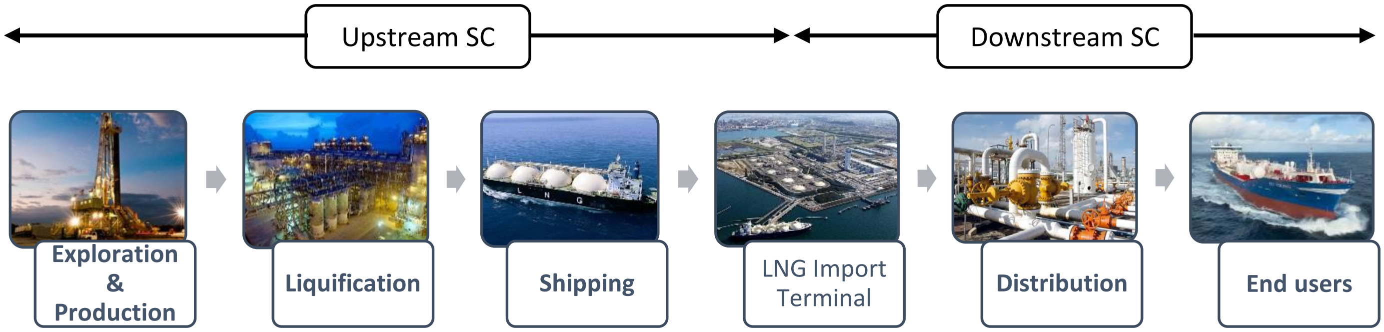


Figure 7. – LNG supply chain

Source: The Danish Maritime Authority, 2012

3.5.3.1 Up-stream LNG supply chain

The upstream phase includes exploration and production, liquification and shipping to large LNG import terminals. Exploration and production begins with the identification of potential gas reservoirs and extends to the extraction and further processing of the gas (The Danish Maritime Authority, 2011). Due to the requirements that natural gas needs to meet before entering the pipeline systems, during its production it is being cleansed from contaminants such as water and carbon dioxide, among other gases and liquids (Jarlsby**,** 2008). Next, gas moves to the liquification facilities, via pipelines, where is being further processed and have more of its components removed. This way the gas becomes compatible with the very low temperature required for the liquification, without risking freezing and causing damage to the equipment (The Danish Maritime Authority, 2011). After its liquification, LNG is being stored and eventually loaded on LNG carriers so that it can be shipped from remote production locations to large LNG import terminals that supply major markets, not accessible via pipeline systems (Jarlsby, 2008).

3.5.3.2 Down-stream LNG supply chain

The downstream supply chain is the part that this study is mostly interested in since the focus is on the use of LNG as marine fuel. The large-scale infrastructure is set to receive large shipments of LNG which after regasification is distributed to industries and households, via the pipeline network. Although supplying end users such as the marine transport sector is still possible, the large-scale infrastructure is not optimized to meet the needs of a different segment of customers who require LNG instead of natural gas. (Jarlsby**, 2008**). In order to facilitate end users who desire to utilize LNG as bunker fuel, small - and medium-scale infrastructure needs to be developed which will act as an intermediate node between the large import terminals and the LNG-fueled vessels (Koers & Vaart B.V., 2015).

The literature (indicatively, PWC, 2013; Koers & Vaart B.V., 2015; Jarlsby, 2008; The Danish Maritime Authority, 2011; LNG in Baltic Sea Ports, 2016; International Maritime Organization, 2016) refers to this part of the LNG value chain as small-scale LNG. PWC (2013), presents small-scale LNG as a new market which acts as a link between the established natural gas chain and the transport market. In countries which do not have local natural gas production, small-scale infrastructure enables the distribution of the large import shipments of LNG in close distance. On the contrary, in countries where natural gas is extracted and produced locally, LNG is produced on a small-scale so that it can be distributed directly (Jarlsby, 2008). This process is also illustrated in Figure 8.

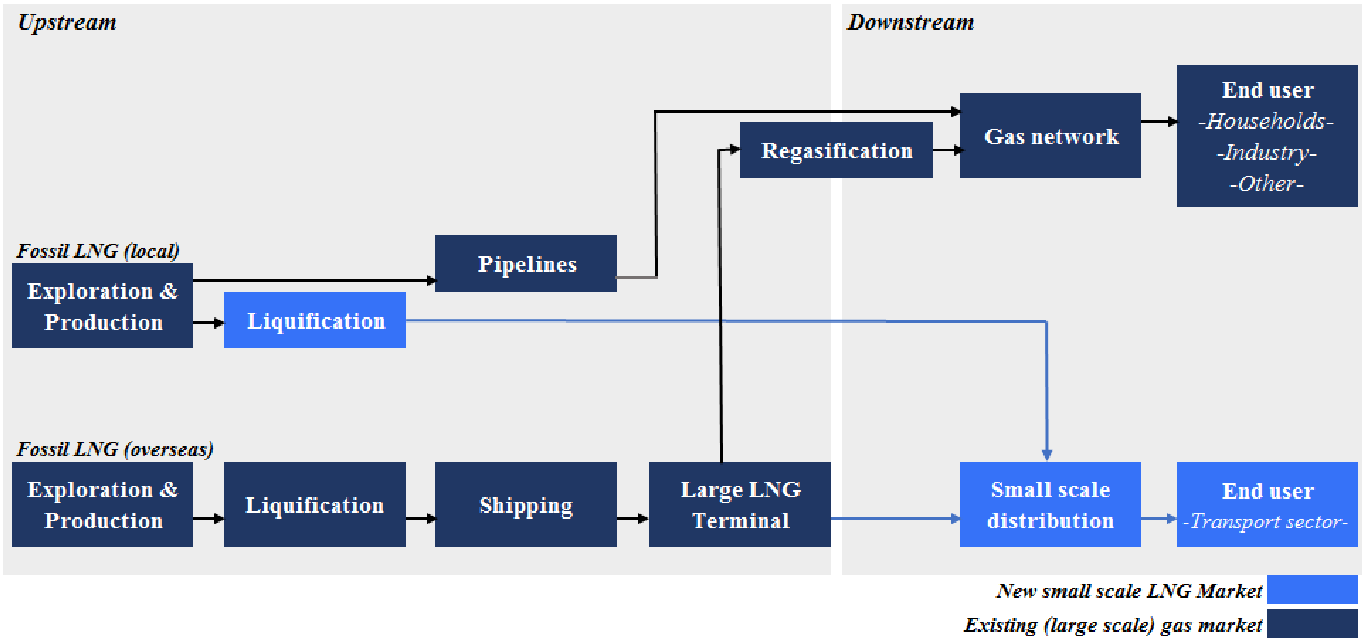


Figure 8. – LNG value chain

Source: PWC, 2013

In cases where the distance between the LNG import terminals and the end users is not economically efficient for feeder vessels and trucks to cover (The Danish Maritime Authority, 2012), the infrastructure for small scale LNG distribution needs to be developed. This includes a medium-scale terminal (also known as break-bulk terminal) with quays and truck loading facilities, apt to accommodate the bunker vessels and the LNG tank trucks which will be supplying the ultimate consumers (PWC, 2013; Koers & Vaart B.V., 2015), the LNG fueled vessels. According to the International Maritime Organization (2016), the preferred bunkering method will depend on a combination of factors, others more generic, such as regulations and local conditions, and others more vessel-specific, such as the type of the ship and the capacity of its onboard LNG tank. Nonetheless, the most common methods of bunkering those vessels are the following:

- ***Truck to Ship bunkering (TTS):*** Although this method is the slowest compared to the alternatives, it is the one that provides the greater level of flexibility. The LNG tank truck is parked on the quay, next to the ship, and the bunkering can be performed with the use of a flexible hose (Jarlsby, 2008). In cases where large quantities of LNG are required, TTS bunkering is not the most efficient solution (Wang & Notteboom, 2014).

- ***Ship to Ship bunkering (STS):*** During STS bunkering, a feeder vessel approaches and connects to the ship which needs to be refueled. This is an operation that can be performed not only while at anchor or while loading and unloading of cargo, which is also the most efficient method for short-sea vessels, but also while sailing (PWC, 2013). However, the feasibility of the latter, is heavily depended on the weather conditions. STS bunkering offers a high level of flexibility as well, but it is efficient for quantities larger than a minimum limit (The Danish Maritime Authority, 2012).
- ***Shore tank to Ship, via pipeline bunkering (TPS):*** During TPS bunkering, the ship is being bunkered from a shore tank via pipeline connection. Accessibility of the berth as well as the distance between the tank and the vessel are critical aspects when considering this option. This method is ideal for cases which require large volumes and short bunkering times, but it is not without its limitations (The Danish Maritime Authority, 2012). Not only the bunkering operations need to take place on a fixed location, but sufficient space for the shore tanks, which need to be located in close distance from the quays, is required as well (Jarlsby, 2008).

In addition to the bunkering methods described above, there is also the option of the LNG tank containers. Technically, container-sized LNG tanks mounted in frames so that can be delivered on the ships (International Maritime Organization, 2016).

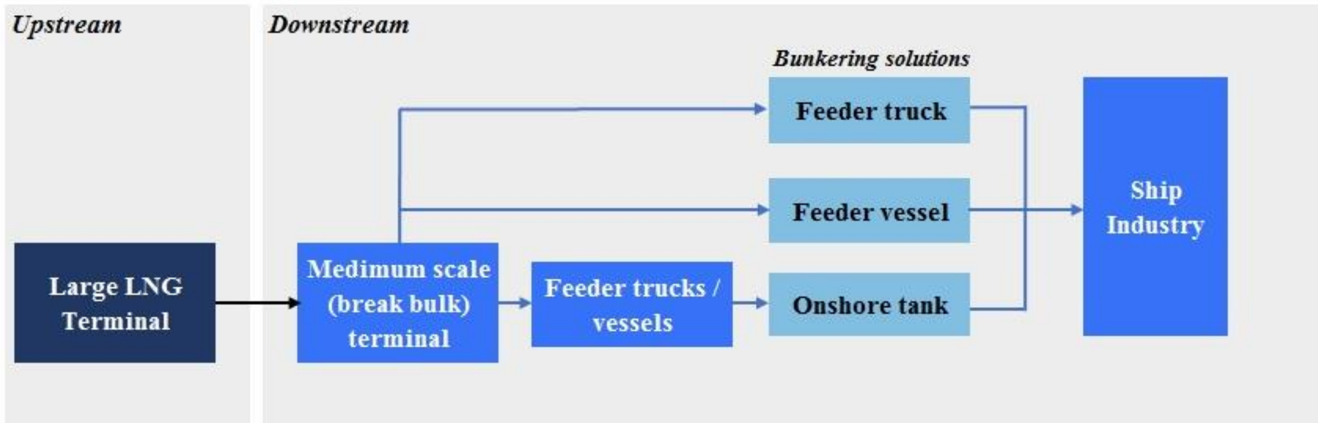


Figure 9. – Small scale LNG Infrastructure

Source: PWC, 2013

3.5.4 Current state and challenges

After taking a closer look at the downstream part of the LNG supply chain, it becomes apparent that operating on LNG is not only a matter of investing on vessels with gas engines. The availability as well as the cost of the infrastructure required to distribute the fuel on a small scale, is also an important factor to consider with regards to the development of LNG as ships' fuel in North Europe (LNG in Baltic Sea Ports, 2016).

The considerations regarding the infrastructure, combined with the significant investment that shipowners need to make, lead to what is often being referred to, in the literature, as the chicken-egg problem. Particularly, the reluctance of the bunker suppliers to invest in infrastructure for the production, storage, distribution and bunkering of LNG until there is sufficient demand, on the one hand; and on the other hand, the hesitation of the shipowners to invest in building LNG fueled vessels until LNG bunkers are available and accessible (Wang & Notteboom, 2014; Faber et al., 2015; PWC, 2013; The Danish Maritime Authority, 2012). Nonetheless, PWC (2013), expects that the chicken-egg problem will be solved due to the numerous initiatives that are being taken the last few years.

With regards to the demand perspective of the chicken-egg paradigm, DNV GL (2015), reports that as of May 2015 the number of the operational LNG fueled vessels, excluding LNG carriers and inland vessels, was equal to sixty-three (63), with 92 % of those operating in Norway and Europe. At the same time, the confirmed orders for LNG fueled vessels up until 2018 were equal to seventy-six (76), 61 % of which are orders for Norway and Europe. More recently, Ziegenfuss (2016), mentions that in 2016 there were sixty-nine (69) LNG ships operating in Europe and sixty (60) more had been ordered until 2019, advocating that it is those early steps that will start shifting the chicken-egg paradigm.

As far as the supply availability perspective is concerned, LNG bunkering for maritime operations is currently available in several North European ports. Namely,

- Rotterdam, The Netherlands
- Amsterdam, The Netherlands
- Moerdijk, The Netherlands
- Antwerp, Belgium
- Brunsbuttel, Germany
- Zeebrugge, Germany
- Stockholm, Denmark

with some of them having already developed infrastructure while for others, more permanent facilities being under construction. In addition to those ports, small-scale distribution and bunkering is also available in a number of ports in Norway (GIE, 2015). According to a more recent source, LNG bunkering for ships with capacity less than 30,000 m^3 is also available in Dunkerque, France and at the port of Klaipeda, Lithuania (GIE, 2017).

Besides the already existing as well as under construction infrastructure, the Connecting Europe Facility (CEF) synergy has recently approved the requests for subsidies for several small-scale LNG projects across Europe, which will further strengthen the efficiency and the sustainability of the transport infrastructure ("EU Approves New Funding in Support of LNG Bunkering Projects", 2017). Moreover, EU legislation is also driving the development of the small-scale

LNG by compelling Member States to establish LNG refueling sites, such as LNG terminals and bunker vessels and barges among others, at maritime and inland ports across the core network, by the end of 2025 and 2030 respectively (DIRECTIVE 2014/94/EU OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 22 October 2014, 2014, pp. 1-20).

Another important aspect of using LNG as fuel for maritime operations is the regulatory regime around bunkering and sailing, as it is one of the essential elements that will facilitate the growth of LNG as bunker fuel, since safety is an essential consideration for all the involved parties (International Maritime Organization, 2016). Until recently, there were no international regulations addressing those perspectives. Besides the cases of the LNG tankers which make use the boil-off gas as fuel and which were being recognized by the IGC code, LNG was not officially considered as fuel for other types of vessels (Wang & Notteboom, 2014).

