A life cycle cost analysis of using alternative technologies on short sea shipping vessels in ECAs

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ABSTRACT

Air emission control has been targeted as an important issue in the decade. In ship industry, MARPOL ANNEX VI regulates the limit of emissions. The regulations will become stricter in the upcoming years. Ship owners face to a cost challenge due to the rising fuel price, especially the low sulphur marine diesel oil. This study focuses on the alternative solutions that fulfil with the MARPOL regulations. By comparing the life cycle cost to help ship owners make their decisions with different operation strategies. The life cycle cost analysis is applied to four vessel types (Ro-Pax, container feeder, cruise vessel and small ferry) which are mostly serviced in emission control area.

To figure out the feasibility of alternative solutions, a review of the most discussed technologies is conducted. Including the basic introduction, influence after installed on board, impacts to operation, cost data and related international conventions/classification rules. The case to switch marine gas oil (MGO) is chosen as a baseline, the life cycle cost analysis is performed with liquid natural gas (LNG), scrubber system and methanol as a fuel.

In the life cycle cost analysis, it is difficult to assess the price of types of fuel in the next 15 year life cycle. Instead of guessing the tendency of price escalation, this study gives four scenarios of price profile. According to the result of those scenarios, the sensitivity of lifecycle cost analysis due to fuel price can be observed. The total life cycle cost and the payback time of initial investment are two key targets in the comparison.

According to the LCCA result shown in this study, each alternative has its own advantages, depending on the type, purpose, routes and life time. There is no best solution for all vessels., but it is obvious that all alternatives are better than switching to MGO for short sea shipping vessels in SECAs.

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1. INTRODUCTION

Plenty of evidences have shown that the emissions of marine vessels significantly accounts for air pollution around the world. Compared to the onshore and aerial vehicles, the marine transportation is still the most efficient solution. At this moment, marine transportation is continually growing and expending in many region. However, Heavy Fuel Oil (HFO) is currently the only significant energy source and it produces a great amount of air pollutant emission such as sulphur oxide (SOx) and Greenhouse Gases (GHGs).

The International Maritime Organization (IMO) has a special responsibility for the regulation of international shipping, the safety at sea, and the prevention of marine pollution. Because of growing limitation and restriction of the international conventions developed by IMO, the ship owners have to face a strict challenge to comply with the environmental regulations. In order to achieve the limit as Nitrogen oxides (NOx), SOx and other GHGs emission control that regulated in International Convention for the Prevention of Pollution from Ships (MARPOL) Annex VI, there are many solutions and methods mentioned in different researches. As ship owners face a numbers of tradeoff in terms of investment and trading when they do business within the further Sulphur limits of Emission Control Areas (SECAs), alternative fuel is considered to be a crucial substitute to solve this problem.

There are many different types of alternative fuels which have been discussed, Marine Gas Oil (MGO) is an option for diesel powered vessels to replace the HFO, with sulphur content complying with the SECA requirement. The price of MGO is, however, extremely higher than HFO which increases the owner’s operation cost with the rising fuel price. Liquefied Natural Gas (LNG) has been suggested to be used as a marine fuel due to its low sulphur content. But the engine modification and fuel tank cost was concerned; the infrastructures and bunkering of LNG are still a question mark. There are few studies mentioned about Methanol, another green energy for the future, a multi-source and multi-purpose fuel. Methanol and di-methyl ether (DME), a production converted from methanol, both can be burned in diesel engine with minor modification.

The shipping industry today is facing severe challenges due to the upcoming exhaust gas emission regulations. The amount of emission of SOx and NOx from shipping is considerable, thus the reduction has to be made. Three main solutions have been investigated for years which are switching to low sulphur fuel, installing scrubbers and using LNG. However, very little information is available on methanol as a marine fuel. The aim of this study is to compare different types of alternative methods for the future. However, the initial study showed that LNG, methanol and scrubbers all come with a space problem onboard the ship, the detail constrain will be mentioned in the following chapter. Therefore, this study focuses on the short sea (in SECAs) transportation vessels with Life Cycle Cost Analysis (LCCA) to analyze the cost and payback between different solutions.

2. LITERATURE REVIEW

2.1. International Regulations

2.1.1. Emission Controls

The MARPOL [1] is the main international convention covering prevention of operational or accidental pollution of the marine environment by ships. MARPOL Annex VI, specifically addressing air pollution from ships entered into force in 2005. The Baltic Sea Sulphur Emission Control Areas has been in force since 2005, and the North Sea and English Channel SECA went into effect in 2007. In August 2012 the North American SECA covering the US coasts and Hawaii came into force and from 2016 the area will encompass NOx emission control requirements. In January 2014 the US Caribbean SECA covering Puerto Rico and the US Virgin Islands is due to take effect.

One of the key factors behind the drive to alternative fuels is the approach of year 2015 when stricter rules under MARPOL Annex VI enter into force in the SECAs. Ship owners with vessels operating in these areas must get their priorities absolutely right. Within SECAs, the maximum allowable sulphur content of fuel oil now is 1%. After 1st January 2015 it will be limited to 0.1%. The currently global maximum sulphur content of fuel oil is regulated at 3.5% and will last until 1st January 2020 (or possibly until 2025) and will be amended to 0.5%.

The red zone in figure 1 shows the current SECAs distribution, and figure 2 represents the sulphur content limitation in SECAs and global area in following years.

Figure 1 Current SECAs

[Lloyd's Register 2012- Understanding exhaust gas treatment systems]

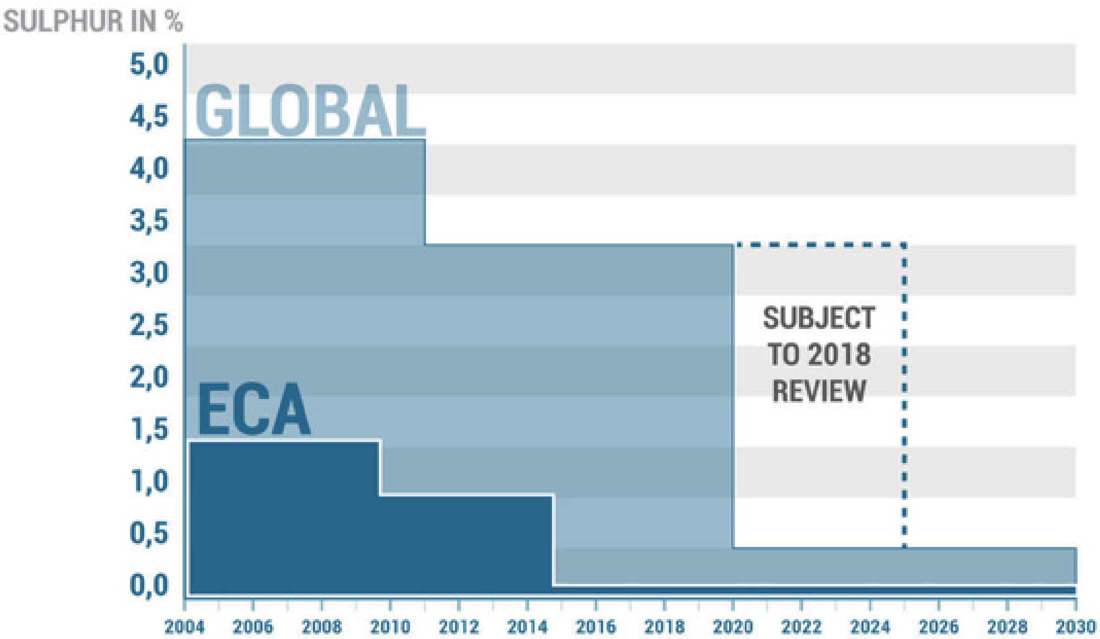


Figure 2 SOx limit by Annex VI regulation

[Lloyd's Register 2012- Understanding exhaust gas treatment systems]

The potential future SECAs includes the Caribbean, the Mediterranean, Japan and Singapore. In addition to the decided designations of SECAs, some additional areas are also discussed as indicated by the map below. The light blue areas are expected to become SECAs in the future.

Figure 3 Estimated SECAs in future
[http://blogs.dnv.com/lng/2011/02/lng-for-greener-shipping-in-north-america/]

Besides the SOx, ship constructed after 1st January 2000 shall comply with NOx Tier I standard regulated in MARPOL Annex VI regulation 13. Ship built on or after 1st January 2011 shall fulfill the Tier II standard. The emission control areas of NOx include North America and United States Caribbean Sea. For vessels engage in ECAs and built on and after 1st January 2016 are to be in accordance with the Tier III standard. But the due date of Tier III is not fixed yet. The Marine Environment Protection Committee (MEPC) considered and agreed to propose an amendment to this regulation [2]. The implementation date of Tier III standard might be postponed to 1st January 2021. The draft amendment will be circulated for consideration at MEPC 66 in 2014.

Table 1 NOx emission limits

Tier	Date	NOx Limit, g/kWh		
		n < 130	130 ≤ n < 2000	n ≥ 2000
Tier I	2000	17	45 · n-0.2	9.8
Tier II	2011	14.4	44 · n-0.23	7.7
Tier III	2016†	3.4	9 · n-0.2	1.96

† In NOx Emission Control Areas (Tier II standards apply outside ECAs).

The limits of NOx emission are dependent on the speed of engine, figure 4 shows the relationship between the engine speed and the limits of different standard.