However, as of 1st of January 2017 the International Code of Safety for Ships using Gases or other Low-flashpoint Fuels (IGF Code), adopted by the IMO's Maritime Safety Committee (MSC), entered into force. The IGF code covers all the design, construction and operating issues of vessels using low-flashpoint fuels for propulsion. At the same time, the amendments to the International Convention on Standards of Training, Certification and Watchkeeping for Seafarers (STCW), and STCW Code, adopted by the MSC, enter into force as well. Those amendments are addressing the crews' minimum requirements and qualifications for vessels subject to the IGF code ("MSC 95th session," 2015).

Another important document which complements the IGF Code has been developed by the International Organization for Standardization (ISO). ISO 20519:2017, *Ships and marine technology – Specification for bunkering of liquefied natural gas fueled vessels,* covers aspects that are not being addressed by the IGC Code. Namely:

- Hardware: liquid and vapor transfer systems
- Operational procedures
- Requirement for the LNG provider to provide an LNG bunker delivery note
- Training and qualifications of personnel involved

- Requirements for LNG facilities to meet applicable ISO standards and local codes

and aims at providing the guidelines that will establish safety and sustainability of LNG bunkering operations (International Organization for Standardization [ISO], 2017).

Apart from what is mentioned above, there are also other factors that impact the take-off of LNG as marine fuel. From a technological point of view, the most important bottleneck is the space-demanding LNG fuel tanks, which becomes particularly relevant considering that the short-sea vessels are more compact than the deep-sea vessels, meaning that the effects on the ships' income and productivity would be more significant (Wang & Notteboom, 2014). Although this consideration can be taken into account while the ship is being designed, it poses a major challenge for the conversion of already existing short-sea vessels which are designed according to different standards (Koers & Vaart B.V., 2015).

From a cost perspective, it is not only the high investment costs required for the installation of LNG systems, but it is also the price differentials between the alternatives that can affect the LNG outspread. Uncertainties regarding both the prices of the oil products as well as the future LNG price make the shipowners hesitant to invest in LNG-fueled ships, as low differentials might lead to long payback periods (Verbeek, Nesterova, van den Beemt, Widdershoven & Spreen, 2014). Considering the solution of a retrofit system where the remaining operational life of a vessel is an important factor to take into account (Wang & Notteboom, 2014), it is an option that might be proven prohibitively expensive.

4. Business case

4.1 Reference vessels

Since the vast majority of the traffic in the North European ECA is constituted by tankers, bulk carriers and container ships, those are the types of vessels that will be under examination. However, since tankers and bulk carriers are considered to be comparable in terms of size, construction and operational costs (Herbert Engineering Corp., 2015; The Danish Maritime Authority, 2012), it is assumed that they will be having similar operational profiles as well. The specifications of the reference vessels can be found in Table 4 and Table 5. Although the power of the auxiliary engines is not mentioned, The Danish Maritime Authority, (2012), assumes that it will be 20 % of the main engine power for diesel engines, and 40 % of the main engine power for gas engines. However, based on more recent and detailed data on vessel specifications, provided by Faber et al., (2015), it is safe to assume that the auxiliary engine power will be equal to 20 % of the main engine power for both engine types. For these ship types, the preferred method of bunkering is STS, and cargo handling is feasible while the bunkering operation is in process (The Danish Maritime Authority, 2012).

Reference Vessel 1 (RV1)

Coastal tanker / Bulk carrier					
Dimensions			**Energy demand**		
Approx length	125-180	m	Estimated main engine power	8,500	kW
Approx breadth	20-27	m	Estimated bunkering volume	500 - 1,000	m^3 LNG
Deadweight	10,000 - 15,000	tonnes	Bunkering frequency	Every 10 - 14	days
Available bunkerig time	8-12	hours	Amount LNG / year (and vessel)	3,200	tonnes

Table 4 – Coastal tanker / Bulk carrier specifications

Source: The Danish Maritime Authority, 2012

Reference Vessel 2 (RV2)

Container ship (700-800 TEU)					
Dimensions			Energy demand		
Approx length	135	m	Estimated main engine power	8,000	kW
Approx breadth	20	m	Estimated bunkering volume	500 - 700	m^3 LNG
Deadweight	9,000	tonnes	Bunkering frequency	Every 10	days
Available bunkerig time	6-12	hours	Amount LNG / year (and vessel)	4,500	tonnes

Table 5 – Container ship specifications

Source: The Danish Maritime Authority, 2012

Apart from the details provided for the reference vessels in Table 4 and Table 5, another important aspect is the operational profiles of the vessels. Details such as the number of port calls per year for the different types of cargo, the amount of time the ship spends at berth in the port for the different types of cargo, the amount of time the ship is sailing in the open sea utilizing its main engine, the amount of time the ship spends lying still operating only on its auxiliary engines (The Danish Maritime Authority, 2012), the average annual operating time, the average load of the engine while sailing, and more, such as the ship design, sea conditions and cargo load (Lindstad & Eskeland, 2015) are factors that can significantly impact the operational costs and could possibly make the difference. This kind of data though, are either difficult or expensive to acquire.

Nonetheless, Nielsen & Schack, (2012) provide data on the operational profile of a medium sized tanker which can be used as indicative for both reference vessels for this study. Thus, as can be seen in Table 6, RV1 and RV2 will be spending a total of 220 days per year sailing and 145 days per year at berth in port[3]. In addition, it is assumed that while the ship is sailing, is utilizing 100 % of both its main and auxiliary engine power, while when lying still it is utilizing 100 % of the auxiliary power and 0 % of the main engine power. The reason that the auxiliary engines, as opposed to the main engine, are assumed to be operating during the total of the annual operating

[3] In terms of hours, 5,280 and 3,480 respectively.

time is that apart from supporting propulsion, they also support other, additional functions such as ship and cargo handling, or even domestic ship services ("Marine engines and auxiliary machinery", 2008).

Vessel operational profile	
Days at sea	220
Days harbour, idling	115
Days harbour, unloading	30

Table 6 – Reference vessels' operational profile

Source: Nielsen & Schack, (2012)

At this point it is important to clarify that assuming a binary, 0% or 100%, constant rate of engine utilization is not realistic. However, assuming any constant rate would not be realistic as well, due to the fact the load of the engines, both main and auxiliary, is volatile. The most realistic approach would be to consider various engine utilization rates throughout the vessels' operating time. However, taking into account factors that can have an effect on those rates, such as weather conditions, cargo, schedule, would require an abundance of assumptions and would have made the approach overly complicated for an individual Master Thesis.

Another important point is that based on the data presented in Table 4, Table 5 and Table 7 it is safe to assume that both RV1 and RV2 could be bunkering 500 m^3 LNG every 10 days with the same process which would last 12 hours. Even though RV1 has higher fuel consumption due to the stronger engine, still, the yearly amount of LNG consumed by the container ship is approximately 40 % larger. According to Gkonis & Psaraftis, (2010), container vessels have significantly higher bunker costs compared to bulk vessels, due to the higher speed of sailing. In order to account for this factor, it is assumed that RV2 will have a 40 % larger fuel consumption rate, compared to RV1, across all fuel alternatives.

4.2 Net Present Value (NPV)

As mentioned earlier, the ship-owners aim not only to comply with the upcoming stringent limits but also to create value for their business by investing in the most profitable solution. The method that will be used to assess the economic feasibility of the investment decision that they will need to make, is NPV. The NPV method, which is one of the most important methods for deciding among investment options (Osborne, 2010), will be used as criterion for the attractiveness of each one of the three investment alternatives with regards to fuel preference. According to Brealey, Myers & Allen, (2014), NPV is a discounted cash flow method which estimates the difference between the cost and the value of an investment or project, by calculating the present value of cash flows while accounting for the initial investment. It is a reliable tool that can be applied in cases with long as well as short horizon and it is widely used by large firms.

Along with NPV, the Internal Rate of Return (IRR) is also an important and well-known discounted cash flow method for assessing the attractiveness of investment alternatives (Ben-Horin & Kroll, 2017). The IRR evaluates the profitability of an investment by comparing the investment's rate of return with the cost of capital and, same with NPV, results in a positive or negative decision regarding an investment option. However, a significant disadvantage of IRR is the fact that it does not consider the value that the investment will generate for the shipowners. This drawback becomes particularly relevant in cases where the investment options are mutually exclusive. While for the NPV method this is a simple question of which alternative has the highest NPV, for IRR a more complicated approach is required (Brealey, Myers & Allen, 2014). This is the reason why the NPV is the most appropriate and reliable method for this study, as the shipowners will have to decide on one of the three fuel alternatives. The NPV formula can be seen in Eq. (1) below:

$$\mathrm{NPV} = -\mathrm{C}_0 + \sum_{1}^{\mathrm{T}} \frac{\mathrm{C_t}}{(1+\mathrm{r})^{\mathrm{t}}} \qquad (1)$$

- C_0: Initial investment (a positive number with a minus sign, representing cash outflow)
- C_t: Net cash flow in the period t = 1 to T
- r: Discount rate
- T: Number of the periods

To apply this general NPV rule in the case under examination, the parameters of Eq. (1) need to be accounted as follows:

Initial Investment: As explained earlier in this study, MGO will be used as the base case for comparison since it requires the lowest amount of capital investments. Vessels running on MGO require the addition of abatement technologies, such as SCR or EGR systems, in order to comply with the Tier III limits. The costs for the acquisition and installation of such systems on a new-built ship are not negligible and need to be considered. Hence, the initial investment component (C_0) of Eq. (1) for the alternatives of LNG and HFO can be seen below in Eq. (2a) and Eq. (2b) respectively:

$$C_0 = C_{LNG} - C_{MGO} \qquad (2a)$$

$$C_0 = C_{HFO} - C_{MGO} \qquad (2b)$$

The capital investment costs for each one of the alternatives as presented in Eq. (2a) and Eq. (2b), include several cost components which can be found in detail in Appendix 2.

Net cash flow: The net cash flow (C_t) will be based on the occurring operational savings or losses of each of the two alternatives compared to the base case, MGO. The amount of those savings and losses will be the difference between the operational costs of each alternative and the base case as can be seen below in Eq. (3a) and Eq. (3b).

$$c_t = c_{MGO} - c_{LNG} \qquad (3a)$$

$$c_t = c_{MGO} - c_{HFO} \qquad (3b)$$

The operational costs will mainly be depended on the fuel prices (The Danish Maritime Authority, 2012). Fuel prices, in combination with the fuel consumption rate for each alternative, as can be seen in Table 7, and subsequently the amount of time in operation, will be shaping the most significant part of these costs. The additional operating costs of the abatement equipment, which are also depended on time in operation, will be considered as well. The formulas for the calculation of the operational costs of LNG, MGO and HFO are represented by Eq. (4a), Eq. (4b) and Eq. (4c) respectively.

	HFO		MGO		LNG
	Baseline	Changes with scrubbers	Baseline	Changes with SCR	Baseline
Specific fuel consumption (g / kWh)	**71**	**72.3**	**67.7**		**61**

Table 7 – Specific fuel consumption

Source: Appendix 3

$$c_{LNG} = (P_{LNG} * F_{LNG} * h_{sea} * E_{main}) + \left(P_{LNG} * F_{LNG} * h_{sea+port} * E_{aux}\right)$$

(4a)

$$c_{MGO} = (P_{MGO} * F_{MGO} * h_{sea} * E_{main}) + \left(P_{MGO} * F_{MGO} * h_{sea+port} * E_{aux}\right) + (c_{SCR} * h_{sea} * E_{main})$$

(4b)

$$c_{HFO} = (P_{HFO} * F_{HFO} * h_{sea} * E_{main}) + \left(P_{HFO} * F_{HFO} * h_{sea+port} * E_{aux}\right) + (c_{SCR} * h_{sea} * E_{main}) + (c_{Scrub} * h_{sea} * E_{main})$$

(4c)

- P: Bunker price
- F: Specific fuel consumption
- E: Engine power
- h: Operating hours per year, either sailing (sea) or at berth (port)

Discount rate: According to Brealey, Myers & Allen, (2014), the discount rate is the "interest rate used to compute present values of future cash flows" and represents the opportunity cost of capital, meaning the required rate of return for the investment. Some studies assume that this rate is equal to the rate of return for bonds. However, in this case the discount rate is assumed to be 10 %, based on the information obtained from Jónsdóttir, (2013)[4].

[4] Guðrún Jónsdóttir, obtained this estimation from Rúnar Þór Stefánsson, the Fleet Manager at HB Grandi, through their email communication which is provided in the appendices of her MSc thesis.

Number of periods: The operational lifetime of a ship will represent the number of periods that will be considered as the horizon for the investment evaluation. PWC (2013), and International Maritime Organization (2016), estimate that a vessel has an average economic life of twenty to thirty years. Thus, for the purpose of this study this period (T) is assumed to be twenty-five years.

4.3 Bunker prices and pricing scenarios

One of the most important factors that will impact the operating costs, is the bunker price for each of the fuel alternatives. The expectations of the shipowners regarding the development of those prices will eventually influence their decision on the most attractive investment. As can be deducted from Eq. (3a), Eq. (3b), Eq. (4a), Eq. (4b) and Eq. (4c), the payback time as well as whether the operations will produce savings or losses will be depending on the bunker price differentials between the alternatives.

At this point, it is important to clarify that when referring to bunker prices, the following will be considered:

- For the HFO price, IFO 380 will be used as the reference value without any concern of having high Sulphur content, since abatement technologies will maintain the emission levels below the Tier III limits.
- For crude oil and for HFO and MGO prices, the North Sea Brent and the Rotterdam fuel prices, respectively, will be used as reference values as they provide a view, more specific to the European market.
- The price for LNG will be a function of the price for natural gas.

Historically, both HFO and MGO are oil indexed. Meaning, that their prices have been strongly correlated with the price of crude oil as can be seen in Figure 10 and Figure 11. Based on current data ("Rotterdam Bunker Prices", 2017a, 2017b), over the past year the prices of HFO and MGO have been respectively 25 % lower and 15.8 % higher, on average, compared to the Brent price (Appendix 3). Thus, due to the lack of more thorough historical bunker prices data, it is assumed that for this analysis the prices of HFO and MGO will stand at those levels relative to the Brent price, for various Brent prices.

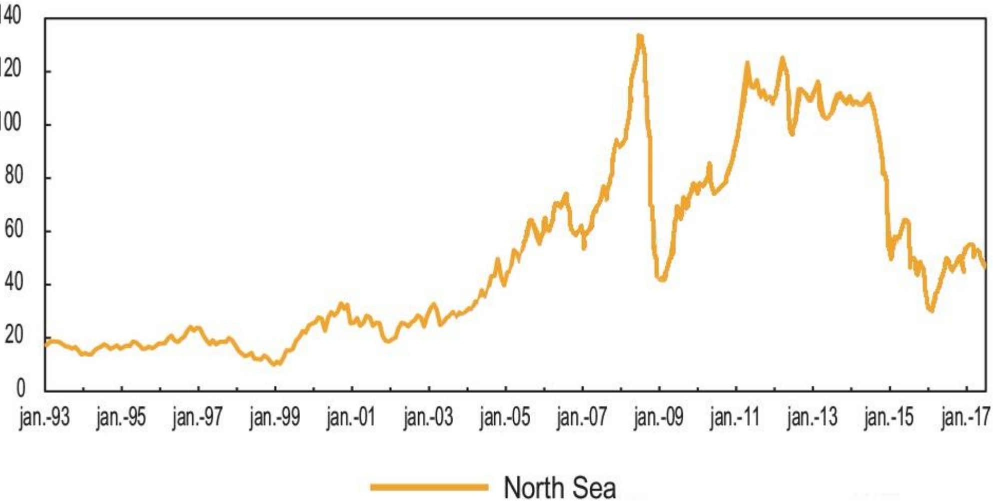


Figure 10. – Average Brent crude oil spot prices in $ / bbl.

Source: International Energy Agency, 2017

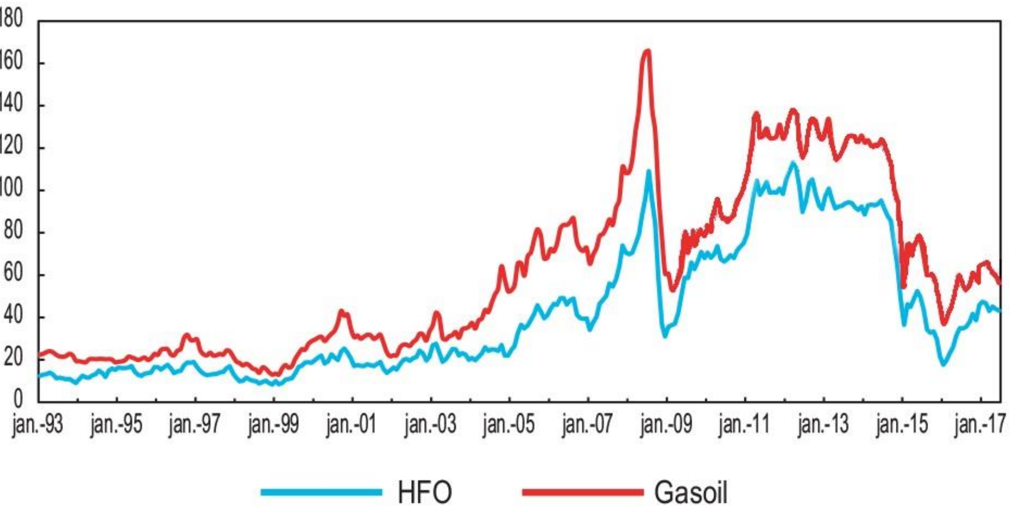


Figure 11. – Average HFO and MGO Rotterdam spot prices in $ / bbl.

Source: International Energy Agency, 2017

LNG Market and Bunker Price

The market for LNG is rather fragmented and the way its price is determined depends on the region, as pricing mechanisms vary between different geographical locations. The three main regions are North America, Europe and Asia Pacific (Verbeek, Nesterova, van den Beemt, Widdershoven & Spreen, 2014). According to Faber et al., (2015) the way the price is set in Europe differs between continental Europe and the UK. As opposed to the UK, a market characterized by numerous buyers and suppliers, where the price of natural gas is not linked to other energy carriers, in continental Europe the price of natural gas is typically linked to oil-based products or coal. However, in North-western Europe a fusion of the two mechanics, while accounting for the hub pricing[5] as well, can be observed over the recent past. An illustration of the relationship between those prices can be seen in Figure 12.

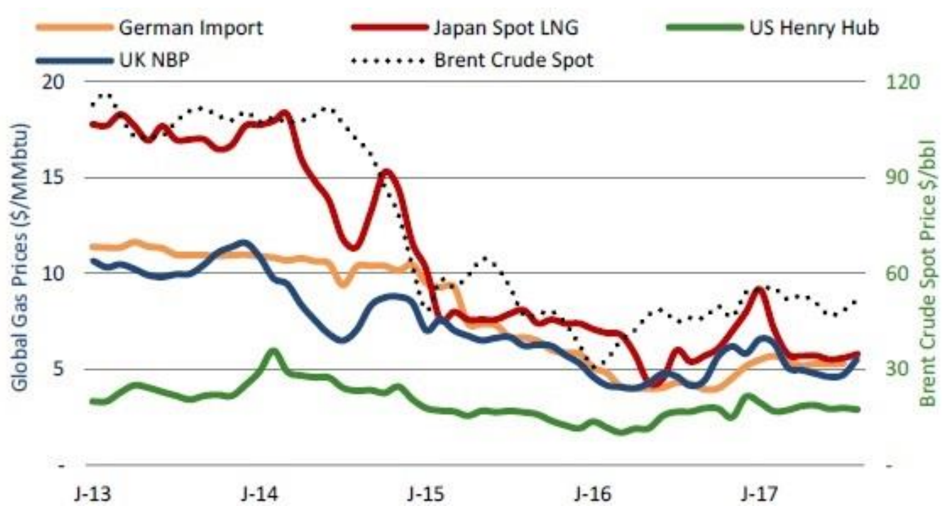


Figure 12. – Regional price differentials – Monthly average prices

Source: Ho & Culley, 2017

With regards to the LNG bunker price, it will need to be estimated as actual figures are not accessible, despite the effort that was put on searching both the Internet as well as publications of

[5] UK NBP for Europe (International Maritime Organization, 2016)

relevant actors. The reason is that currently there is not a large number of vessels running on LNG, therefore, the bunker prices are mostly agreed upon on a contractual basis with the different ship operators and are not made publicly available (Faber et al., 2015). The LNG prices that can be retrieved from public sources are not representative of the actual bunkering prices as they do not include all the cost components that shape the final price (DNV GL, 2015). Jarlsby, (2008), breaks down the LNG bunker price into two components as can be seen in Eq. (5).

$$LNG\ bunker\ price\ = Market\ based\ gas\ price\ + Cost\ of\ supply\ logistics \quad (5)$$

The market based gas price refers to the import price, regardless it is supplied through the pipeline grid or in large import terminals, while the logistics costs refer to the cost of transportation and the cost of the bunkering operation. DNV GL, (2016), estimated that for an STS bunkering method those distribution costs will be about 2 $/MMBtu[6]. Regarding the import price, Faber et al., (2015), based on The World Bank data, estimates that in 2020 it will be ranging between 8 and 10 €/MMBtu while in 2025 will be setting to 8 €/MMBtu[7].

Pricing scenarios

As previously mentioned, whether the investment decision of the shipowners will be the optimal, between the given alternatives, is related to the level of the fuel prices throughout the economic lifetime of the vessels. Although it might be more appropriate to consider various prices for oil and gas in that timeframe, not only more detailed data, looking further into the future, are required but also the calculations of the NPV would be more complicated. Therefore, the preferred approach is to consider pricing scenarios for specific oil and gas prices in the future.

[6] 106.76 €/Mt (Appendix 4)
[7] 427.04 €/Mt (Appendix 4)

The price of oil can be highly volatile as it has been proven over the past few years. However, as can be seen in Figure 13, historically the consumption of oil has been significantly higher than the consumption of gas. In addition, the oil reserves are shorter compared to the gas reserves (Jarlsby, 2008; PWC, 2013).

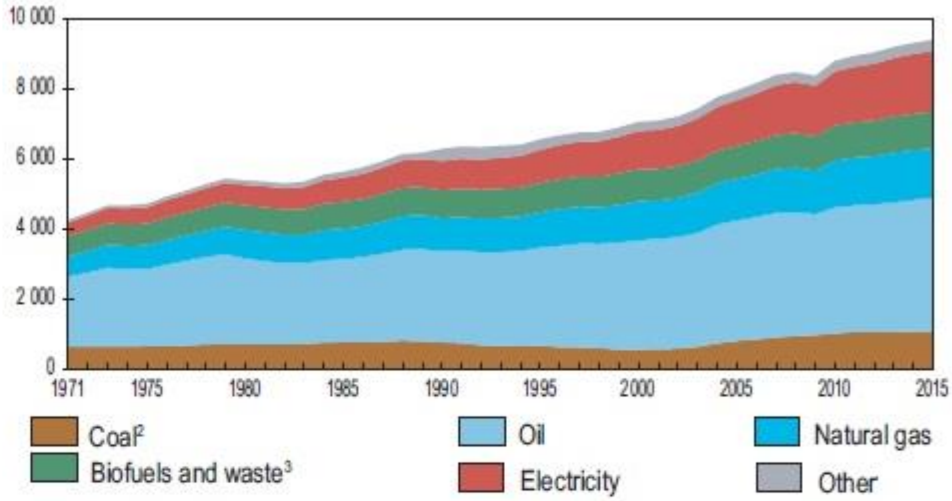


Figure 13. – World Total Final Consumption by fuel

Source: International Energy Agency, 2017

According to the most likely scenario of EIA, (2017a), in their annual energy outlook report, the crude oil prices are expected to rise, but with a higher rate in the short term than in the long term. Specifically, with projections to 2050, it is estimated that the Brent price from an average of 43 $/bbl. in 2016 will reach the level of 86 $/bbl. in 2025 and will rise to 95 $/bbl. in 2030. The following decades it will keep moving upwards reaching the levels of, 102 $/bbl. in 2035, 109 $/bbl. in 2040, and eventually 117 $/bbl. in 2050 (EIA, 2017b).

Based on those projections, two scenarios will be considered regarding the price development of crude oil. A central, and a high price scenario. It is assumed that the 2025 price of 86 $/bbl.[8] will represent the former, while the 2050 price of 117 $/bbl.[9] will represent the latter.

[8] 551.68 €/Mt (Appendix 4)
[9] 750.55 €/Mt (Appendix 4)

On the other hand, regarding the price development of natural gas, three scenarios will be considered. A low price, a central price and a high price scenario. According to Raval, (2017 July 5), UK recently received its first large shipment of low-priced US LNG, which pushed the NBP price to the lowest of any regional hub in August 2017. Considering how the pricing mechanisms for natural gas work in North-western Europe, meaning that natural gas is not exclusively oil-indexed, contemplating a low-price scenario for natural gas seems more appropriate.

Thus, it is assumed that the low import price will be represented by the 2025 price of 8 €/MMBtu, as estimated by Faber et al., (2015), while the central and high prices are assumed to be on the levels of 9 €/MMBtu[10] and 11 €/MMBtu[11], respectively. An overview of the scenarios and their respective bunker prices can be seen in Table 8 below.

Pricing Scenarios	Natural gas low 8 €/MMBtu	Natural gas central 9 €/MMBtu	Natural gas high 11 €/MMBtu
Crude central 86 $/bbl.	<u>Scenario 1.1</u> P_{HFO} 413.76 €/Mt P_{MGO} 638.85 €/Mt P_{LNG} 533.8 €/Mt	<u>Scenario 1.2</u> P_{HFO} 413.76 €/Mt P_{MGO} 638.85 €/Mt P_{LNG} 587.18 €/Mt	<u>Scenario 1.3</u> P_{HFO} 413.76 €/Mt P_{MGO} 638.85 €/Mt P_{LNG} 693.94 €/Mt
Crude high 117 $/bbl.	<u>Scenario 2.1</u> P_{HFO} 562.91 €/Mt P_{MGO} 869.14 €/Mt P_{LNG} 533.8 €/Mt	<u>Scenario 2.2</u> P_{HFO} 562.91 €/Mt P_{MGO} 869.14 €/Mt P_{LNG} 587.18 €/Mt	<u>Scenario 2.3</u> P_{HFO} 562.91 €/Mt P_{MGO} 869.14 €/Mt P_{LNG} 693.94 €/Mt

Table 8 – Pricing scenarios and bunker prices

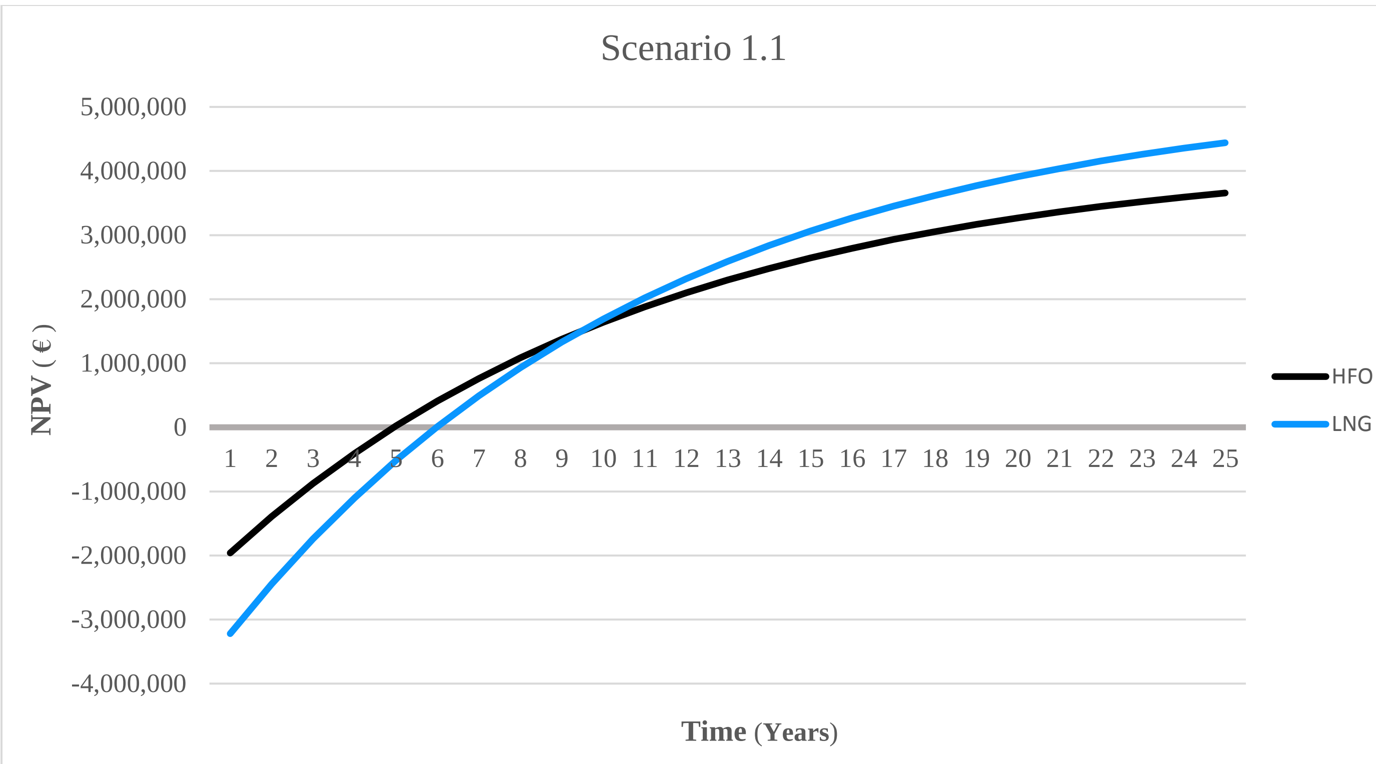
Thus, the NPV of the different fuel – vessel combinations will be calculated based on the above bunker prices estimates.