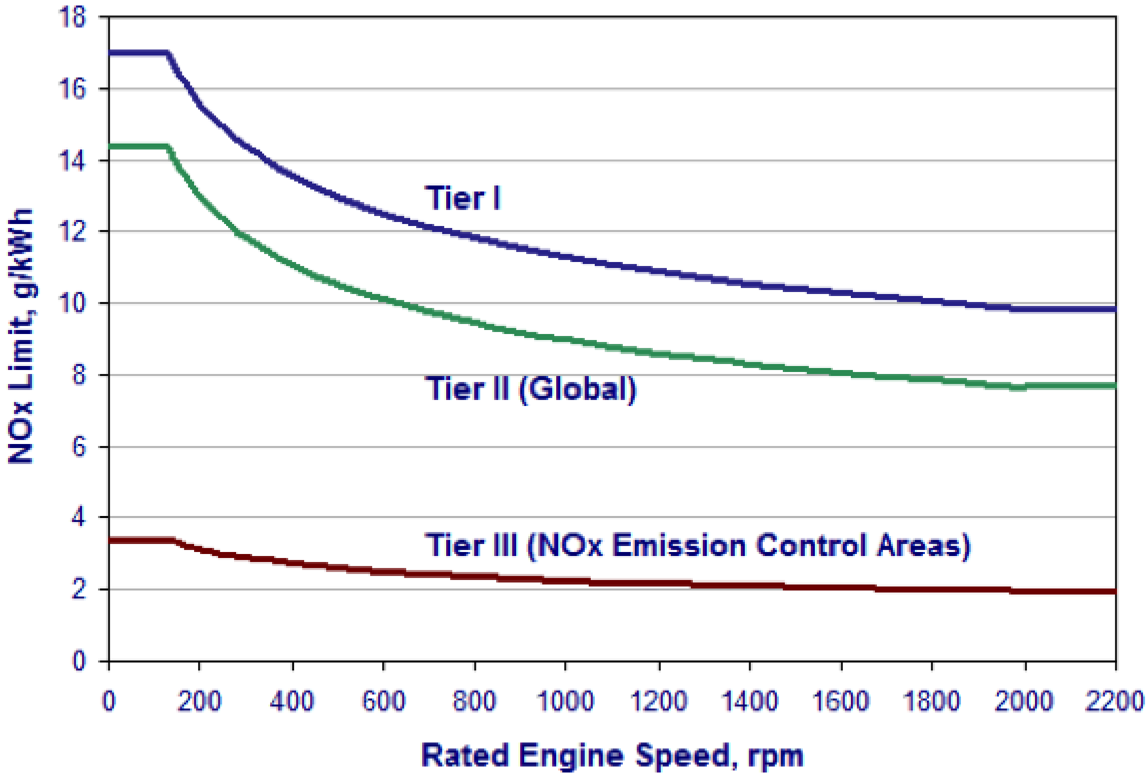


Figure 4 NOx limit related to engine speed

Although international shipping is the most efficient mode of cargo transport, a global approach to further improves its energy efficiency and effective emission control is needed. Therefore, IMO has been pursuing the limitation and reduction of GHGs emissions from international shipping. The new chapter of MARPOL Annex VI entitled "Regulations on energy efficiency for ships" was adopted by IMO's MEPC. Including Energy Efficiency Design Index (EEDI) for new ships and the Ship Energy Efficiency Management Plan (SEEMP) for all ship. The regulations apply to all ships 400 gross tonnage and above and entered into force in 2013.

2.1.2. Safety Issue

As the regulations of NOx and SOx are getting stricter, the ship industry needs to use new types of fuel and / or implement exhaust gas clean techniques. The maritime industry will face a fuel and / or technology shift in the near future. Some of these shifting come with safety impact of ship operation.

The researchers have developed many solutions for ship owner to select [3]. Marine Gas Oil (MGO) can be use directly as conventional marine fuel without any conversion. The scrubber systems are design to eliminate the pollutant in exhaust gas. Vessels need a conversion to the exhaust system of engine; the huge weight and volume are to be considered. The stability of vessels affected by the installation should be calculated according to the requirements in International Convention for the Safety of Lifer at Sea (SOLAS) Chapter II-1 [4]. And additional piping system must comply the machinery and fire protection chapters. But there is no special requirement added into SOLAS.

LNG is actively discussed as an alternative fuel for marine transportation recently [5]. The storage of LNG is difficult compared to the conventional fuels. At the atmospheric pressure, natural gas is a liquid when it is cooled to -162°C. The main safety challenge is the explosion risk, because the LNG is flammable material when it is mixed with air. Moreover, when the temperature is low, the contact between leaked LNG and normal steel can cause crack damage. Normally LNG carriers would comply with the International Code for Construction and Equipment of Ship Carrying Liquefied Gases in Bulk (IGC Code) [6]. In this case LNG only carried as fuels other than cargo, therefore IMO establishes a new International Code of Safety for Ship Using Gases or other low-flash point fuels (IGF Code) [7], which is planned to be published and enter into force in 2014.

Methanol is not new power resource but it can be a new clean fuel for ship industry [8]. Methanol has a flash point at 12°C and is a flammable gas. As a result, different statutory regulations would need to be applied. The provisions about using methanol as a fuel will also be regulated in IGF code. Due to the fact the up-to-date draft does not specifically define the limitation, iIt might be an uncertainty of this study.

Classification societies are also responsible for the safety onboard the vessels. To ensure the safety operation of this upcoming conversion, classification societies are developing their own regulations and rules to await the arrival of the changeable future. There are a numbers of regulations and rules for gas fuelled ship published by classification societies. However, for low flash point fuel as methanol, only Det Norske Veritas (DNV) first released their rule on 1_{st} July 2013 and Lloyd's Register (LR) will publish theirs in 2014. Table 2 list the existing rules from each classification societies until 2013.

Table 2 The classification Rules about LNG and Methanol fuelled vessel

Class Society	Rules Name	Year of Publishing	Ship Class Notation
ABS	Propulsion and auxiliary systems for gas fuelled ships	1-May-2012	Gas Fuelled Ship – GFS
BV	Safety Rules for "Gas-Fuelled Engine Installations in Ships" Design & Installation of Dual Fuel Engines using Low Pressure Gas	May 2011 June 2007	
DNV	Gas fuelled engine installations, Part 6, Chapter 13 - Rules for classification of ships – Ships/High speed light craft and naval surface crafts, Special equipment and systems Additional class, New buildings	1-Jan-2011	GAS FUELLED
GL	Guidelines for the Use of Gas as Fuel on Ships Design and Installation of Dual fuel Engines Liquefied Gas Carriers (See I-1-2, Section 16) Machinery Installations (See I-1-2, Section 2)	2010	GF BGF
LR	Provisional Rules for Methane Fuelled Ships LR Rules for Natural Gas Fuelled Ships	2012	GF
PRS	Publ. 88/P - Guidelines on Safety for Natural Gas- fuelled Engine Installations in Ships	2010	
RINA	Gas Fuelled Ships, Rules Appendix 7	2012	Gas Fuelled Ship
DNV	Tentative Rules for Low Flashpoint Liquid Fuelled Ship Installations	1-Jul-2013	LFL FUELLED

ABS-American Bureau of Shipping **BV-Bureau Veritas** **DNV-Det Norske Veritas**

GL-Germanischer Lloyd **LR-Lloyd's Register** **PRS-Polish Register of Shipping**

RINA-Registro Italiano Navale

2.2. LNG Fuel Application

In January 2000, Glutra, the first ro-ro/passenger ferry in the world powered by LNG, starts service with MRF company. At present, MRF is merged to Fjord1, which is the largest domestic ferry company in Norway operating 12 LNG fuelled ferries currently.

M.V. Glutra [9] equipped with four Mitsubishi GS12R-PTK LNG engines with generator sets and the propulsion system driven by electric motor. The LNG is stored onboard the vessel in two vacuum and perlite insulated, stainless cryogenic tanks are located under the main deck of the ferry in double walled, rockwool filled, sheet metal stainless steel containers. The extra containers represent barriers for LNG escaping from the tanks and prevent the cryogenic fluid to reach and cool down the ordinary steel hull of the ferry causing steel brittleness. They have a maximum net LNG volume of 27,2 m^3 for each tank at the allowed maximum of 85% filling.

After the experiment of M.V. Glutra, ship owners looking forward to order new build LNG fuelled vessels, table 3 and 4 shows the list of exist vessel and the confirmed orders. Especially in recent years, the owners trying to face the emission problem in advance, there are more and more orders and types of LNG fuelled vessels. In this study, the different design will be compared to figure out the suitable solution for the future maritime market.

Table 3 Confirmed LNG fuelled vessel order book

Year	Type of vessel	Owner	Class
2013	Ro-Ro	Norlines	DNV
2013	Ro-Ro	Norlines	DNV
2013	Car/passenger ferry	Torghatten Nord	DNV
2013	Car/passenger ferry	Torghatten Nord	DNV
2013	Car/passenger ferry	Torghatten Nord	DNV
2013	Car/passenger ferry	Torghatten Nord	DNV
2013	RoPax	Viking Line	LR
2013	Tug	Buksér & Berging	DNV
2013	PSV	Harvey Gulf Int. Marine	ABS
2013	PSV	Harvey Gulf Int. Marine	ABS
2013	Car/passenger ferry	ferry Society of Quebec ferries	LR
2014	Car/passenger ferry	ferry Society of Quebec ferries	LR
2014	Tug	Buksér & Berging	DNV
2014	PSV	Harvey Gulf Int. Marine	ABS
2014	PSV	Harvey Gulf Int. Marine	ABS

Table 4 Existing LGN fuelled vessels

Year	Type of vessel	Owner	Class
2000	Car/passenger ferry	Fjord1	DNV
2003	PSV	Simon Møkster	DNV
2003	PSV	Eidesvik	DNV
2006	Car/passenger ferry	Fjord1	DNV
2007	Car/passenger ferry	Fjord1	DNV
2007	Car/passenger ferry	Fjord1	DNV
2007	Car/passenger ferry	Fjord1	DNV
2007	Car/passenger ferry	Fjord1	DNV
2008	PSV	Eidesvik Shipping	DNV
2009	PSV	Eidesvik Shipping	DNV
2009	Car/passenger ferry	Tide Sjø	DNV
2009	Car/passenger ferry	Tide Sjø	DNV
2009	Car/passenger ferry	Tide Sjø	DNV
2009	Patrol vessel	REM	DNV
2009	Car/passenger ferry	Fjord1	DNV
2010	Patrol vessel	REM	DNV
2010	Car/passenger ferry	Fjord1	DNV
2010	Patrol vessel	REM	DNV
2010	Car/passenger ferry	Fjord1	DNV
2010	Car/passenger ferry	Fjord1	DNV
2010	Car/passenger ferry	Fosen Namsos Sjø	DNV
2011	Patrol vessel	DOF	DNV
2011	Car/passenger ferry	Fjord1	DNV
2011	Patrol vessel	SolstadRederi	DNV
2012	Car/passenger ferry	ferry	DNV
2012	General Cargo	Nordnorsk Shipping	DNV
2012	PSV	Olympic Shipping	DNV
2012	PSV	Eidesvik	DNV
2012	PSV	Eidesvik	DNV
2012	Ro-Ro	Sea-Cargo	DNV
2012	Ro-Ro	Sea-Cargo	DNV
2012	High speed Ropax	Buquebus	DNV
2012	PSV	Island Offshore	DNV
2012	PSV	Island Offshore	DNV
2012	PSV	REM	DNV

2.3. Methanol Fuel Application

There is no vessels practically operated with methanol as fuel, but few projects are running with it. Methanol Auxiliary Power Unit (METHAPU) project [10] sponsored by EC aimed to evaluate methanol as a fuel onboard a cargo vessel engaged in international trade. The M/V Undine, a pure car and truck carrier equipped with Wartsila WF20 fuel cell generator onboard. And they concluded, use of an ‘alternative’ fuel successfully demonstrated onboard a ship which engaged in international trade and in compliance with all relevant statutory and classification requirements.

Stena Line is a firm believer in methanol as a marine fuel. Stena has decided to invest in methanol for their current ship. Spireth project [11] which is currently underway, has the aim testing methanol and di-methyl ether (DME) in marine engines. Project members include SSPA Sweden, ScandiNAOS, Stena Rederi, Haldor Topsøe A/S, Wartsila, Methanex and Lloyd’s Register EMEA. An auxiliary engine will be fuelled with a blend of methanol and DME utilize a technology called On Board Alcohol to Ether (OBATE). Methanol will be tested directly in a marine diesel engine in second test stream.