[10] 480.4 €/Mt (Appendix 4)
[11] 587.2 €/Mt (Appendix 4)

4.4 Results

In this section the results of the calculations of NPV, for the two reference vessels, are presented and illustrated for each one of the different pricing scenarios.

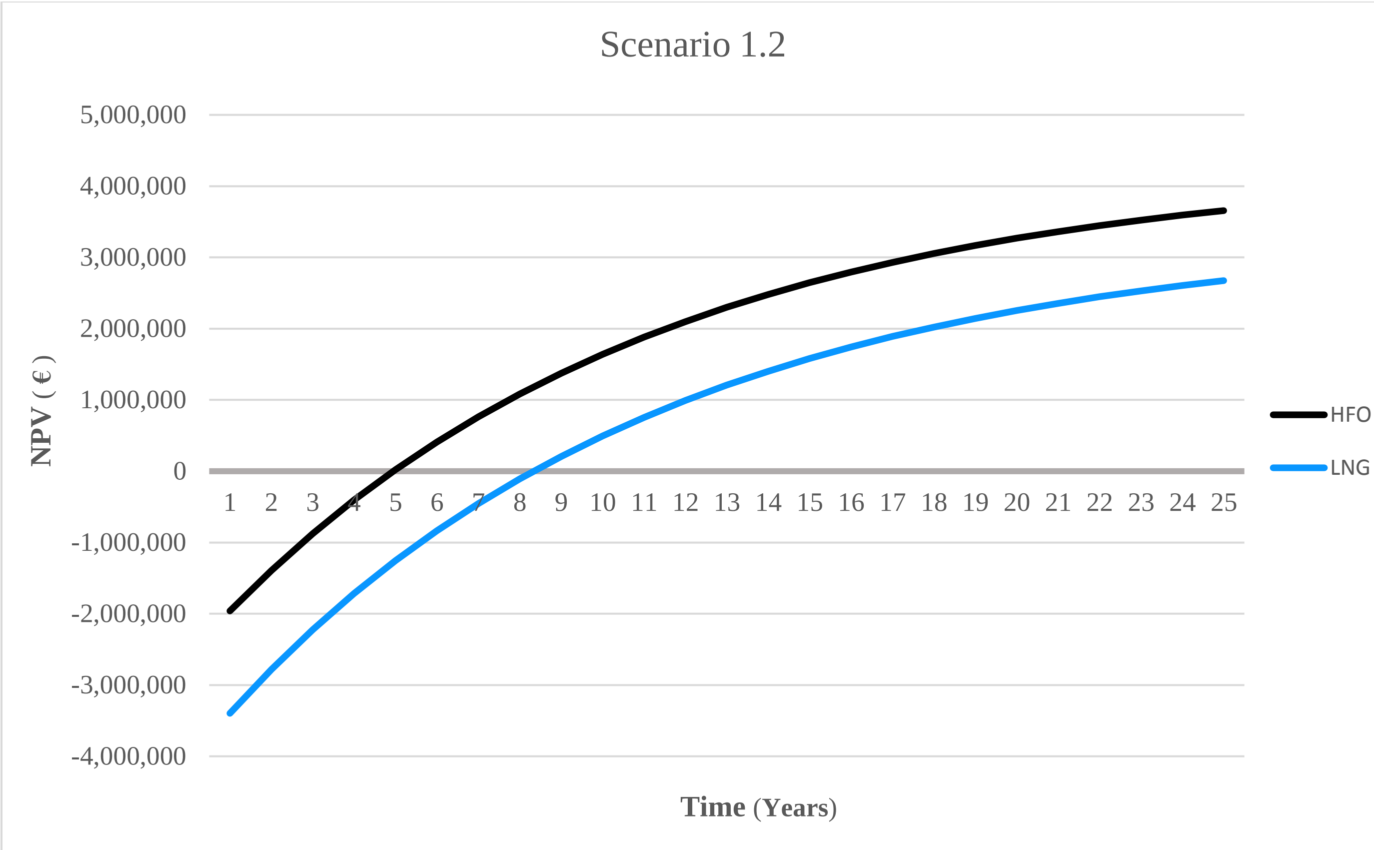
<u>Reference vessel 1</u>



NPV$_{\mathbf{HFO}}$ = € 3,656,364.69 **NPV**$_{\mathbf{LNG}}$ = € 4,440,656.31

Figure 14 – NPV Scenario 1.1, Reference vessel 1

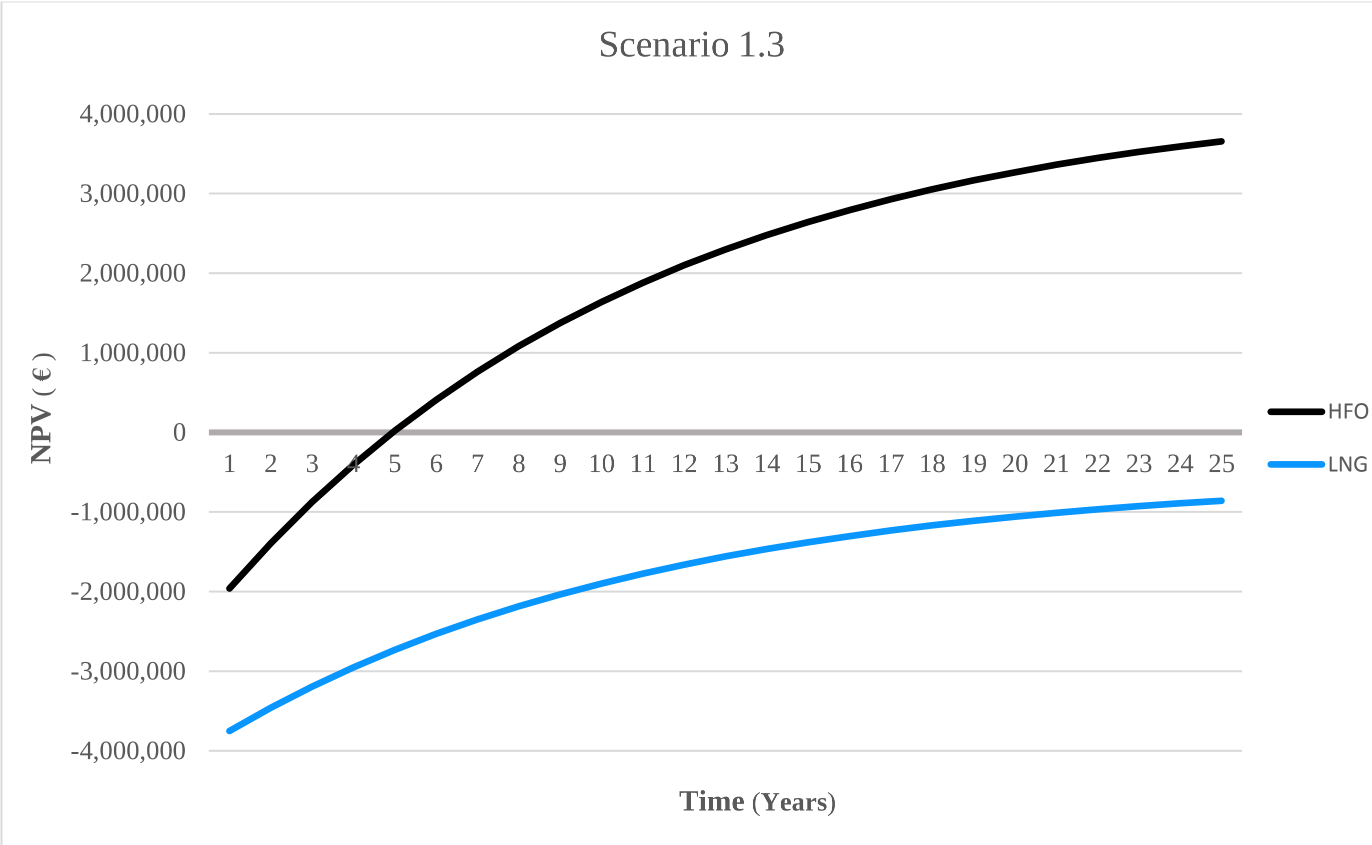
As can be seen in Figure 14, the NPV$_{LNG}$ starts from a value of - 3,220,367.74 € and reaches the value of 4,440,656.31 € by the end of the twenty-five-year period, while the NPV$_{HFO}$ starts from a value of - 1,960,791.75 € and reaches the value of 3,656,364.69 €. The payback time for those investments is six and five years respectively.



NPV$_{\mathbf{HFO}}$ = € 3,656,364.69 **NPV**$_{\mathbf{LNG}}$ = € 2,674,006.62

Figure 15 – NPV Scenario 1.2, Reference vessel 1

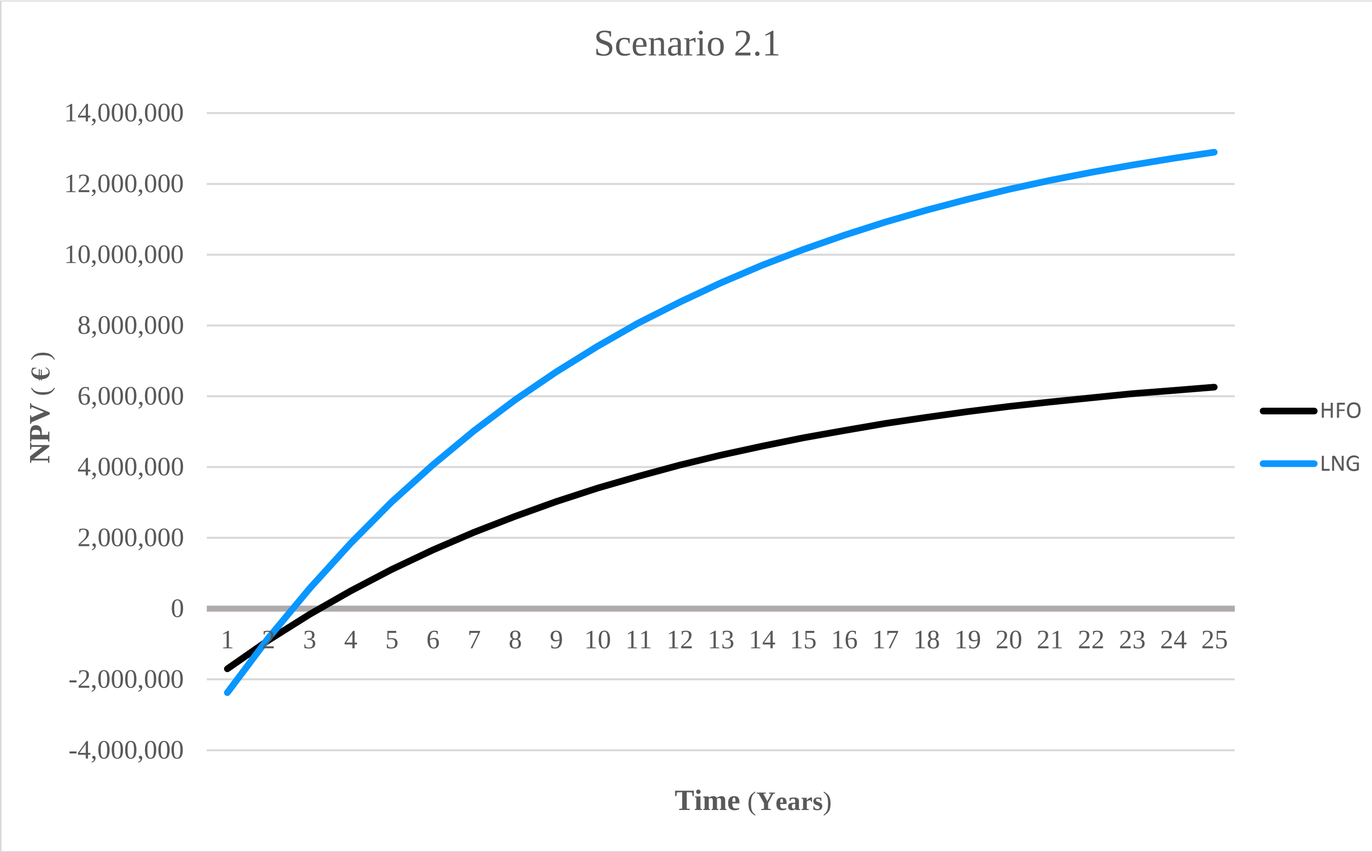
As illustrated in Figure 15, the NPV$_{LNG}$ starts from a value of - 3,397,302.64 € and reaches the value of 2,674,006.62 € by the end of the twenty-five-year period, while the NPV$_{HFO}$ starts from a value of - 1,960,791.75 € and reaches the value of 3,656,364.69 €. The payback time for those investments is nine and five years respectively.



NPV_{HFO} = € 3,656,364.69 **NPV_{LNG}** = - € 859,292.77

Figure 16 – NPV Scenario 1.3, Reference vessel 1

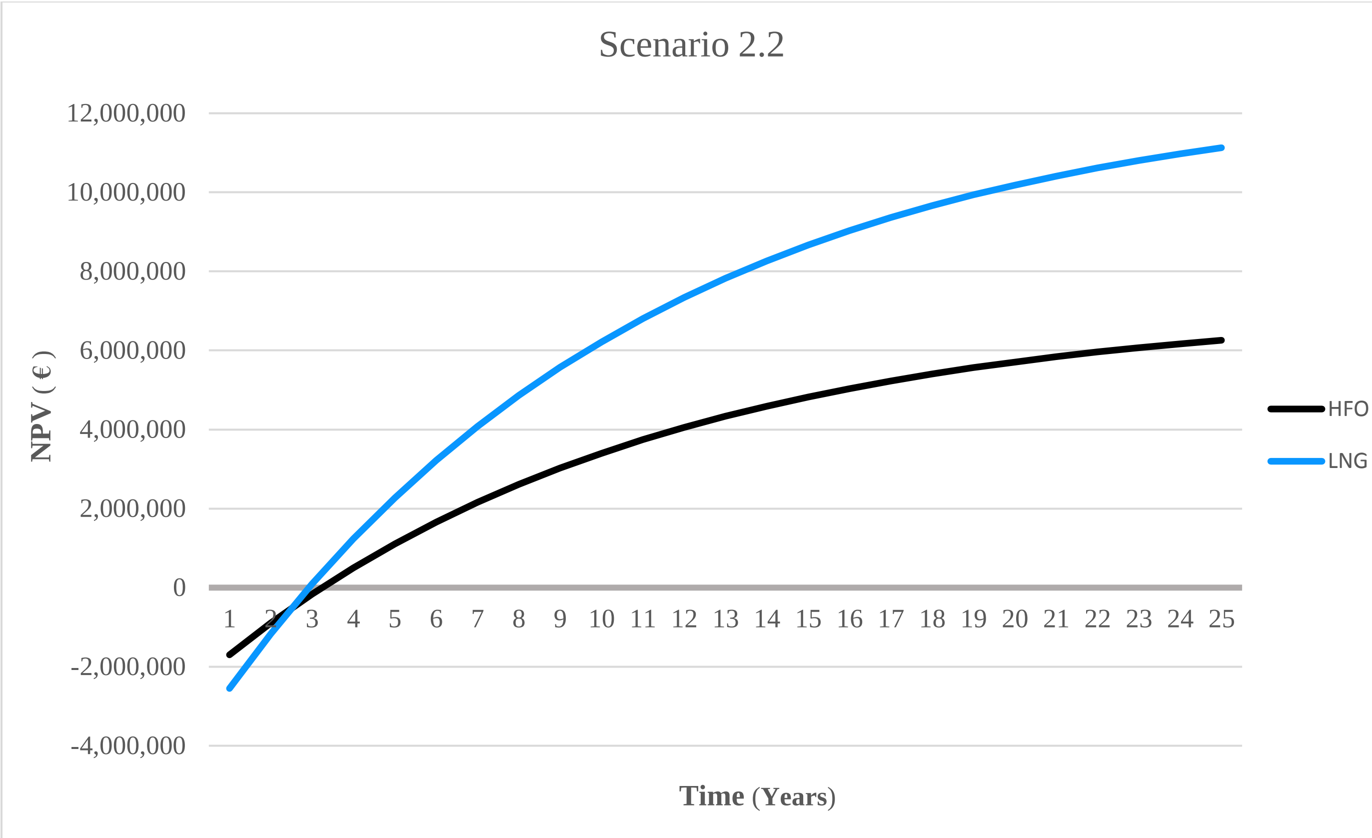
As shown in Figure 16, the NPV_{LNG} starts from a value of - 3,751,172.44 € and reaches the value of - 859,292.77 € by the end of the twenty-five-year period, while the NPV_{HFO} starts from a value of - 1,960,791.75 € and reaches the value of 3,656,364.69 €. The payback time for the HFO solution is again five years while the LNG solution does not pay back for the amount of the initial investment.



NPV$_{HFO}$ = € 6,257,472.70 **NPV$_{LNG}$** = € 12,895,012.59

Figure 17 – NPV Scenario 2.1, Reference vessel 1

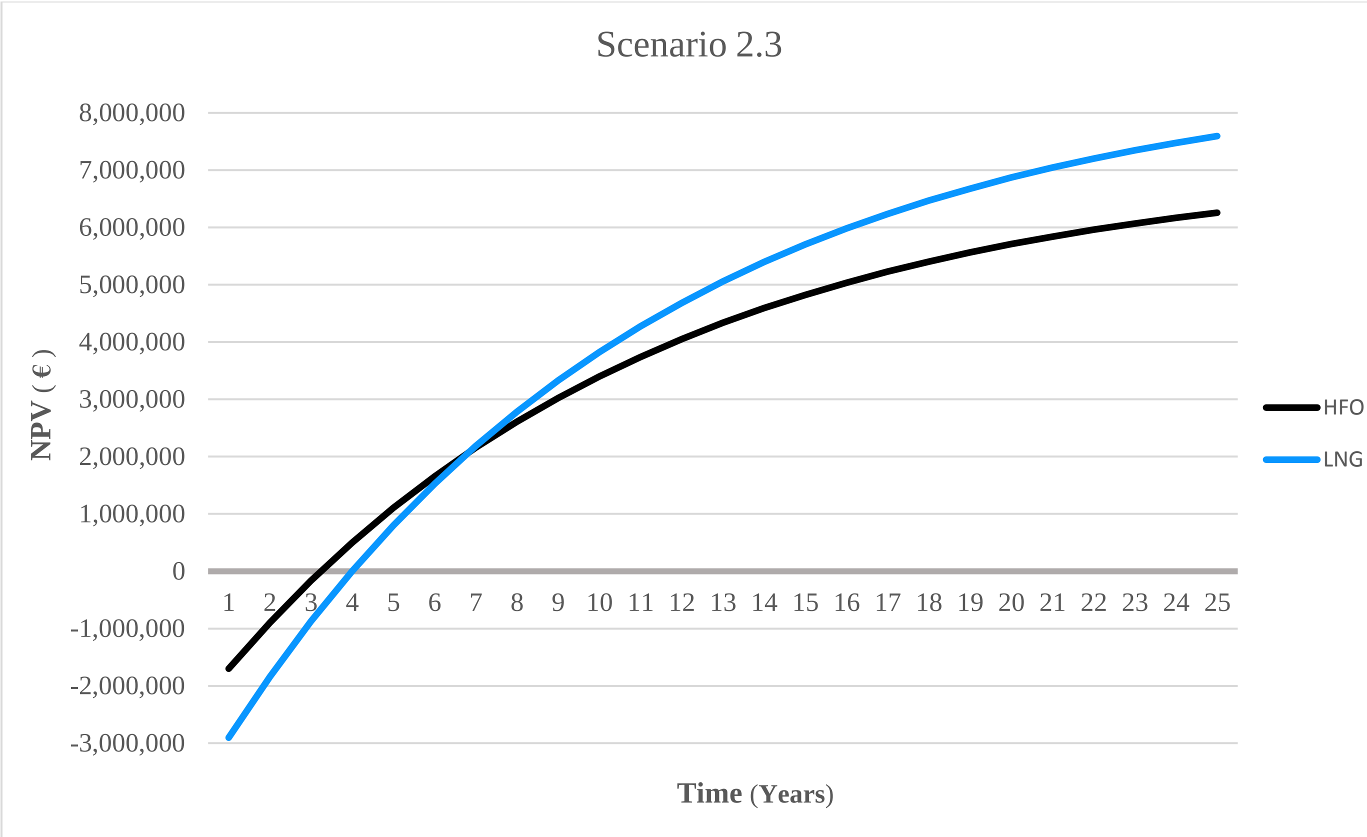
Figure 17 shows that the NPV$_{LNG}$ starts from a value of - 2,373,640.34 € and reaches the value of 12,895,012.59 € by the end of the twenty-five-year period, while the NPV$_{HFO}$ starts from a value of - 1,700,283.51 € and reaches the value of 6,257,472.70 €. The payback time for those investments is three and four years respectively.



NPV$_{\mathbf{HFO}}$ = € 6,257,472.70 **NPV$_{\mathbf{LNG}}$** = € 11,128,362.90

Figure 18 – NPV Scenario 2.2, Reference vessel 1

As can be seen in Figure 18, the NPV$_{LNG}$ starts from a value of - 2,550,575.24 € and reaches the value of 11,128,362.90 € by the end of the twenty-five-year period, while the NPV$_{HFO}$ starts from a value of - 1,700,283.51 € and reaches the value of 6,257,472.70 €. The payback time for those investments is three and four years respectively, same as with scenario 2.1 .

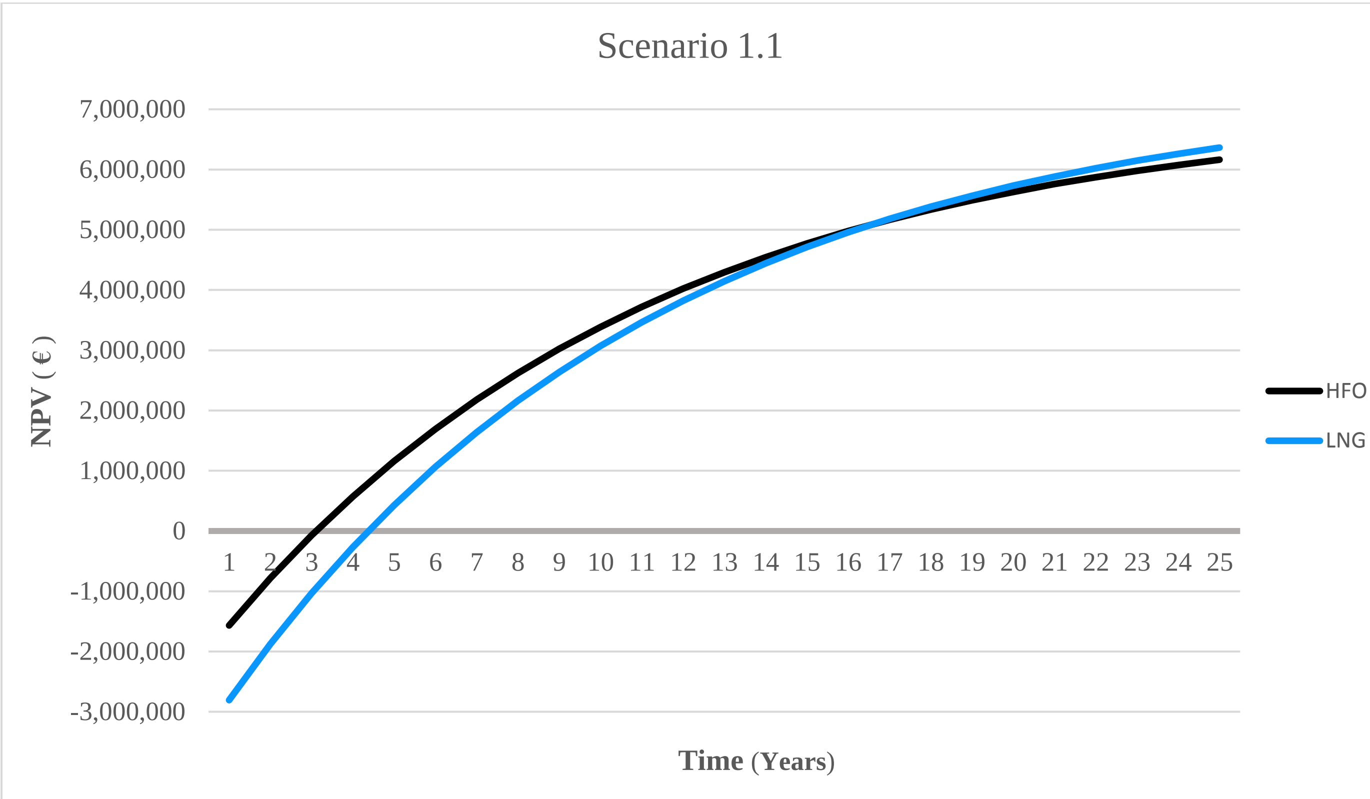


NPV_{HFO} = € 6,257,472.70 **NPV_{LNG}** = € 7,595,063.51

Figure 19 – NPV Scenario 2.3, Reference vessel 1

According to Figure 19, the NPV_{LNG} starts from a value of - 2,904,445.05 € and reaches the value of 7,595,063.51 € by the end of the twenty-five-year period, while the NPV_{HFO} starts from a value of - 1,700,283.51 € and reaches the value of 6,257,472.70 €. The payback time for both alternatives is four years.