Stena announced that the M/V Stena Germanica will be converted to use its main engine to trial methanol. This will take place during 2014. If the trial proves successful, they will rebuild a further 24 vessels through to 2018 or 2020.

2.4. Life Cycle Cost Analysis for Alternative Fuels

The purpose of the Life Cycle Cost Analysis (LCCA) method is to define the overall cost of project alternatives and to select the design that ensures a reduction in Life Cycle Cost (LCC). LCCA became popular in 1960's, US government used it as a tool to improve cost effectiveness of public construction and equipment procurement.

LCC is concerned to optimize value of money in the ownership of physical assets by taking into consideration all the cost factors relating to assets during its operational life. Woodward [12] summarized the procedure and the process of information acquisition and application. LCC approach identifies all future cost and benefits and defines the elements such as discount rate, operating, maintenance and disposal costs. In order to evaluate the robustness and performance of LCCA, uncertainty and sensitivity analyzes are important.

Many departments of governments and universities started to use LCCA as their methodology to analyze their investment. Scholars and experts crate their own LCCA procedures such as [13] and [14]. In 1996 Sieglinde K. Fuller published a Life-Cycle Costing Manual [13] for the US Federal Energy Management Program to evaluate the economic performance of energy and water conservation projects. LCCA can be applied to any capital investment project estimating all costs arising from owning cost (design and build) and also operating, maintaining and ultimately disposing cost. This handbook provides guidance to US federal agencies in reducing the future cost of federal facilities.

In 2006, Department of Land and Buildings of Stanford University developed a guideline [14] to process the evaluation of the economic performance of a building over its entire life. Stanford classified the whole project into following general categories, including energy systems, mechanical systems, electrical systems, building envelope and structure systems. By comparing the LCC of various design configurations, LCCA can explore trading off between low initial cost and long-term cost saving. It can identify the most cost effective system, and determine how long it will take for a specific system to pay-back its incremental cost.

International Standard Organization (ISO) also presents a standard for LCCA in ISO 15686-5:2008 [15]. This document gives guidelines for performing LCCA of buildings, constructed assets and their parts. LCCA should cover a defined list of costs about the physical, technical, economic or functional life of a constructed asset, over a defined period of analysis.

Regarding the impact of MARPOL Annex VI to the ship industry, some researches used LCCA to evaluate the benefit of solutions that have potential to achieve the requirements. In 2009, AEA Technology at the request of European Commission reported a cost analysis of the new IMO marine fuel and engines standards and a potential extension of emission control areas [16]. To illustrate the abatement of unit cost of NOx and SO_x from shipping, address the scenario comparison among closed loop scrubbers, open loop scrubbers and low sulphur fuels, the unit costs are based on the costs for installation, maintenance, operation and fuel penalties for using the equipment. It concluded the use of scrubbers might be an economically attractive option in SECA.

As scrubber seems to be an option, a scrubber selection guide from the Glosten Associates described the LCCA of different scrubber types [17], Shih-Tung Shu established a complete LCCA for four types of ship with different scrubbers [18].

As LNG technique becomes more practical, Torstein R. Alvestad compared MGO, LNG and scrubber for chemical tanker in different remaining lifetime of vessels [19]. It concluded that for new built vessels LNG might be the most economical alternative. MGO seems to be a costly solution that only will be appropriate for very old vessels. Scrubbing technology can be the best choice for medium aged and old vessels. The Glosten Associates had another report for Washington State Ferries which compared the efficiency of diesel engines, diesel/LNG dual fuel engines and LNG engines onboard a new 144 cars ferry [20]. The modification of the vessel design for LNG fuel will result in a higher capital cost of the vessel. However, the operational cost savings offset the increased capital cost, and a payback period of approximately 6 years is anticipated for the gas fuelled vessel designs. If the life cycle is over 30 years, single fuel LNG engines can save more money than dual fuel engines.

3. ALTERNATIVE FUELS FOR MARINE TRANSPORTATION

As many documents mentioned before, there are mainly two alternative fuels for the ship owners, MGO and LNG. A concept of using methanol as a fuel comes up and could be a new option. Scrubber is a solution without changing fuel. On the other hand ship owner can give up trading in SECAs if it is not profitable with the new limitation.

This chapter will describe the basic information of each alternative and discuss the advantages and drawbacks.

3.1. Marine Gas Oil

The first alternative is to switch over to a type of distillate fuel. There are two types to choose, marine diesel oil (MDO) or MGO. These types of oil are obtained from petroleum distillation. Comparing to normal HFO, these are clean but MDO is a heavier distillate that contains some residuals. MGO is a pure distillate containing less sulphur, and having maximum 0.1% of sulphur content. Thus MGO is a cleaner alternative that complies with the SECAs requirement after 2015.

The biggest advantage of MGO is that it can be burned directly in normal marine diesel engines with slightly modification. MGO can be stored in normal fuel tank without additional treatment. MGO is the most convenient alternative fuel for ship owner because of no additional training cost, equipment cost and other additional material cost.

However, using 0.1% sulphur content MGO can only solve the SO_x problem. To comply the limit of NO_x Tier III the engine still need some NO_x abatement technologies.

The price of MGO is the main reason that owners seek for other alternatives. This type of fuel is more expensive than HFO, which is being burned by vessels operated in SECAs today. Figure 5 shows that MGO price is always 40% to 50% higher than HFO and will reach 1300 USD/tonne in 2025. In comparatively, HFO cost is estimated around 800 USD/tonne, which causes the difference is 500 USD/tonne. It becomes a motivation to use other technologies instead of using

One possible solution could be that the production cost of MGO is reduced. Especially for old vessels with short remaining life, ship owners are willing to keep operation without major conversion. In this case, MGO remains the first choice.

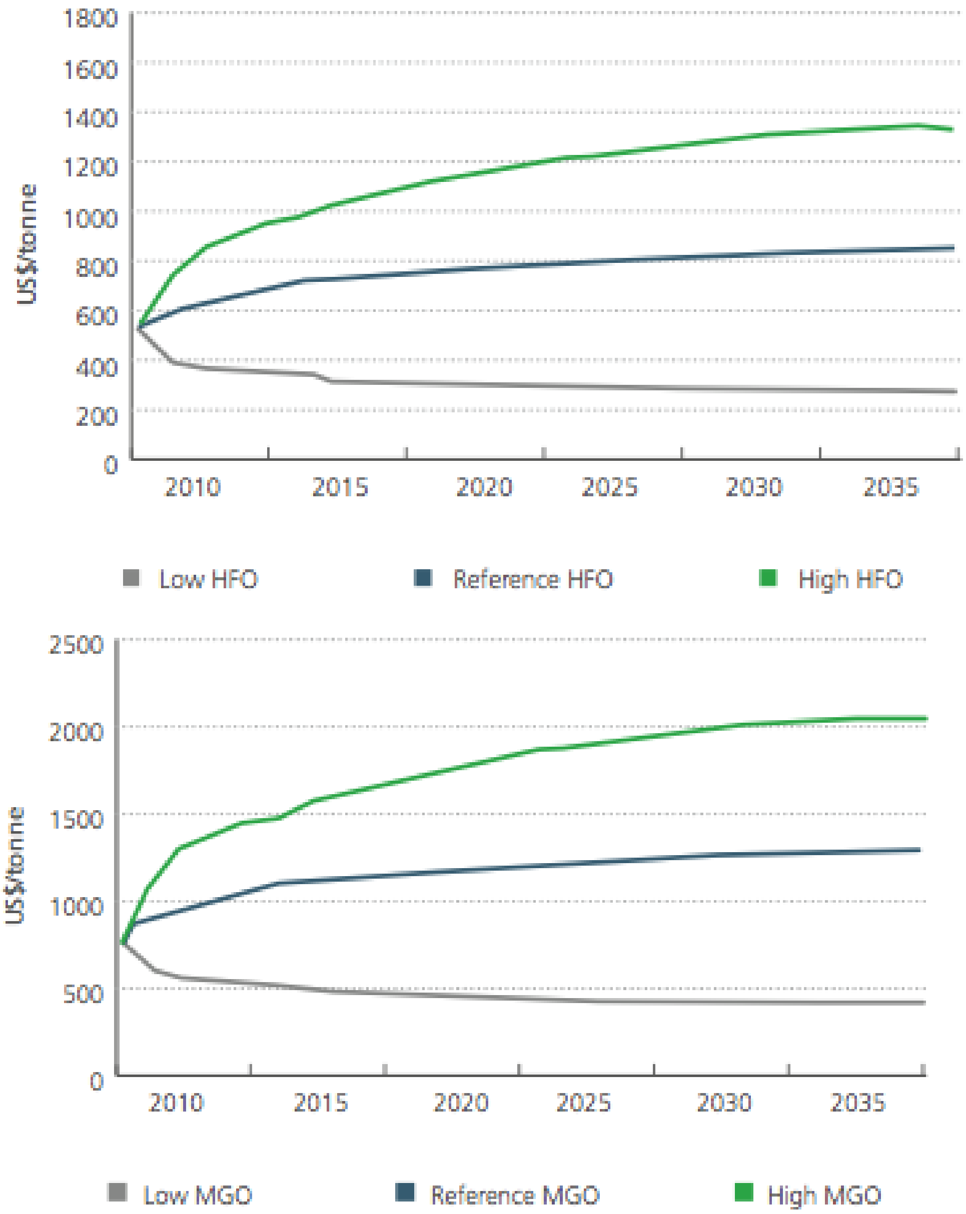


Figure 5 Price forecast of HFO and MGO [DNV Shipping 2020]

3.2. Liquefied Natural Gas

Natural gas is an energy source that expected to grow substantially in the future, it is wildly available and has many advantages compared to petroleum and coal. This section will give a brief introduction of the natural gas and LNG.

3.2.1. Basic Knowledge of Natural Gas and LNG

The natural gas composition varies from area to area, but mainly consists of 80-90% methane (CH4), and other hydrocarbon such as ethane (C2H6), propane (C3H8) and butane (C4H10). LNG is natural gas that has been cooled to the point that it condenses to liquid, which occurred at a temperature of -162°C and only takes 1/600 part of the volume natural gas has in gaseous state. The liquefaction process involves removal of oxygen, carbon dioxide, sulphur and water from the natural gas, thus LNG is almost pure methane.

LNG is a clean fuel for marine industry. Burning LNG can reduce air pollution emissions. Using LNG as a ship fuel has recently gained increasing attention not only in Europe but also in Asia and the USA. According to the report published by Germanischer Lloyd and MAN [21], using LNG as ship fuel will reduce SO_x emission about 100% and NO_x emission by 80% to 85%. The lower carbon content of LNG compare to traditional fuel enables a reduction of carbon dioxide emissions by 20% to 25%.