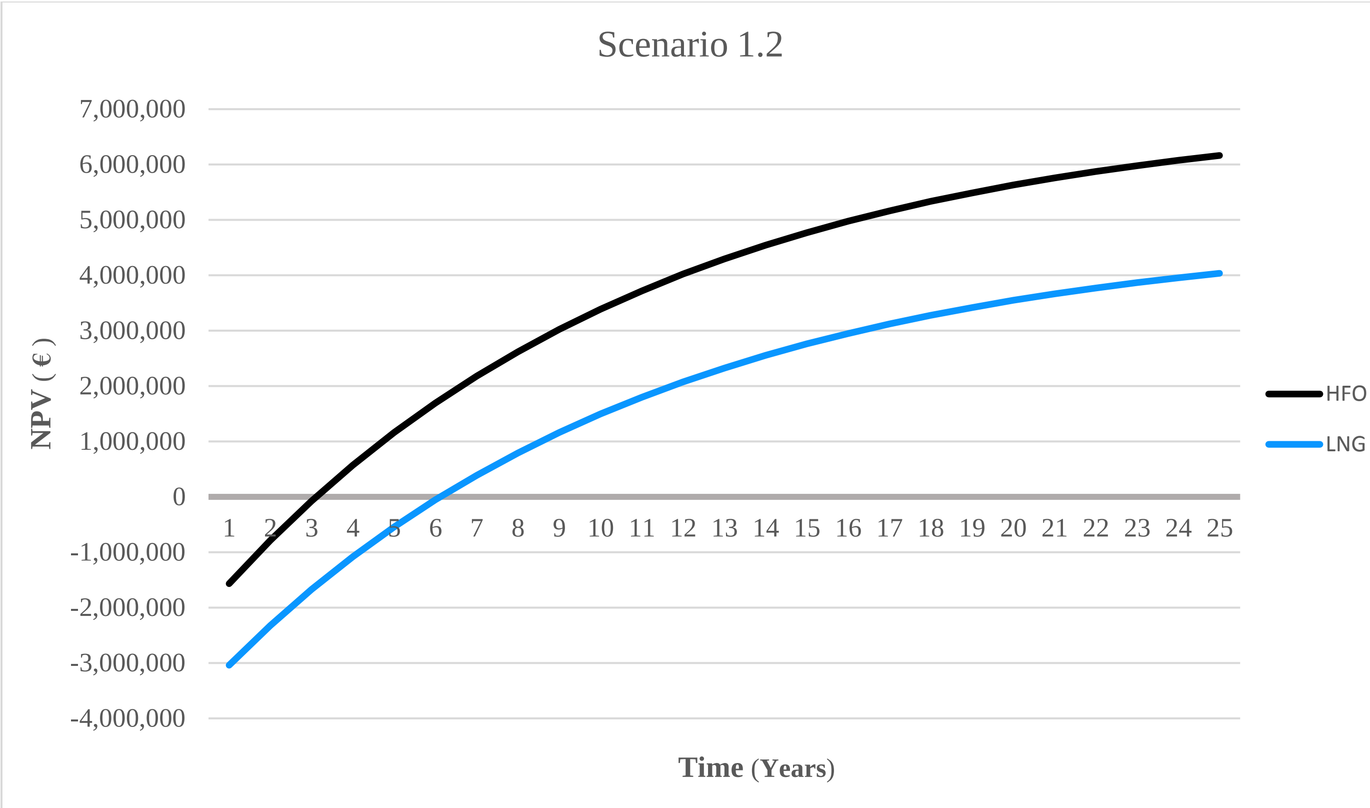
Reference vessel 2



NPV$_{\mathbf{HFO}}$ = € 6,163,511.07 **NPV**$_{\mathbf{LNG}}$ = € 6,363,897.22

Figure 20 – NPV Scenario 1.1, Reference vessel 2

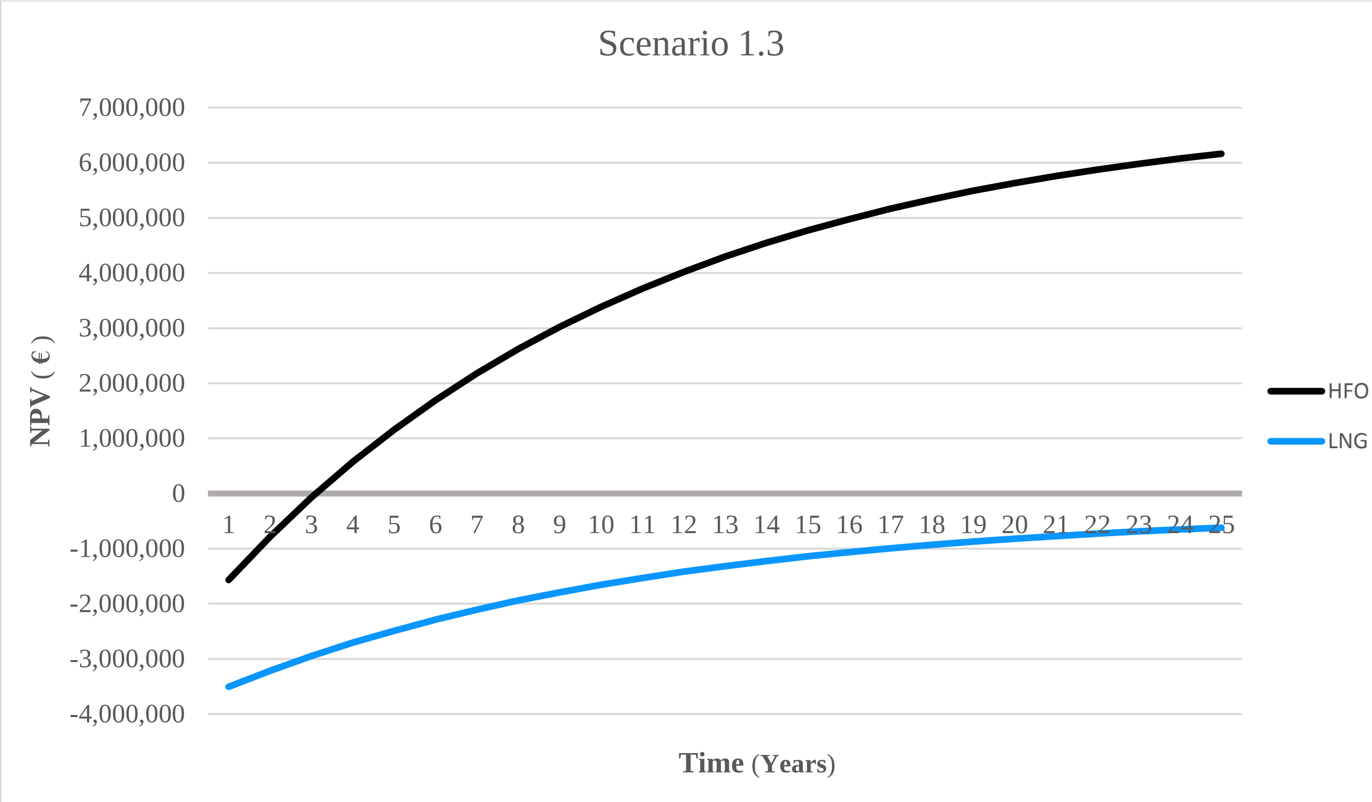
As can be seen in Figure 20, the NPV$_{LNG}$ starts from a value of - 2,807,094.66 € and reaches the value of 6,363,897.22 € by the end of the twenty-five-year period, while the NPV$_{HFO}$ starts from a value of - 1,567,752.13 € and reaches the value of 6,163,511.07 €. The payback time for those investments is five and four years respectively.



NPV_{HFO} = € 6,163,511.07 **NPV_{LNG}** = € 4,036,076.45

Figure 21 – NPV Scenario 1.2, Reference vessel 2

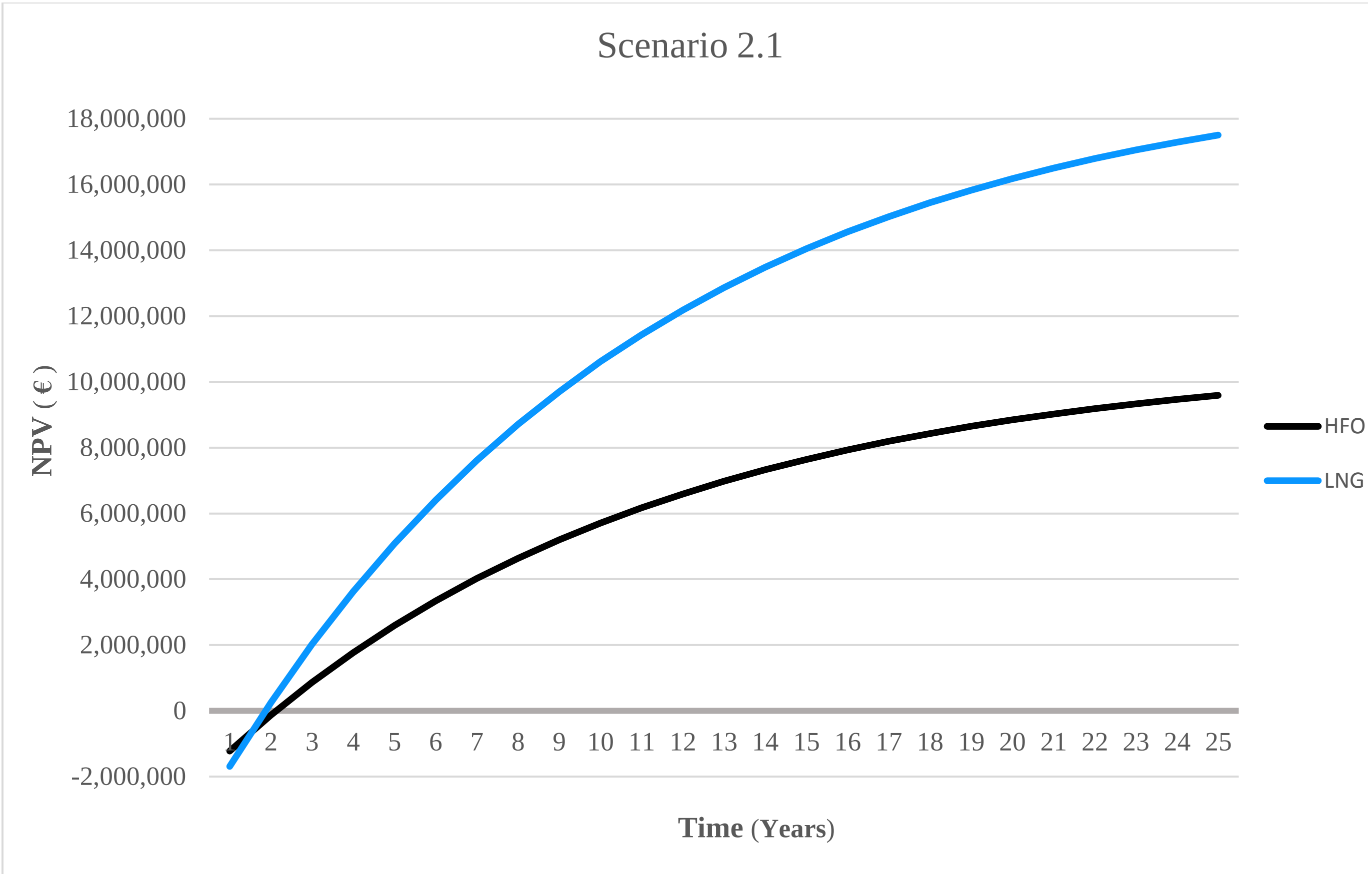
As illustrated in Figure 21, the NPV_{LNG} starts from a value of - 3,040,232.41 € and reaches the value of 4,036,076.45 € by the end of the twenty-five-year period, while the NPV_{HFO} starts from a value of - 1,567,752.13 € and reaches the value of 6,163,511.07 €. The payback time for those investments is seven and four years respectively.



NPV$_{HFO}$ = € 6,163,511.07 **NPV$_{LNG}$** = - € 619,565.10

Figure 22 – NPV Scenario 1.3, Reference vessel 2

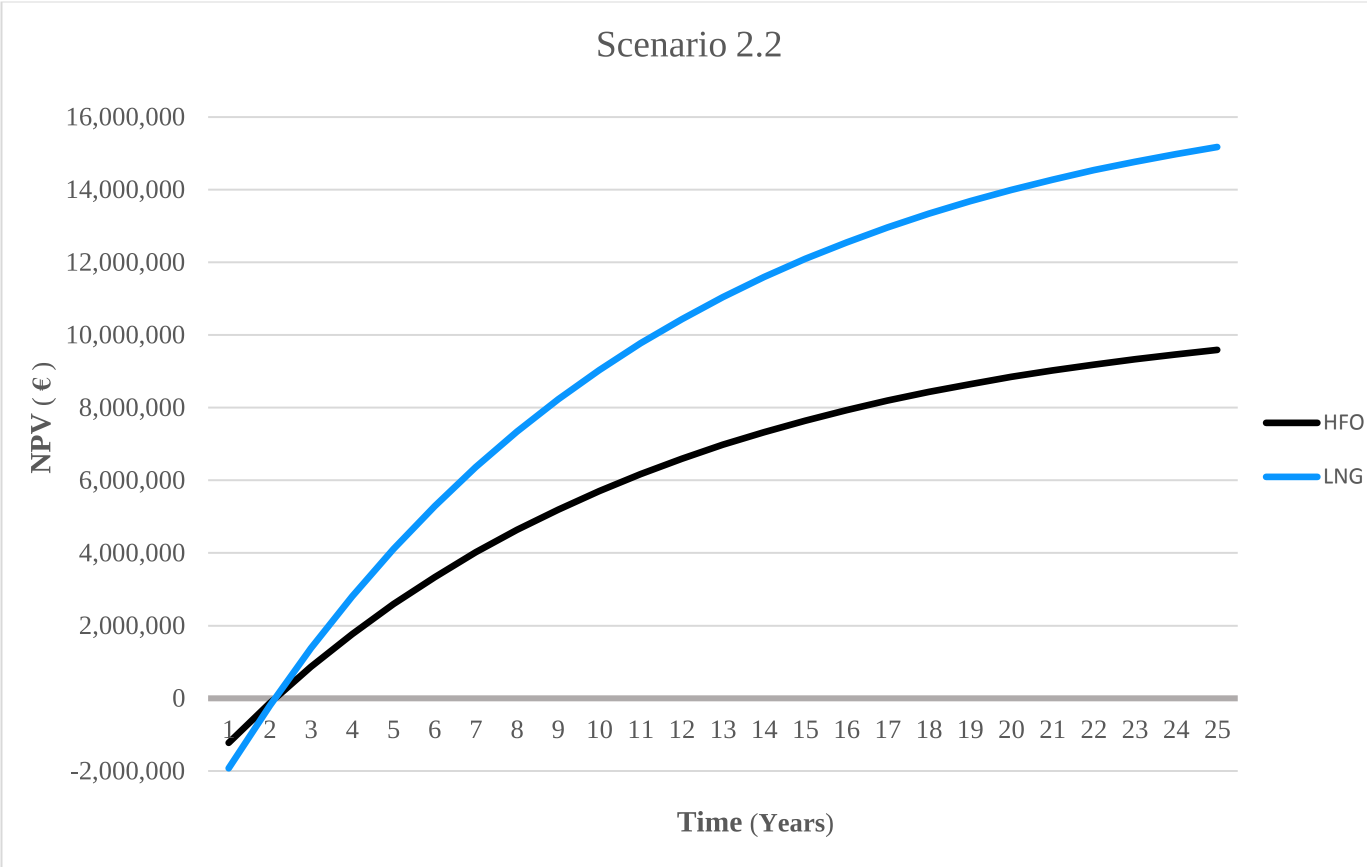
As shown in Figure 22, the NPV$_{LNG}$ starts from a value of - 3,506,507.91 € and reaches the value of - 619,565.10 € by the end of the twenty-five-year period, while the NPV$_{HFO}$ starts from a value of - 1,567,752.13 € and reaches the value of 6,163,511.07 €. The payback time for the HFO solution is four years while the LNG alternative does not manage to payback for the amount of the initial investment.