The price is also an advantage of LNG. Generally natural gas is sold by its energy content and not per unit of volume. It is common to state the cost of gas to industrial customers in terms of dollars per million British thermal units (MMbtu). One MMbtu is equivalent to 293 kilowatt hour (kWh). Due to the different energy content in fuels; it is more accurate to compare fuel price by the propulsion power rather than the quantity. Table5 shows that LNG is cheaper than MGO per unit propulsion power.

Table 5 Fuel price per unit propulsion power

	USD/ton	USD/MMbtu	USD/MWh
IFO 380	590.5	N/A	52.6
MGO	1015	N/A	79.17
LNG	N/A	12~17	41~58

The above advantages make LNG considered to be an alternative fuel for ship to achieve those emission limitations in the near future.

3.2.2. LNG Supply Chain

Depending on where the natural gas is found, its composition, distance to the market and size of the field, energy companies will determine how the energy is transported. For LNG transportation, it can be summarized as following steps.

Figure 6 The LNG production chain with per cent of total cost

1. Energy companies explore and produce the natural gas. At this stage, the energy is taken from the supply source, either offshore or onshore facilities, through pipelines into the processing facilities.
2. The LNG is produced. From the row product to LNG, the purpose is to concentrate the energy density. Liquefaction and remove the component other than methane.
3. After LNG is made, it can be transported to any place where requires this energy. LNG can be transported by rail, truck or vessels. Shipping becomes the most profitable solution when the distance is increasing. Today the capacity of the largest LNG carrier can carry 266,000 cubic meters. The LNG is kept cooled during transportation.
4. The LNG is sent to the receiving facility, which includes unloading from the LNG carrier and storage.
5. In the end, LNG is delivered to customers as fuel. LNG can be transfered by a bunker vessel or discharge from the storage directly.

3.2.3. Challenges

Space requirement is a common issue for LNG. From ship owner's perspective, the challenge related to room for LNG tank is important. Not only the LNG itself need more space than conventional fuel with the same energy content, the cylindrical form of the storage tank require 3-4 times the space of current fuel systems. Losing cargo space or passenger cabin is a big issue for ship owners. Due to different types of vessel, the location of fuel tanks will be various. Designers are required to modify the arrangement to get more space and consider the safety issue simultaneously.

LNG as a liquid is not flammable or explosive. However, when LNG as gas state and mixed with air, an explosion can happen in a enclose space. The mixture is between 5 and 15 percent, and ignition source is present. The proper designs, detect system, regulations and personnel training are needed to prevent any hazard occur.

LNG availability is also a limitation. Part of the infrastructure for distribution and bunkering of LNG is not available today in many places. This is a chicken and egg situation, the gas provider are not too keen to invest in the infrastructure if the demand from ship owners is not sufficient. On the other hand ship owners will not invest driven vessel if the LNG is too difficult to buy. According to LR's investigation in 2012 [22], 5 of 13 investigated ports are developing LNG infrastructure. It can be expected to increase quickly in the future.

3.2.4. LNG Fuelled Engine

Most of engines operated today are two stoke or four stoke diesel engines. There are also some gas turbines. Gas engines for marine applications have been developed, and it is possible to buy gas engines and dual- fuel engines on the market. There are two types of combustion technology provide by Wartsila. The LNG propelled ship today are either equipped with lean burn gas engine or dual fuel engine. First the lean-burn gas engines run only on gas; lean refers to a high air-fuel ratio. The extremely lean air-fuel mixtures lead to lower combustion temperatures and therefore lower NO_x emission. The engine operates under Otto cycle. At the end of compression phase a small quantity of gas-air mixture feed into a prechamber and ignited by a spark plug as shown in figure 7.

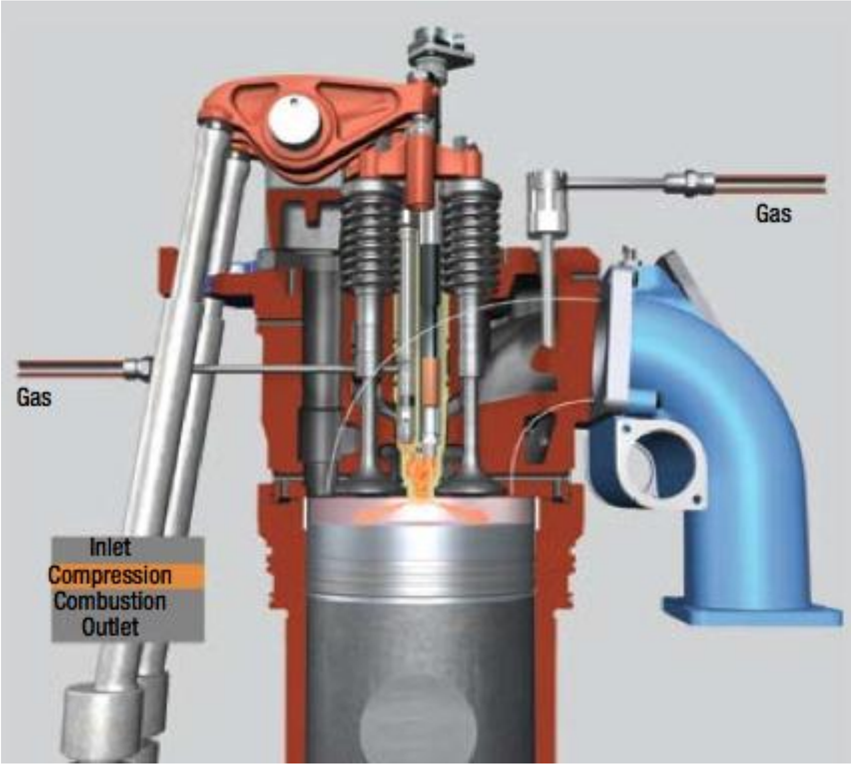


Figure 7 Single gas fuel engine combustion processes
[http://www.wartsila.com/en/power-plants/technology/combustion-engines/multi-fuel-engines]

The second choice is Dual-fuel engine that can run in either gas mode or diesel mode. The engine works according to the lean-burn Otto principle in gas mode, but the lean air mixture is ignited by the injection of a small amount of diesel fuel into the combustion chamber instead of a spark plug. The injected diesel fuel is normally less than 1% of the total fuel based on energy. The dual fuel engine is also equipped with a buck-up fuel system. In diesel mode, the engine works according to the normal diesel cycle with diesel fuel injected at high pressure just before top dead center. Gas admission is activated but pilot diesel fuel is still injected. Figure 8 shows the duel fuel mode combustion principle.

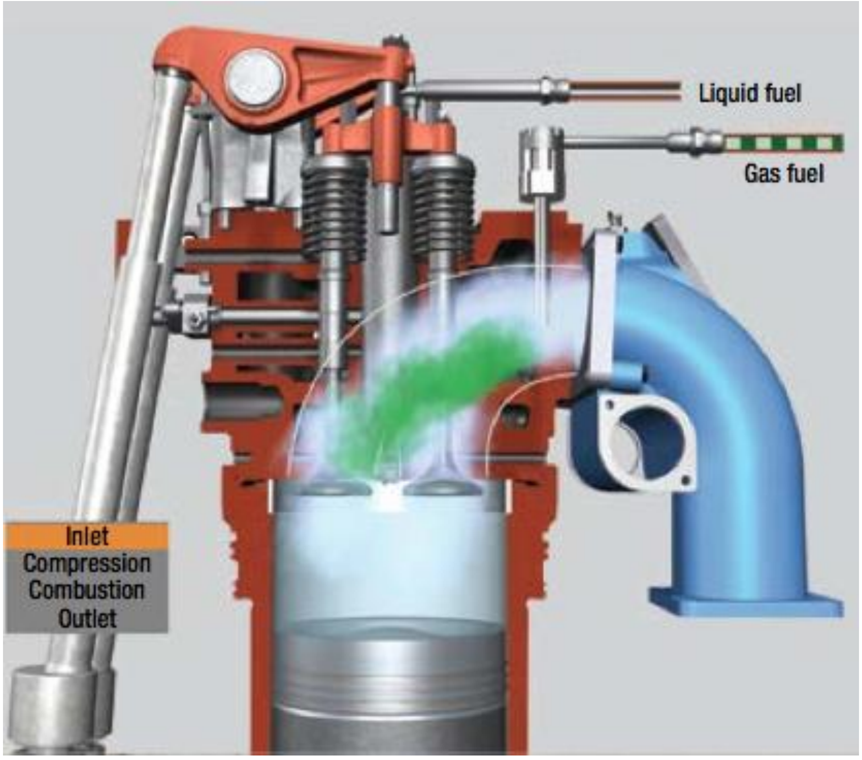


Figure 8 Dual fuel engine combustion processes

[http://www.wartsila.com/en/power-plants/technology/combustion-engines/multi-fuel-engines]

3.3. Methanol (CH_3OH)

Also known as methyl or wood alcohol, methanol is a colorless organic liquid at room temperature and pressure. This section summarizes the character of methanol as a chemical compound, the life cycle or value chain of methanol and uses of methanol.

3.3.1. Basic Knowledge of Methanol

Methanol has almost the same molecular structure and properties as natural gas. The methanol molecule contains a single carbon, with the formula CH3OH. Methanol also called wood alcohol because it was once produced as a byproduct of the destructive distillation of wood. Modern methanol is produced in a catalytic industrial process directly from carbon monoxide, carbon dioxide and hydrogen. Methanol is also useful as an energy carrier. It is easier to store than hydrogen, burns cleaner than fossil fuels, and is biodegradable. Methanol burns in oxygen including open air, forming carbon dioxide and water.

$$2\ CH_3 + 3\ O2 \rightarrow 2\ CO_2 + 4\ H_2O$$

For these reason, methanol is being seen as a renewable energy today.

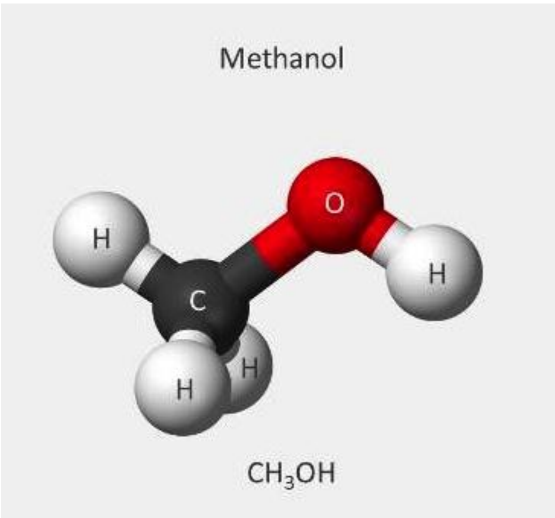


Figure 9 Molecule structure of methanol

Methanol has equally good environmental properties as LNG. CO_2 emission is at par with LNG. Also reduce the SO_x and NO_x similar amount as LNG as fuel. However the engine manufacturer select duel fuel technology to combust and the pilot fuel method for fuel ignition, the engine can only achieve NO_x Tier II standard currently. Methanol can be store in normal fuel tank onboard the vessels and transported at ambient temperature.

Di-methyl-ether (DME) is produced from methanol and can also be a alternative fuel for diesel engine. Its chemical formula is CH_3OCH_3. It can be produced from methanol by:

$$2CH_3OH \rightarrow CH_3OCH_3 + H_2O$$

DME has higher energy density than methanol, but in normal temperature it is in gaseous state. DME gas density is 1.97 kg/m^3, so it is heavier than air.

The price of methanol today is about 274~400 Euro/MT (364.42~532$/MT) depending on different area around the world, to compare per unit power price with diesel fuel the methanol price must be multiplied by 2.05 to have energy content equivalent to MGO. The lowest price of methanol is about 16% lower than MGO. However, the current methanol price in Europe is much higher than other country, according to report of Puworld [23], the import price of Europe is $50/MT higher than China's from Middle East.

3.3.2. Methanol Producing and Availability

Methanol can be produce from coal, municipal waste, landfill gas and carbon dioxide, which can be capture from industrial processes, thus why methanol is expected as a renewable energy in the future. Today, the most common methanol feedstock is natural gas. The production cost of methanol is more expensive than LNG, but under atmosphere temperature and pressure methanol can be transported and stored easily. So the delivered cost of LNG and methanol are expected to be similar.

The methanol industry spans the entire globe, with production in ASIA, North and South America, Europe Africa and Middle East. Worldwide, over 90 plants have a combined production capacity of about 100 million metric tons per year and keeps increasing fast due to the huge demand of China. In 2013, global methanol demand is expected to reach 65 million metric tons. More than 100,000 tons of methanol is used as a chemical feedstock or as a transportation fuel and more than 80,000 tons of methanol shipped for one continent to another. Methanol is widely used in industrial production. The biggest producer in Europe is Norway nowadays.

In a typical plant, methanol production is carried out in two steps. The first step is to convert the feedstock natural gas into a synthesis gas steam consists of CO, CO_2 and H_2O and hydrogen. This is usually accomplished by the catalytic reforming of feed gas system. Partial oxidation is another possible route. The second step is the catalytic synthesis of methanol from the synthesis gas. Each of these steps can be carried out in a number of ways and various technologies. Conventional steam reforming is the simplest and most wildly application of synthesis gas production. Following formulas perform the process of methanol manufacture. And the flow chart performs an overview of the two step producing process.

$$2\ CH_4 + 3\ H_2O \rightarrow CO + CO_2 + 7H_2 \text{ (Synthesis Gas)}$$

$$CO + CO_2 + 7H_2 \rightarrow 2\ CH_3OH + 2\ H_2 + H_2O$$

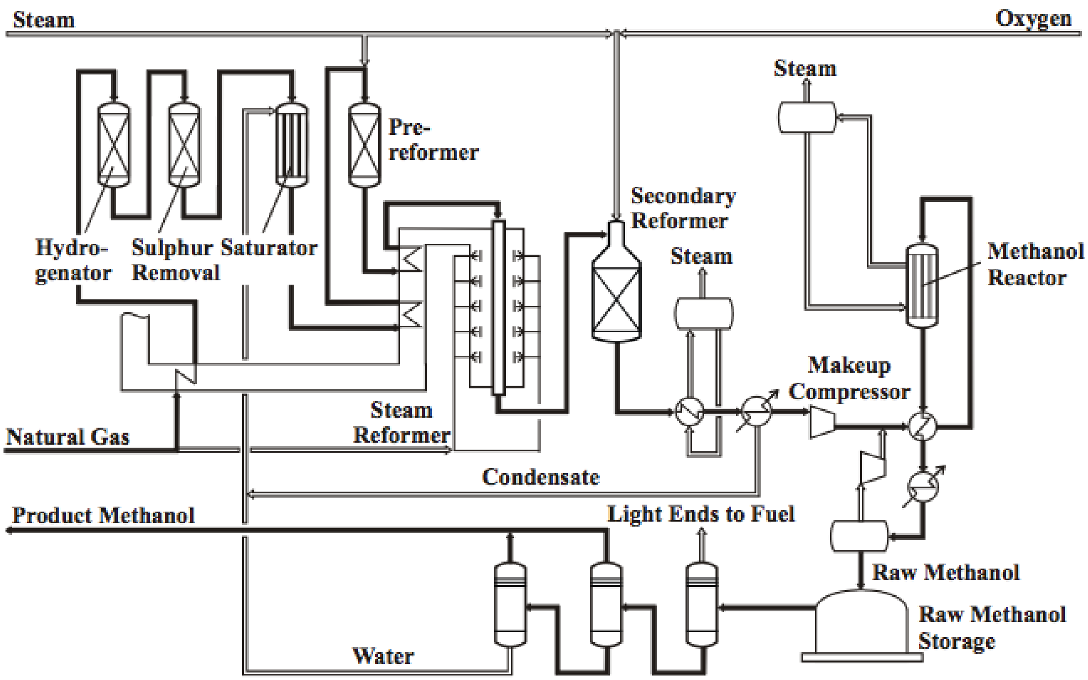


Figure 10 Methanol production by two steps reforming flow chart [24]

3.3.3. Challenges

Methanol has a high toxicity in humans. Methanol is easily and rapidly absorbed by all routes of exposure and distribute rapidly throughout human body. The primary route of entry into the body are by inhalation, absorption through the skin as a result of contact, eye contact, and ingestion by either eating and drinking. Ingestion of 10 ml can cause blindness and 60-100 ml can be fatal if the condition is untreated. The following table illustrates some of the potential methanol exposure routes and added methanol body burden expected from the exposure for 70kg person.

Table 6 Added body burden of methanol

Exposure/Dose	Added Body Burden of Methanol
Background in a 70 kg body	35 mg*
Hand in liquid methanol, 2 min	170 mg
Inhalation, 40 ppm methanol for 8 hr	170 mg
Inhalation, 150 ppm for 15 min	42 mg**
Aspartame sweetened products 0.8 liter diet beverage	2-77 mg 42 mg
Ingestion of 0.2 ml of methanol	170 mg
Ingestion, 25-90 ml)	Lethal (~20000-71000 mg)
*Estimated from (0.73 mg/l) of blood **Assuming 100% absorption in lung (60%-85% more likely)	

Onboard the vessel, the main reason of methanol exposure might be vapour relief from the fuel tank or leakage.

The second challenge of methanol is the fire risk. Methanol is extremely flammable, it release vapours at or below ambient temperatures. When mixed with air, methanol can burn in the open space. Methanol vapours are heavier than air, with a low flash point at 12 °C and a wide flammable range (6~36 vol%). Flash point is defined as the minimum temperature at which the vapour pressure of a liquid is sufficient to form an ignitable mixture with air near the surface of the liquid.

Due to the energy density, compare to conventional marine fuel methanol has about half energy of HFO for the same space. Correspondingly, using methanol as a fuel needs double of space for fuel storage.

3.3.4. Methanol Fuelled Engine

Much work has been done in many countries to identify the proper ways to use methanol or in blend with gasoline as fuel on automobile. China is currently the largest producer and consumer of methanol and leader in blending it with gasoline. Methanol as a marine fuel was discussed before, in 1992 Yoichi Nakamura ran a test on a single cylinder four stoke engine [25] and gave some suggestion to the design the injection system and governing system. But there is no vessel driven by methanol main engine today, a Swedish ship owner Stena Line put a Wartsila WFC20 fuel cell fuelled by methanol onboard M/V Undine to test the feasibility of methanol. They also planned to convert M/V Stena Germanica to burn methanol directly in the main engine, if the trial succeed they will continue rebuilding a further 24 vessels through to 2018 or 2020.

On July 1, 2013, MAN Diesel & Turbo announced the development of a new ME-LGI dual fuel engine. This engine enable to use methanol and Liquefied Petroleum Gas (LPG) as fuel. A Vancouver based Waterfront Shipping ordered four MAN G50ME-LGI engines; the engines will be built from end of 2013 and delivered in summer of 2015.

The ME-LGI concept is an entirely new concept that can be applied to all MAN Diesel & Turbo low speed engines, either ordered as an original unit or through retrofitting. Running in two-stoke Diesel principle, all methanol molecules will be burned. Other than four stoke Otto cycle engine, ME-LGI has no fuel slip, so formaldehydes will not be generated in the exhaust gas system. Therefore the after treatment in exhaust gas system is not required.

Methanol has a poor self ignition quality, thus it will need some kind of ignition source when it is to be use in a diesel process. Using pilot oil as the ignition source was selected in ME-LGI engine to solve this problem. The disadvantage is that a sealing oil will have to be built into every running surface for the fuel system, because methanol dissolves all lubricating compounds. New corrosion resistant materials will have to be investigated and specially selected for methanol fuelled engine. The manufacture provides a newly developed booster injector to supply the fuel for combustion. The sealing/lubricating oil has higher pressure than fuel in the injector to avoid contamination of sealing/lubricating oil.

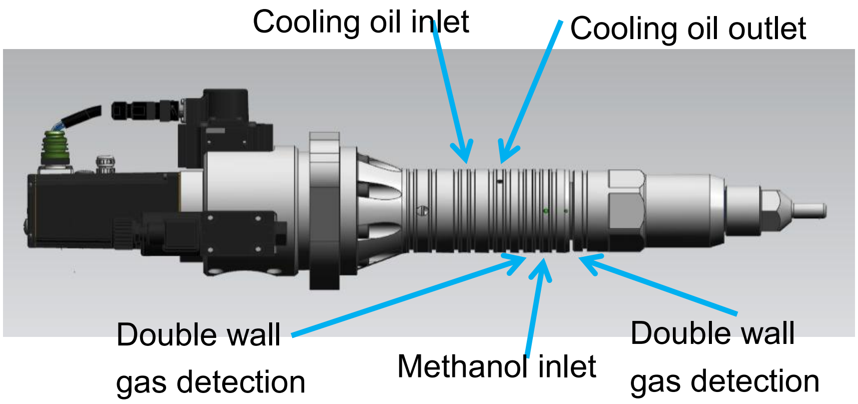


Figure 11 ME-LGI booster injector

The hydraulic sealing booster is only activated during injection, hence a small amount of sealing oil is used in next drawing.