NPV$_{HFO}$ = € 9,590,853.38 **NPV$_{LNG}$** = € 17,503,754.90

Figure 23 – NPV Scenario 2.1, Reference vessel 2

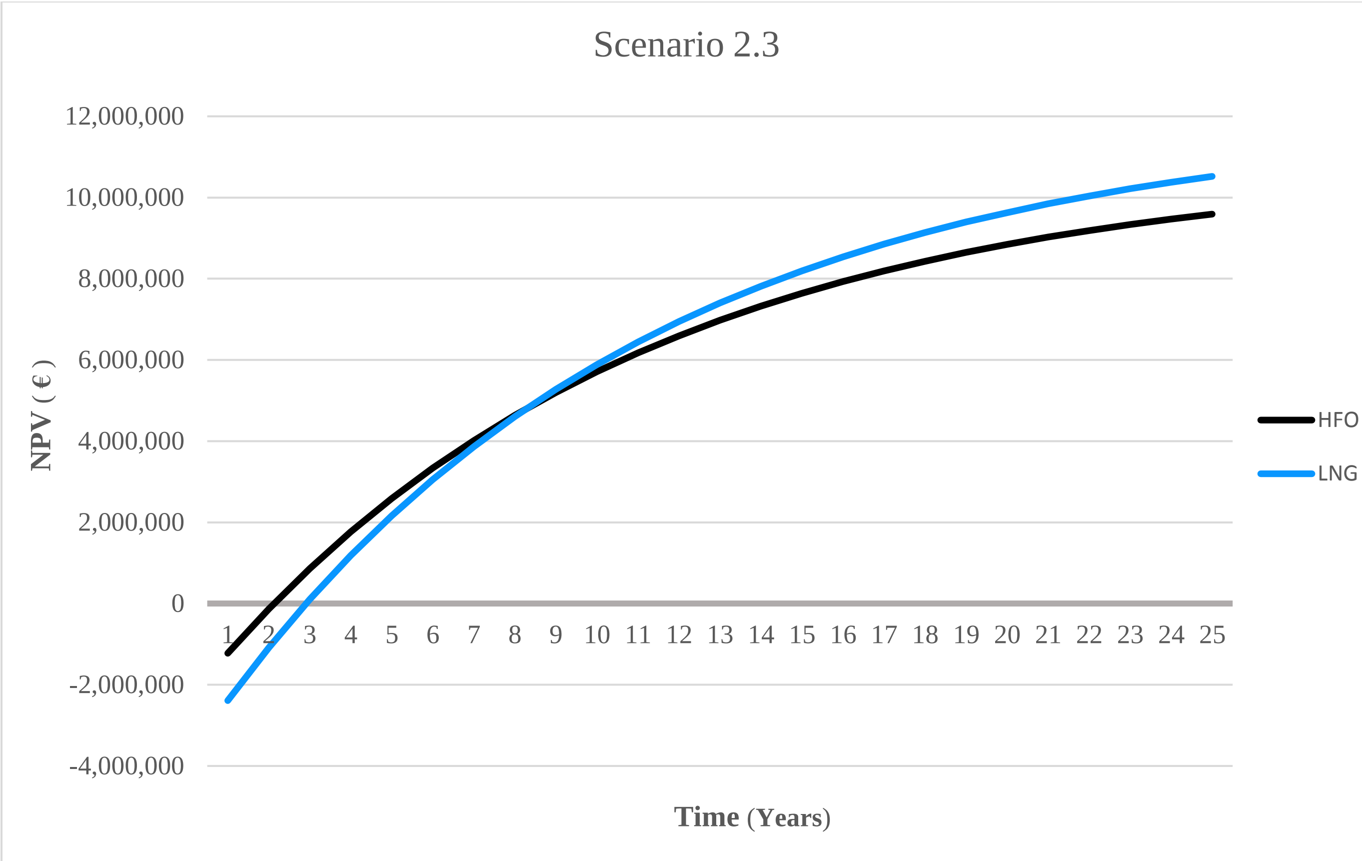
As can be seen in Figure 23, the NPV$_{LNG}$ starts from a value of - 1,691,406.80 € and reaches the value of 17,503,754.90 € by the end of the twenty-five-year period, while the NPV$_{HFO}$ starts from a value of - 1,224,494.23 € and reaches the value of 9,590,853.38 €. The payback time for those investments is two and three years respectively.



NPV_{HFO} = € 9,590,853.38 **NPV_{LNG}** = € 15,175,934.13

Figure 24 – NPV Scenario 2.2, Reference vessel 2

Figure 24 shows that the NPV_{LNG} starts from a value of - 1,924,544.55 € and reaches the value of 15,175,934.13 € by the end of the twenty-five-year period, while the NPV_{HFO} starts from a value of - 1,224,494.23 € and reaches the value of 9,590,853.38 €. The payback time for both investment alternatives is three years.



NPV$_{HFO}$ = € 9,590,853.38 **NPV$_{LNG}$** = € 10,520,292.58

Figure 25 – NPV Scenario 2.3, Reference vessel 2

According to Figure 25, the NPV$_{LNG}$ starts from a value of - -€ 2,390,820.05 € and reaches the value of 10,520,292.58 € by the end of the twenty-five-year period, while the NPV$_{HFO}$ starts from a value of - 1,224,494.23 € and reaches the value of 9,590,853.38 €. Same as with scenario 2.2, the payback time of both alternatives is three years.

4.5 Discussion

Prior to discussing the results, as illustrated in the previous section, it is important to point out two details. First, the presented NPV values, for both HFO and LNG, are the outcome of the comparison of those fuels with the MGO solution, which is the base case. The calculated capital investment costs as well as the annual cashflows result from the difference of the costs between

MGO and each of the other two alternatives. Thus, the horizontal axis of the graphs not only represents the years of the operational life of the vessels but could be considered as the NPV of MGO too, which would be zero.

Second, although the results of the NPV calculations appear to have high values, what is not obvious is that the capital costs do not represent the total cost of a newbuild ship, but only the cost of the propulsion system. Including the cost of building the ship in a shipyard, would not have an effect on which solution is most cost-effective, as this cost would be the same for each vessel across scenarios, but would make the payback time of the investment longer due to the higher capital costs.

Nonetheless, by examining the graphs it becomes apparent that there is no scenario in which MGO is the most attractive investment option compared to the alternatives.

In scenario 1.1 HFO is the fuel with the lowest bunker price, followed by LNG and, subsequently MGO, which is the fuel with the highest bunker price in nearly all scenarios. In this pricing scenario, LNG is the most cost-effective fuel for both reference vessels. For RV1, the NPV value for LNG, compared to the HFO NPV value, is approximately 800,000 € higher while the payback time occurs during the 5th year for HFO and during the 6th year for LNG. For RV2 though, the difference between the NPV values is smaller, with LNG having an NPV value approximately 200,000 € higher than HFO and payback times of 5 and 4 years respectively.

In scenario 1.2 the bunker prices of HFO and MGO remain the same as with scenario 1.1 but the LNG bunker price rises due to the medium level of the natural gas price. Nevertheless, LNG is still more expensive than HFO and more economical compared to MGO. In this scenario, solely from a cost perspective, HFO is the most attractive solution among the alternatives. For RV1 the NPV value of HFO is approximately 1,000,000 € higher than the NPV value of LNG, while for RV2 the difference is approximately 2,100,000 €. With regards to the payback time, for RV1 payback occurs during the 5th year for HFO and during the 9th year for LNG, while for RV2 during the 4th and the 7th year respectively.

Scenario 1.3 introduces the highest price of natural gas which subsequently drives the LNG bunker price to a level above the MGO bunker price, since the price of crude oil remains stable at its medium level. This is the only scenario in which MGO is not the most expensive fuel. Same as with scenario 1.2, HFO is the most attractive solution to invest on, as it results in the highest NPV value for both vessels, but with RV2 having an NPV 69% higher than RV1 by the end of the twenty-five-year period. However, in this case The NPV of the LNG solution results in a negative value. A negative NPV for LNG means that both MGO and, consequently, HFO are more cost-effective solutions compared to LNG. Hence, investing in the installation of abatement technologies for diesel engines is more attractive than investing in a gas engine. Regarding the payback time of the HFO solution it will occur during the 5th year for RV1 and during the 4th year for RV2 while for LNG, the investment generates losses.

In scenarios 2.1, 2.2 and 2.3, the crude oil price settles on its high value while the price of natural gas is following the same pattern as in scenarios 1.1, 1.2 and 1.3. Therefore, in scenario 2.1 where the price of natural gas is on its low level, the bunker price of LNG is more competitive even than the price of HFO. Thus, it becomes apparent that investing on LNG will be the most cost-effective solution for both vessels. In addition, compared to scenario 1.1 the results show that in this case LNG generates substantially higher NPV than HFO. Specifically, for RV1 the NPV for LNG compared to that for HFO, is approximately 6,600,000 € higher and with payback times occurring during the 3rd and the 4th year respectively. Though, for RV2, as opposed to scenario 1.1, the difference between the NPV values is even larger with LNG having an NPV value approximately 7,900,000 higher than HFO and payback times of 2 and 3 years respectively.

In scenario 2.2, same as with scenario 1.2, the bunker price of LNG is lower than this of MGO and higher than HFO. However, in this case the price differentials are different as the LNG price is much closer to that of HFO. This results in NPV values which are far more favorable for LNG than HFO. Specifically, for RV1 LNG generates an NPV which is approximately 4,900,000 € higher than that of HFO while for RV2 the difference is approximately 5,600,000 €. The payback time for LNG and HFO is 3 and 4 years, respectively, for RV1 while for RV2 payback occurs during the 3rd year for both fuel alternatives.

In scenario 2.3, both crude oil and natural gas are standing on their high prices. As opposed to scenario 1.3 where LNG is the least cost-effective compliance solution, in this case its NPV is even higher than that of HFO for both vessels. Specifically, for RV1 the difference is approximately 1,300,000 € while for RV2 is approximately 900,000 €. In addition, it is interesting to notice that with the price differentials of this scenario, both the HFO and the LNG solutions share the same payback time. Payback occurs during the 4th year for RV1 and during the 3rd year for RV2.

The results show that investing on vessels running on LNG is a more cost-effective solution than investing on vessels running either on HFO or MGO, for most pricing scenarios. Though, there are also other points that can be made regarding fuel prices, consumption rates, and payback times.

By comparing, the amount of capital that needs to be invested in order to install each of those systems, with the NPV that is generated from that investment, it can be advocated that the impact of the operational costs or savings on the NPV is substantially more critical than that of the capital costs. This is not surprising as the annual operating costs are a considerable fraction of the initial investment. Thus, it becomes apparent how important the role of the fuel prices is, as their levels, as well as their differentials, could really subvert what is considered as cost-effective and what not. It is important to point out that although in this analysis the fuel prices remain constant throughout the twenty-five-year period, in a real case scenario the fuel prices could be highly variable in a timeframe of twenty-five years which would significantly impact the NPV of each alternative.

It is also important to notice that the higher consumption rates of RV2 have a significant effect on the NPV's. Therefore, the impact of the fuel prices on NPV, will be more significant for RV2 than it will be for RV1 in general. In addition, since vessels running on either HFO or LNG generate savings compared to vessels running on MGO, higher consumption rates will result to higher savings. This means that regardless which of the three alternatives will be the most cost-effective, the cost of the initial investment will be recovered in shorter time for RV2.

Furthermore, as it can be seen from the results in scenarios 2.1, 2.2 and 2.3 where the crude oil stands on its higher price, the payback period of investing in either LNG or HFO is less than five years, on top of the payback period of the MGO solution, for both RV1 and RV2. However, for RV2 specifically, this time is even shorter as payback for investing in the LNG solution in scenarios 2.1, 2.2 and 2.3 occurs during the 2nd, the 3rd and the 3rd year respectively. Such a short payback period means that, given technical challenges are overcome, retrofitting could potentially be a feasible option too, in some cases, regardless the limited remaining operating life.

Finally, it is interesting to mention that several ports around the North European ECA are offering financial incentives that further encourage shipowners to invest in vessels with better environmental performance, or LNG specifically. Good examples are the port of Rotterdam, The Netherlands which offers discounts in the gross tonnage portion of the port dues depending on the environmental performance of a vessel ("Port of Rotterdam promotes cleaner shipping", 2017) as well as a 10% discount on vessels which are bunkering LNG in the port until 2020 ("Port of Rotterdam offers discount for vessels bunkering LNG", 2015), the port of Tallinn, Estonia which offers a 4% discount on tonnage fees for LNG vessels ("Ships that use LNG receive a discount at Port of Tallinn harbours | Tallinna Sadam", 2017), the port of Pori, Finland which offers a 10% discount on LNG vessels ("10% discount to LNG-fueled vessels | Port of Pori", 2017), the port of Gothenburg which offers a discount of 20% to LNG fueled vessels (Port of Gothenburg, 2018) and possibly more. However, quantifying the impact of those reductions on the business case is difficult due to the lack of port calls data for the reference vessels, as well as the fact that the amount of those reductions varies from port to port.

5. Conclusion

The purpose of this study was to evaluate whether LNG can be considered as a competitive fuel alternative for short-sea shipping in the North European waters, under the IMO’s Tier III regulatory regime. The researched subject is not only broad, but it is also under ongoing development. An in-depth research of the topic requires examining several perspectives as the number of the involved parties is large, and each has its own interests. Within the scope of an individual Master Thesis is not possible to examine all those perspectives in detail though.

This study examines the relevance of LNG as marine fuel, and what its current state is, and focuses on the factors that have the most direct effect on the take-off of LNG. Namely, environmental regulations in the area under discussion, the most competitive alternative solutions, and under what future pricing scenarios would LNG be the most cost-effective solution.

The results of the research show that for newbuild tankers, bulk carriers and container vessels that spend 100% of their operating time inside the North European ECA, LNG is a competitive alternative indeed.

LNG as marine fuel is not new. It is a subject that is being researched for longer than a decade and the technology to utilize it as fuel is already in place. Large engine manufacturers have been developing a variety of engines and tanks that, although space demanding, can sufficiently support the dedicated use of LNG. However, bunkering operations are heavily depended on the availability of small-scale infrastructure, as the existing infrastructure is optimized for other types of end-users.

Investing in small-scale infrastructure is a considerable risk for the bunker suppliers given the uncertainty of the demand for bunker LNG. Though, the same stands for the shipowners regarding the uncertainty of the LNG supply. The literature describes this situation as the chicken-egg problem. Nonetheless, there are indications that this situation is likely to be resolved in the short-to-medium-term. Apart from the increasing number of LNG vessels on order and the ports with existing or under construction small-scale infrastructure, there are also other factors, such as subsidies, standardization of operation processes, and legislation, that further encourage the outspread of LNG as marine fuel.

Another important aspect of this study concerns the upcoming environmental regulations, which will enforce the Tier III limits in the North European ECA, and how LNG compares to its strongest competitors, HFO and MGO, under those stricter emission limits. The research shows that natural gas is cleaner than crude oil, and that LNG outperforms both HFO and MGO from an environmental perspective. Whereas vessels utilizing gas engines and running on LNG will be in compliance with the stricter limits, vessels utilizing diesel engines will require the installation of additional abatement technologies in order to comply. However, despite the costs for the acquisition and installation of the additional equipment, investing in a gas fueled system is significantly more expensive.