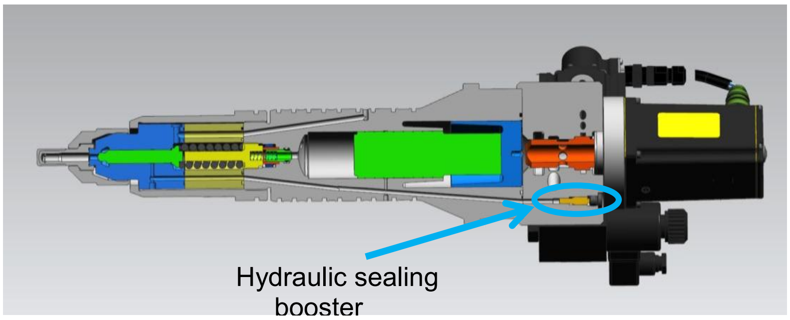


Figure 12 Detail structure of booster injector

The sealing pressure will be supplied to the side of fuel plunger via a groove around the plunger. The sealing oil will continue down to the boring and supply the side of the cut-off shaft and a groove around the spindle.

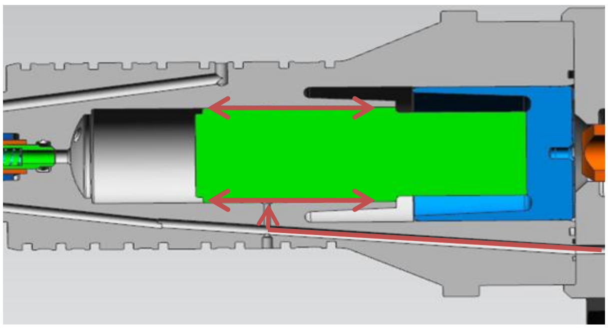


Figure 13 Sealing/lubricating of fuel plunger

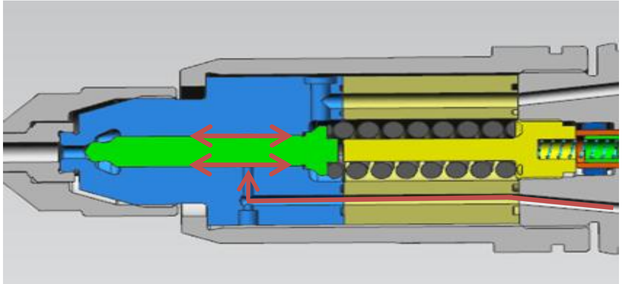


Figure 14 Sealing/lubricating of spindle

To apply engine to burn methanol, some modifications to be considered listed by engine maker as a reference for shipyard in design stage:

-Methanol supply station: explosion proof motor, suction filters, control valve, pulsation dampers, sensors and coolers to control the temperature to operate the fuel safely.

-Drainage tank: methanol cannot be exposed in open air, it should be led to an special tank or back to fuel tank.

-Ventilation system: the ventilation system must be able to detect methanol vapour. The air intake will be taken from a gas safe area.

-Piping: double-walled piping, double block and bleed valves are to be used in fuel system.

3.4 Other Solutions

The other comment solution for SOx and NO_x removal is abatement technology. For SO_x it's called marine exhaust gas cleaning system, general referred to scrubbers. There are four technology are known to be utilized:

1. The sea water scrubber (open loop scrubber)
2. The fresh water scrubber (close loop scrubber)
3. The hybrid technology (a combination of 1 and 2)
4. The $CSNO_x$ system (which targets not only sulphur but also nitrogen oxides and CO_2)
5.

However, a report from UK Chamber of Shipping [26] state that Sweden and Finland government acknowledged the limitations of using sea water scrubber (SWS) in Baltic Sea. For example, where alkalinity is lower than normal because of minimal exchange of water through the Danish straits (it is usually constant and high). At low alkalinity SWS can still operate, but it can lead to lower cleaning efficiency and low effluent PH figures. Sweden notes that closed fresh water scrubber may be more appropriate/acceptable.

To reduce NOx emission, there are Selective Catalytic Reduction (SCR) or Exhaust Gas Recirculation (EGR) to select. The combination of SOx and NOx abatement technology is considered to have good prospect to fulfill the requirement of regulations.

The main advantage of scrubber with either SCR or EGR is that readily available to use high sulphur HFO to keep low fuel cost. The owner can operate vessels with the same procedure and easy to manage.

To install this additional equipment, space arrangement is to be considered. Due to the characteristic of scrubbing process, most of the scrubber units are installed near the funnel. The weight of scrubber system can up to hundreds tons depending on the engine output and type of technology. This huge weight in engine room can affect the stability and reduce the cargo capacity of the vessels. Cost of using scrubber include initial investment, the discharge or handling fee of waste produced by scrubber, crew training cost, extra manning cost, maintenance cost and chemical consumption cost.

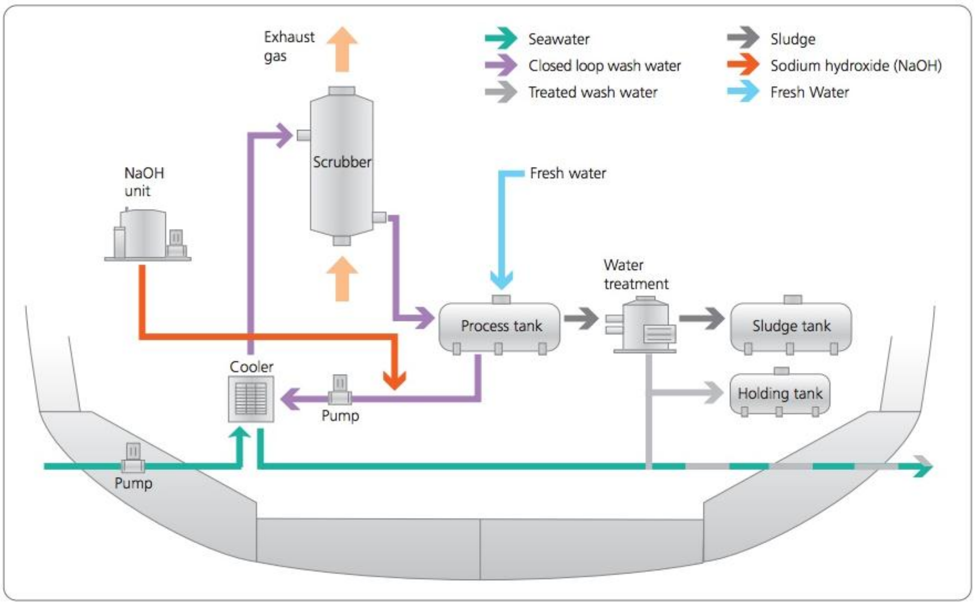


Figure 15 A closed loop wet SO_x scrubbing system
[Lloyd's Register 2012- Understanding exhaust gas treatment systems]

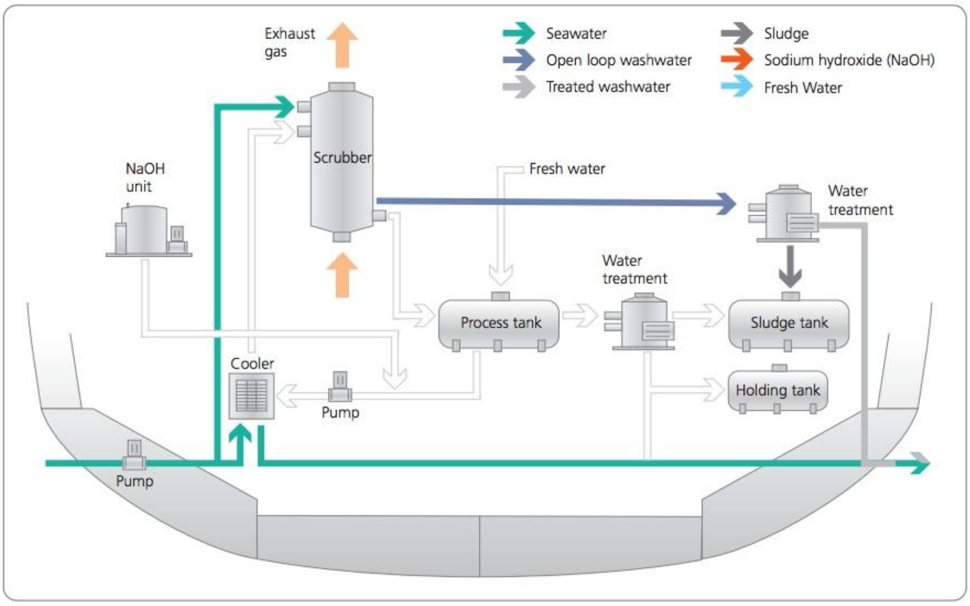


Figure 16 A hybrid SOX scrubbing system, operating in open loop mode
[Lloyd's Register 2012- Understanding exhaust gas treatment systems]

3.5. Summary

For ship owners who want to operate vessels in SECA, the above methods are provided to comply the regulations with different advantages and drawbacks. Next table summarize the conditions for consideration. With extra equipment scrubber and LNG solution have higher initial capital cost. MGO price will be more expensive than others. LNG handling and piping systems are more complicated compare to the rests. Comparisons of other miscellaneous items are listed below. The chart below shows the performance of each application on recuing the pollutant emission in exhaust gas. To make a decision, owners may compare the economic benefit of each solution. Therefore, the LCCA be performed in following chapters.

Table 7 Summary of alternative technologies

Alternatives	HFO+Scrubber	0.1%MGO	LNG	Methanol
Initial investment	Median	Low	High	Low
Fuel cost	Low	High	Low	High
Required fuel storage space	Low	Low	High	Median
Require extra space for equipment	Yes	Yes	No	No
Machinery and piping system change	Low	Low	High	Low
Additional risk	No	No	Yes	Yes
Sludge handling	Yes	Yes	No	No
Infrastructure investment	Low	Low	High	Low
Extra chemical cost	Yes	No	No	No

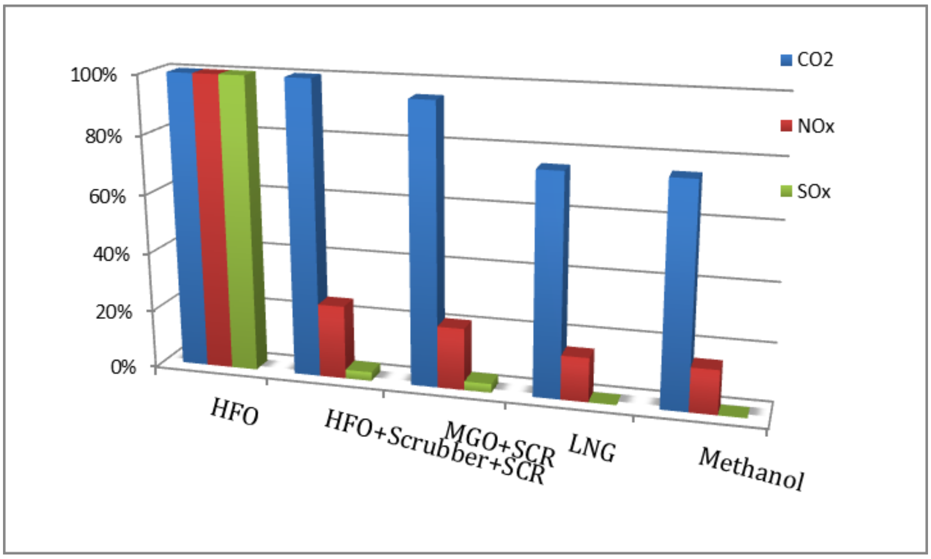


Figure 17 Pollutant emission of each application

Table 8 Equivalent fuel price calculations

Industrial name	Composition	Sulphur weight	Price, $/MT	Price, $/MMbtu	Price, Euro/MT
Intermediate Fuel Oil 380 (IFO380)	98% residual oil 2% distillate oil	2.7%	600.5*	N/A	451.5
Intermediate Fuel Oil 180 (IFO180)	88% residual oil 12% distillate oil	2.7%	620.5*	N/A	466.5
Marine Gas Oil (MGO)	100% distillate oil	0.1%	913*	N/A	686.5
Liquefied Natural Gas (LNG)	92~99% methane & others	0.0%	N/A	12~17**	365.2~517.3***
Methanol	100% methanol	0.0%	365~450**	N/A	562.4~693.6***

*Price of port Rotterdam from Bunkerworld on August 19, 2013
**Estimated delivery price from different region in 2013
***Equivalent price to MGO energy/ton
Exchange rate 1.33 Euro/USD

Table 8 summarized the fuel price of each alternative and compared the price of LNG and methanol equivalent to one ton MGO. From this table, HFO and LNG are much cheaper than MGO; methanol price is between LNG and MGO and may be higher than MGO depends on the market. These prices will be considered in LCCA and sensitivity analysis.

4. METHODOLOGY OF LIFE CYCLE COST ANALYSIS

Life Cycle Cost Analysis is a method to assess total cost of facility ownership. It takes into account all cost appearing during the whole lifetime. In this study the cost correspond to all expense from design stage until the vessel scrapped. The costs were defined as four main categories in ISO 15686-5, construction cost, operation cost, maintenance cost and end-of-life cost shows in next figure. LCCA is especially useful for project alternatives that fulfill the same performance, but accompany with different initial costs and operating costs. This is why LCCA is an appropriate tool for economic evaluation in this study. In this chapter, the detail definitions and sequence of assessment will be described.

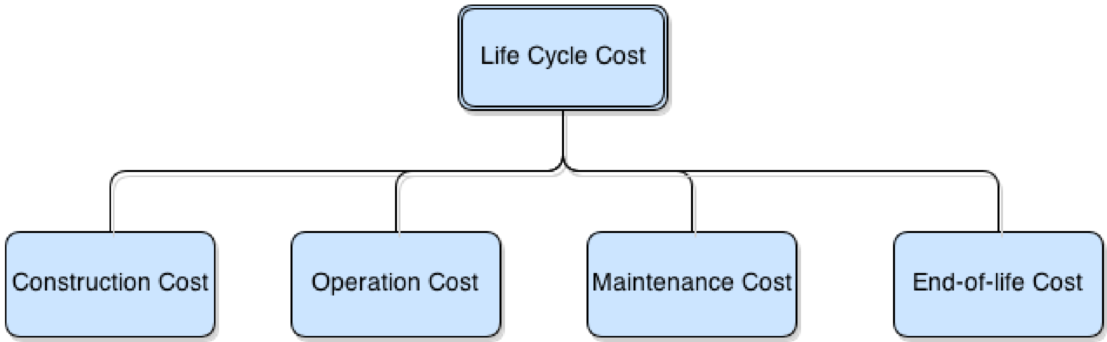


Figure 18 Categories of costs

4.1 Principle and Definition

The purpose of an LCCA is to estimate the gross costs of alternative solutions and to select a design that the target will consume lowest cost with normal function operation and similar performance. The LCCA should be performed in early design stage when there is still a chance to improve the design to identify a reduction in LCC. The main parameters are defined as following.

4.1.1. Design Alternatives

A LCCA begins with the selection of alternatives that will achieve the same performance for a project. These alternatives which put into consideration usually come with significant influence to LCC.

4.1.2. Cost

There are numbers of costs associated with acquiring, operating, maintaining and disposing of a building were described in many documents. For shipbuilding project, the significant costs can be simplified and summarized to following items.

- Initial costs – Design, construction and purchase costs
- Operation costs – Labor, management, survey and fuel cost
- Maintenance costs – Maintenance, repair spare parts cost

4.1.3. Life Cycle Period

The length of duration of analysis target is also an important parameter in LCCA. Depending on alternatives, the solution with high initial capital cost and low operation cost might obtain more benefit in long life cycle. Oppositely, low initial cost and high operation cost alternative is more suitable for short life cycle. The lifetime can vary from ten to fifty years for different user and cases. Generally, a vessel is designed to service for 20 to 25 years. The study period is usually shorter than the design life span. Therefore, in LCCA the life cycle is selected to 15 years.

4.1.4. Discount Rate and Inflation

It is also essential that the same discount rate and inflation treatment be used in LCCA of multiple project alternatives. In order to add and compare cash flows that incurred at different timing during the life cycle of a project, discount rate is used to make equivalent price to a common point in time. We can find the present value PV of a future value F_t at year t, using next formula with discount rated.

$$PV = \frac{F_t}{(1+d)^t} \tag{1}$$

Inflation reduces the purchasing power of dollar over time; deflation increases it. To make meaningful comparison between costs occurring at different timing, there are two definitions of discount rate to consider the effect of inflation. First called “real discount rate” used to estimate future cost in constant currency exclude the rate of inflation. The other called “nominal discount rate” used to estimate future cost with in current currency, this rate include rate of inflation. The relationship between real discount rate and nominal discount rate shows as below.

$$REAL = \frac{1 + NOMINAL}{1 + INFLATION} - 1 \tag{2}$$

In order to combine all future cost for comparing, the expenses have to be converted to the same currency unit on the same time point by discount rate and inflation rate. The term of Net Present Value (NPV) and Net Present Cost (NPC) are to be computed with discount and inflation from the future cash flow summation.

4.2. LCCA Procedure

There exist many procedure developed to perform LCCA and none of these is a standard or recognized as a best approach. To make a proper LCCA procedure for each project, it can be adjusted slightly. The procedure in this study was refer to many documents and summarized below.

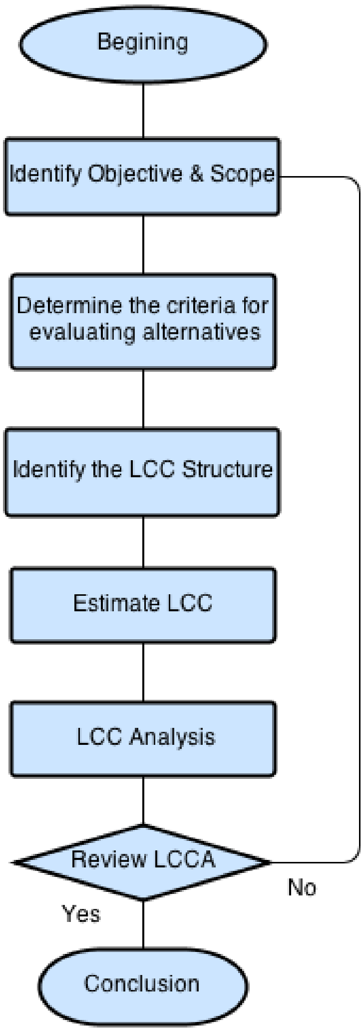


Figure 19 Flow chat of LCCA

Step 1: Identify the scope and objective. Objective must be clarified in the beginning. The alternatives could not be defined without a clear objective.

Step 2: Determine the criteria for evaluating alternatives. Specify the methods to compare the alternatives. Generally there are two types of variable used to evaluate the performance of alternatives, life cycle cost and payback time. Life cycle cost represent whole expanse during the lifetime and payback time perform the time required for reclaim the initial investment.

Step 3: Identify LCC structure. Define the key parameters in LCC to build whole model to be able to run the calculation. Give the limitation and assumption like real cost value, discount rate, inflation rate and life cycle period for LCC. Choose the alternatives with significant impact of the objective and criteria.

Step 4: Estimate LCC. Perform LCC calculations for each alternative. Put real cost information and assumptions into LCC model built in step 3 to obtain the total cost during life cycle based on the present value.

Step 5: LCC analysis. From the result of previous steps, analyze the result to select the optimized alternative for the objective defined in step 1. Discuss other impact besides the cost of the alternative and make sure the solutions are feasible for the project.

Step 6: Review LCCA. Using uncertainty assessment and analyze the sensitivity to verify the calculation. Sensitivity analysis is useful for identifying which number of uncertain input values has the greatest impact on a specific measure of economic evaluation. The sensitivity analysis might conclude different alternative base on the impact of uncertainties. If the result is not efficient as expected or never get payback for the cost in life cycle. Rerun the step 1 to 5, modify the parameters to get reasonable and useful result.

4.3. LCC Calculation

To calculate the LCC, first compute the present value of each cost incurred during the study period, using discount rate. The following is a general formula for the LCC present value model:

$$LCC = \sum_{t=0}^{N} \frac{C_t}{(1+d)^t} \quad (3)$$

where:

LCC = Total LCC in present value of a given alternative

C_t = Sum of all relevant cost in year t

N = Number of years in the life cycle

d = Discount rate used to adjust cash flows to present value

Another expression of LCC is to compute by sum of costs in different categories:

$$LCC = I + OP + M + O \quad (4)$$

where:

LCC = Total LCC in present value of a given alternative

I = Present value of initial investment cost

OP = Present value of operation cost

M = Present value of maintenance cost

O = Present value of others cost

In this case the fuel cost occupy the highest rate of operation cost during the lifetime. The future fuel price evaluation turns into an important term in LCCA calculation. The escalation rate will be conducted in estimate fuel price in the future, combine with the discount rate described in paragraph 4.1.1 to calculate the corresponding present value.

$$PV = F \times \left[\frac{1+e}{1+d}\right]^t \quad (5)$$

Where PV is present value, F is current fuel price, e is the escalation rate and d is the discount rate.

4.4. Uncertainty Assessment in LCCA

In LCCA the future cost is estimated, when perform LCCA the "best guess" was taken into account. There may still exist some uncertainty of the prediction. If the is substantial uncertainty concerning cost and time information, it may give a different decision making of LCCA. Therefore it makes sense to assess the degree of uncertainty associated with the LCC result and to take that additional information into account when making decisions. In this study, the effect of uncertainty will be evaluated by sensitivity analysis.

Sensitivity analysis can help in several ways to assess the uncertainty of an LCCA. Giving a reasonable varying range to input data such as fuel cost and maintenance cost or the key parameters in LCCA, for example discount rate and escalation rate. Then check the impact to the LCCA result from each input data. This analysis can help to identify which input data has the biggest impact on the LCC result and how robust the final decision is. It can also varying more than one parameter to observe the interaction between variables to have complete appearance. If the uncertainty leads to different result of LCCA, the possibility of uncertainty can be considered.