To assess the economic feasibility of LNG compared to its alternatives, the preferred method is the development of pricing scenarios for crude oil and natural gas, and the calculation of the NPV for two reference vessels. Data for costs and fuel prices were obtained from the literature and the Internet. The price levels that were considered for the scenarios were a low, medium and high price for natural gas, and a medium and high price for crude oil. LNG proved to be the most cost-effective solution, for both reference vessels, in all the scenarios where the crude oil stands on its high price. Though, when the crude oil stands on its medium price, LNG is the most cost-effective solution only when the price of natural gas stands on its low value, for both vessels as well. In the rest of the cases, the HFO solution is the most cost-effective one.

However, this study it is not without its limitations. What could be considered as the main drawback of the research, is the assumptions that were made, due to the lack of data, in order to calculate the operating costs of the vessels. Aspects of the operational profiles of the vessels that could possibly have a significant effect on the outcome of the calculations, are not being accounted for. Given how significant the impact of the operating costs has been on the calculated NPV’s, it would be interesting to see how those parameters would affect the results.

Concluding, it is evident that this study cannot be used as a tool for making a decision on which compliance solution to invest on. Nonetheless, it provides insight in one of the alternatives to the already established HFO and MGO, and a rough estimate of what the costs and financial benefits would be for the shipowners. Though, apart from LNG there are also other alternatives to the crude oil products that could comply with the Tier III limits, such as gas-to-liquids (GTL) fuels. According to Brown, (2013) GTL diesel is a product of natural gas transformation, is nearly Sulphur-free and shares the same physical characteristics with the diesel produced from crude oil. Meaning, that GTL diesel can utilize the existing, and already developed, downstream oil infrastructure to its full potential. Hence, GTL would make a very interesting case to build upon the existing scope and further research as a competitive alternative to LNG. Eventually, it is the fuel prices that will determine the most cost-effective solution. Though, given how volatile they might be, it would not be surprising to see periods of deeps or peaks, during the operating life of a vessel, swinging the analysis in favor of another option.

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APPENDICES

Appendix 1.

<u>Adjusting for inflation</u>

The adjustment for inflation will be based on the industrial Producer Price Index (PPI) which measures the development in price movements of wholesale products, excluding any kind of taxes, transport and trade margins burdening the buyer ("Prices - Producer price indices (PPI) - OECD Data", 2017)

According to OECD data, and with 2010 as the base year (2010 = 100), the Manufacturing PPI of EU 28 in 2012 was equal to 107.92 and in 2016, equal to 102.88.

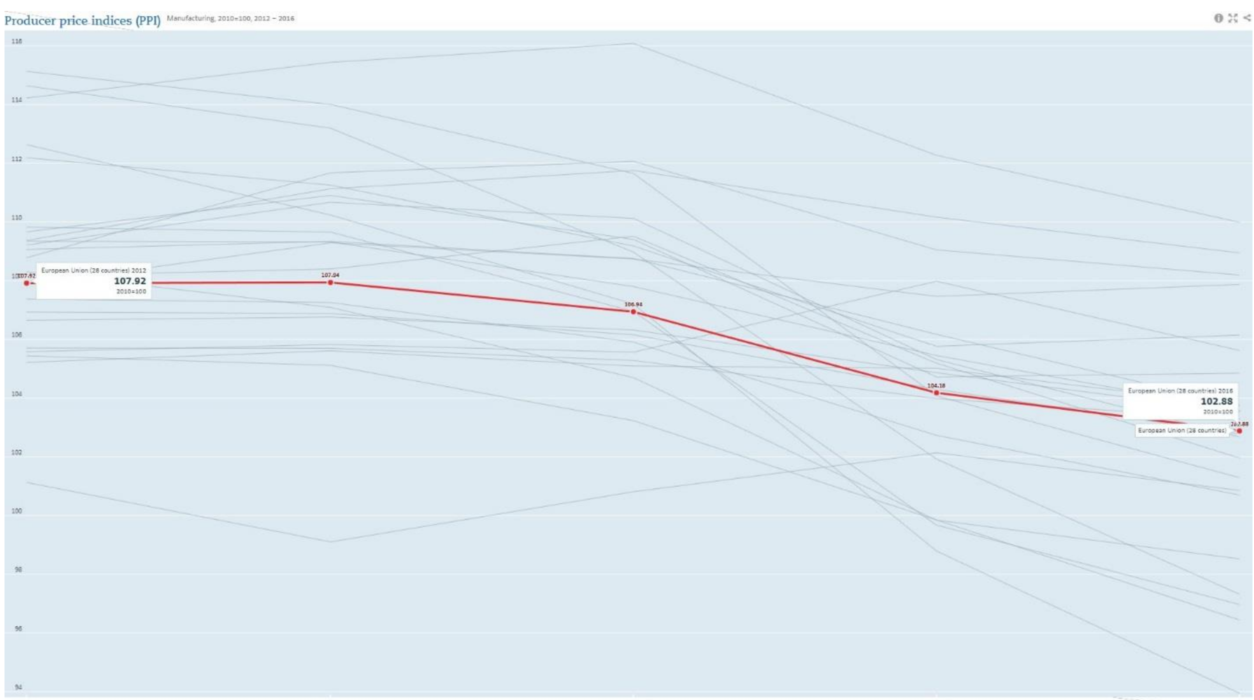

Figure I – Small PPI Manufacturing, 2010 = 100, 2012 - 2016

Source: "Prices - Producer price indices (PPI) - OECD Data", 2017

Thus, the adjustment ratio for the 2012 costs will be:

$$Adjustment\_Ratio = \frac{PPI_{2016}}{PPI_{2012}} = \mathbf{0.956}$$

Appendix 2.

<u>Capital and operational costs data</u>

INVESTMENT COSTS (New builds) - MGO		
Investment motor conversion/fuel cooler/fuel pumps	95,600	€
Investment SCR (incl installation new built)	43	€ / $kW_{main+aux}$
Investment engine	172	€ / kW_{main}
Investment Generators, Electric system, (Propulsion, Steering)	229	€ / kW_{aux}

The auxiliary engine is assumed to be 20 % of the main engine's installed power

Source: The Danish Maritime Authority (2012)

INVESTMENT COSTS (New builds) - HFO / Scrubber		
Investment scrubber (incl waste storage)	143.4	€ / kW_{main}
Investment SCR (incl installation new built)	43.02	€ / $kW_{main+aux}$
Investment engine	172.08	€ / kW_{main}
Investment Generators, Electric system, Propulsion, Steering	229.44	€ / kW_{aux}
Installation cost scrubber	172.08	€ / kW_{main}

The auxiliary engine is assumed to be 20 % of the main engine's installed power

Source: The Danish Maritime Authority (2012)

INVESTMENT COSTS (New builds) -LNG: Spark ignition 4-stroke		
Investment gas engine	335	€ / kW_{main}
Investment Generators, Electric system, (Propulsion, Steering)	382	€ / kW_{aux}
Investment LNG fuel gas supply system + tank	234	€ / kW_{main}
Installation cost	96	€ / $kW_{main+aux}$

The auxiliary engine is assumed to be 20 % of the main engine's installed power

Source: The Danish Maritime Authority (2012)

Operational costs for SCR	0.007	€ / kWh_{main}

Source: The Danish Maritime Authority (2012)

Operational costs for scrubbers	0.00239	€ / kWh_{main}

Source: The Danish Maritime Authority (2012)

All the costs presented in the above tables have been adjusted for inflation.

Appendix 3.

Consumption rates

The specific consumption rates, as can be seen in the table below, that Bengtsson, Andersson & Fridell, (2011), provide for the different alternative solutions, do not seem to be fit for this study despite the fact they are focused on short-sea vessels.

	HFO		MGO		LNG
	Baseline	Changes with scrubbers	Baseline	Changes with SCR	Baseline
Specific fuel consumption (g / kWh)	213	217	203		183

Specific fuel consumption

Source: Bengtsson, Andersson & Fridell (2011)

The reason is the annual amount of consumed LNG that results from those rates. By taking RV2 as a reference, the annual amount of consumed LNG is equal to 14,412.8 Mt. Though, according to more recent sources this number is not indicative.

Specifically, as can be seen in Table 5, The Danish Maritime Authority, (2012), gives an annual consumption of 4,500 Mt, which is approximately 3.2 times lower. In addition, Faber et al., (2015), for a container ship of total installed power of 12,194 kW gives an annual consumption of 10,988 m3, which translates to 4,944.6 Mt (Appendix 5). This is approximately 2.9 times lower.

Thus, to get more realistic results regarding the total amount of fuel consumed per annum, the consumption rates that will be considered for the case, as can be seen in Table 7, will be as provided by Bengtsson, Andersson & Fridell, (2011), but divided by 3.

Appendix 4.

<u>Prices data</u>

Since the data for capital and operational costs are given in euros, while the fuel costs are given in US dollars it becomes apparent that an exchange rate value is needed as reference. Therefore, the EURO to USD exchange rate that will be used is the 90 days average, as of November 21, 2017, as provided by XE: Convert EUR/USD. Euro Member Countries to United States Dollar, (2017) and which will be equal to 1 EUR = 1.17382 USD.

Date	Brent crude price $/bbl.	Brent crude price $/mt	IFO 380 Rotterdam $/mt	Brent/IFO 380 Price Differential $/mt	Brent/IFO 380 % Price difference	MGO Rotterdam $/mt	Brent/MGO Price Differential	Brent/MGO % Price difference
14-11-16	44.43	334.56	249.5	85.06	25.42%	394.5	-59.94	-17.92%
22-11-16	49.12	369.87	261	108.87	29.43%	422.5	-52.63	-14.23%
29-11-16	46.38	349.24	268	81.24	23.26%	414.5	-65.26	-18.69%
05-12-16	54.94	413.7	285.5	128.2	30.99%	445	-31.3	-7.57%
13-12-16	55.72	419.57	307	112.57	26.83%	457	-37.43	-8.92%
21-12-16	54.46	410.08	305.5	104.58	25.50%	467	-56.92	-13.88%
05-01-17	56.89	428.38	312.5	115.88	27.05%	477.5	-49.12	-11.47%
13-01-17	55.45	417.54	312	105.54	25.28%	472.5	-54.96	-13.16%
23-01-17	55.23	415.88	307.5	108.38	26.06%	466	-50.12	-12.05%
01-02-17	56.8	427.7	295.5	132.2	30.91%	472.5	-44.8	-10.47%
10-02-17	56.7	426.95	303	123.95	29.03%	478.5	-51.55	-12.07%
21-02-17	56.66	426.65	308	118.65	27.81%	484	-57.35	-13.44%
03-03-17	55.9	420.93	304	116.93	27.78%	478	-57.07	-13.56%
15-03-17	51.81	390.13	276	114.13	29.25%	444.5	-54.37	-13.94%
28-03-17	51.33	386.51	278	108.51	28.07%	441.5	-54.99	-14.23%
06-04-17	54.89	413.32	296	117.32	28.38%	467	-53.68	-12.99%
18-04-17	54.89	413.32	301.5	111.82	27.05%	474	-60.68	-14.68%
27-04-17	51.44	387.34	285.5	101.84	26.29%	451	-63.66	-16.44%
04-05-17	48.38	364.3	277.5	86.8	23.83%	427	-62.7	-17.21%
16-05-17	51.65	388.92	292	96.92	24.92%	440	-51.08	-13.13%
25-05-17	51.46	387.49	306	81.49	21.03%	460.5	-73.01	-18.84%
06-06-17	50.12	377.4	285.5	91.9	24.35%	428.5	-51.1	-13.54%
16-06-17	47.37	356.7	279	77.7	21.78%	419.5	-62.8	-17.61%
21-06-17	44.82	337.49	274	63.49	18.81%	408.5	-71.01	-21.04%
03-07-17	49.68	374.17	292.5	81.67	21.83%	428	-53.83	-14.39%
14-07-17	48.91	368.74	288.5	80.24	21.76%	435	-66.26	-17.97%
25-07-17	50.2	378.23	292	86.23	22.80%	441	-62.77	-16.60%
09-08-17	52.7	396.83	305.5	91.33	23.01%	467	-70.17	-17.68%
18-08-17	52.72	396.98	295	101.98	25.69%	461.5	-64.52	-16.25%
30-08-17	50.86	381.47	299	82.47	21.62%	465.5	-84.03	-22.03%
07-09-17	54.49	410.31	313.5	96.81	23.59%	491.5	-81.19	-19.79%
15-09-17	55.62	418.52	320.5	98.02	23.42%	501	-82.48	-19.71%
25-09-17	59.02	444.42	322	122.42	27.55%	509.5	-65.08	-14.64%
03-10-17	56	421.68	317.5	104.18	24.71%	504.5	-82.82	-19.64%
12-10-17	56.25	423.56	317.5	106.06	25.04%	496	-72.44	-17.10%
25-10-17	58.44	440.05	328	112.05	25.46%	499.5	-59.45	-13.51%
06-11-17	64.27	481.62	358	123.62	25.67%	533	-51.38	-10.67%
13-11-17	63.16	475.59	365	110.59	23.25%	542.5	-66.91	-14.07%
Average					24.99%			-15.77%

Source: "Rotterdam Bunker Prices", (2017a, 2017b); "CO1 Commodity Quote - Generic 1st 'CO' Future", (2017)

Appendix 5.

Conversions of units

The conversion of MMBtu to Metric tons (Tonnes), for LNG, is achieved using the table below as provided by the International Gas Union, (2012). Thus, 1 Mt of LNG equals 53.38 MMBtu.

multiply by

	Tonnes LNG	m^3 LNG	Nm^3 gas	ft^3 gas	mmBtu	boe
Tonnes LNG		2.222	1,300	45,909	53.38	9.203
m^3 LNG	0.450		585	20,659	24.02	4.141
m^3 gas	7.692×10^{-4}	0.0017		35.31	0.0411	0.0071
ft^3 gas	2.178×10^{-5}	4.8×10^{-5}	0.0283		0.0012	2.005×10^{-4}
mmBtu	0.0187	0.0416	24.36	860.1		0.1724
boe	0.1087	0.2415	141.3	4,989	5.8	

Source: International Gas Union, (2012)

However, for the conversion of bbl. to Metric tons, the data presented on Appendix 3 have been used and based on the calculations, it is assumed that 1 Mt of Brent crude oil equals approximately 7.53 bbl.