For example, if fuel cost in the future varies from 20 to 100 USD, and from 20 to 80 USD results alternative A; 80 to 100 USD results alternative B. The possibility of A and B could be considered when making decision. But the owners must take some risk when another result happens in the future.

5. INSTALLATION IMPACT

Except using MGO as fuel, others alternative methods mentioned in this study are accompany with some design impact no matter the hull structure or the machinery systems. At the owners' and shipyards' view, they are more interest in the design impact and the influence of operation. On the other hand, government authorities pay their attention on the impact on environment and port facilities. This chapter introduces the impacts of different technologies in different direction.

5.1. Space

Utilizing the alternative technologies onboard, the additional equipment or the extra fuel tank space may be required. The loss of cargo or passenger space is to be considered at design stage.

5.1.1. Space Impact of LNG

LNG fuel tanks take up about twice amount of space as a conventional fuel tank in order to get the same amount of energy as from a given volume of conventional fuel. Adding to the space constrains, cylindrical shape LNG tank require more space than a typical rectangular fuel tank. The total space required by LNG fuel tank room is 3.5 to 4 times of traditional one. In addition, if the dual fuel engine is selected, it needs one more tank for the diesel fuel. The tank can be place in different place such as double bottom, upper deck or stern deck according to types of vessels.

Following pictures shows the various designs to locate the LNG fuel tanks. First is fastest catamaran ferry in the world, the "Lopez Mena", equipped two 40 m^3 LNG tanks above ship's double bottom. The second design is a cruise ferry "Viking Grace", the first large scale passenger ferry powered by LNG. Two 200 m^3 storage tanks placed on the stern deck. Last one is a tanker design to use LNG as fuel with two LNG storage tanks on upper deck in front of the accommodation.

Figure 20 LNG fuel tanks installation on catamaran
[http://worldmaritimenews.com/archives/51865/]

Figure 21 LNG fuel tanks on a large scale passenger vessel
[http://worldmaritimenews.com/archives/47583/]

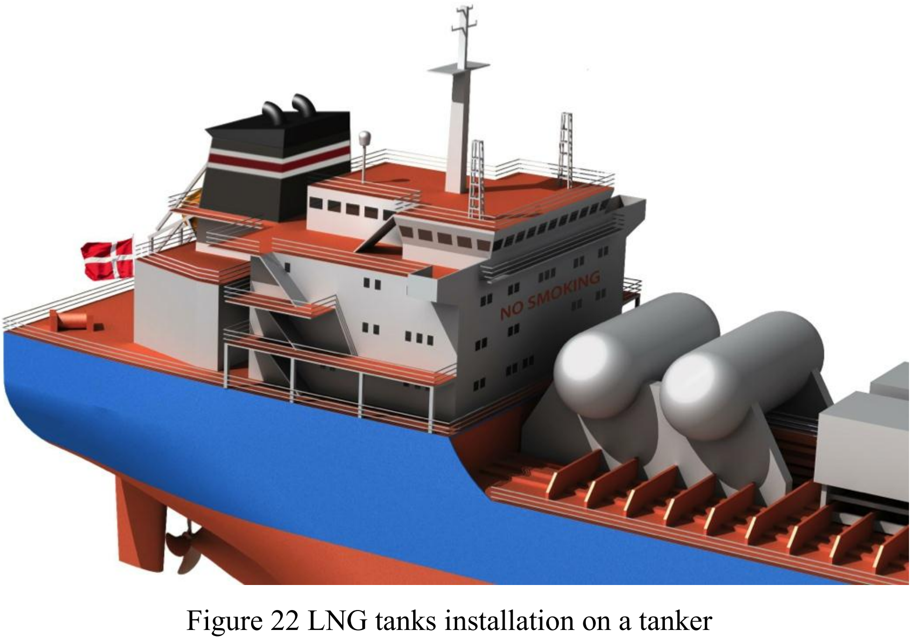


Figure 22 LNG tanks installation on a tanker
[http://www.greenship.org/lowemissionconceptstudy/ecaretrofitstudy/]

5.1.2. Space Impact of Methanol

Unlike LNG, methanol is a liquid in ambient temperature, so it can be store in typical fuel tank. Next table lists the energy density calculation of different fuels. The density and low heating value have small difference from different resource and manufacturer. Regarding to the result in this table, burning methanol to obtain the same quantity of power require around 2.5 times the space of HFO and 2.25 times the space of MGO. But for short sea transportation, depending on the routes of the vessels, usually berth in ports frequently. If it is possible bunkering in most of ports, the designer can consider shortening the maximum cruising range to reduce the required fuel tank capacity.

Table 9 Energy property of alternative fuels

	LNG	Methanol	MGO	HFO
Density (kg/L)	0.46	0.791	0.84	0.98
Low heating value (kJ/kg)	49200	20094	42700	40600
Energy density (kJ/L)	22632	15894	35868	39788

5.1.3. Space Impact of Scrubber System

Regarding to different types of scrubber systems, instruments are placed onboard such as scrubber unit, washwater treatment system, pumps, fresh water tank, caustic soda tank and control and monitoring systems. Those additional parts take a huge space and usually installed near funnel with some parts in engine room. The size of units depending on engine rated power and type of system. Wet type scrubbers are usually smaller and lighter than dry scrubbers. Generally it is not a problem for cargo ship (bulk, container, tanker etc.), but for ferries or cruise ship usually they don't have a large space for engine room. And to have a slinky shape, designer must consider the location and size of scrubber system. The following figure summarized the space taken by Wartsila wet type scrubber systems for various engine powers.

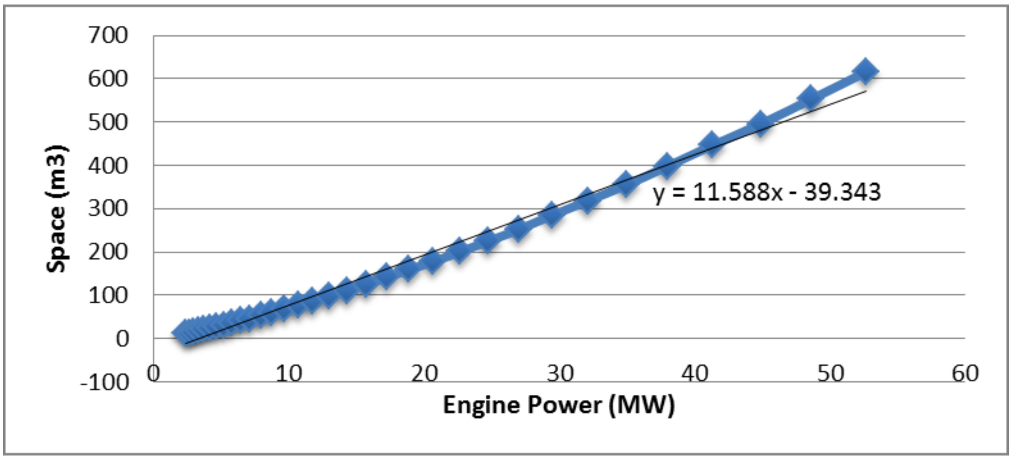


Figure 23 Spaces impact of scrubbers

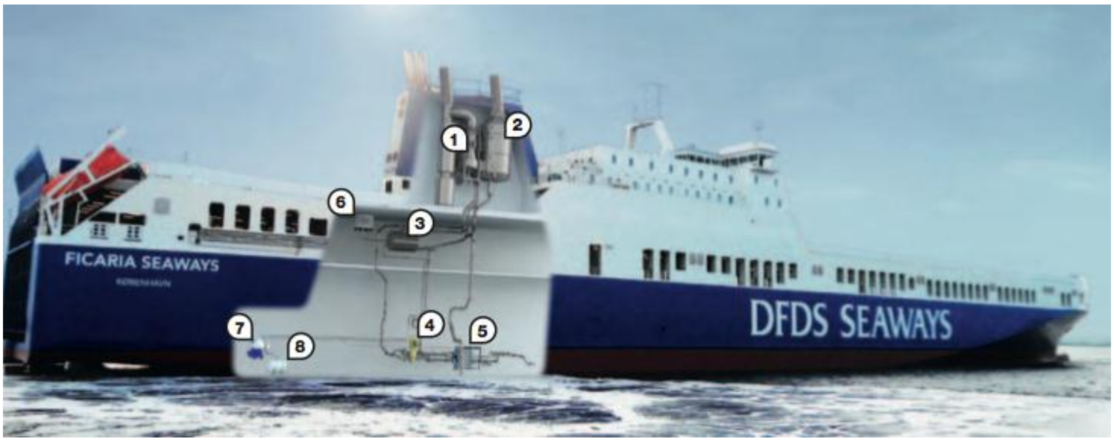
In above figure, the data was linearized to a simple equation for estimated require space of scrubber systems. With a given engine power, the approximate space of scrubber can be computed as equation (6):

$$\text{Space } (m^3) = 11.588 \times \text{engine power(MW)} - 39.343 \quad (6)$$

The designers can use this to estimate and consider the general arrangement in the early design stage. For example, a vessel with total engine power 10 MW will need around 76 m^3 spaces for installation.

Next two pictures show the installation and arrangement of Alfa Laval PureSO_x hybrid scrubber system on a Ro-Ro vessel "Ficaria Seaways". The scrubber was placed beside funnel and other equipment was placed in engine room.

Figure 24 Scrubber installation in the funnel of "Ficaria Seaways"
[http://www.aalborg-industries.com/scrubber/rm_references.php]



1) Jet scrubber 2) Absorber 3) Circulation tank 4) Circulation pump 5) Plate heat exchanger 6) Caustic soda tank 7) Water cleaning 8) Sludge tank

Figure 25 Scrubber installation in the funnel of "Ficaria Seaways" [http://www.alfalaval.com/industries/marine/oiltreatment/Documents/PureSOx%20product%20brochure.pdf]

5.2. Weight

The additional equipment not only occupies the space but also extra weight. Which will reduce the deadweight of vessels, it also cause losing of cargo / passenger capacity. For safety reason, masses and location of installation are to be taken into account when calculate the stability and trim. This mass loss will cause money loss, thus it perform as a cost in LCCA.

5.2.1. Weight Impact of LNG

Even LNG take double volume as conventional fuel, the total weigh of LNG is lighter than conventional fuel because of the density of LNG is smaller than the other. The main mass to be concerned is the LNG storage tank and fuel supply system. The weight of tank is based on the energy capacity required. Follows shows the relationship between total energy capacity and weight given by Wartsila LNGPac particular data. Also a simple linear formula (7) can help designers to have a general idea about the weight of LNG fuel tank quickly.

$$\text{Weight(tons)} = 0.1437 \times \text{Total energy capacity(MWh)} + 14.575 \quad (7)$$

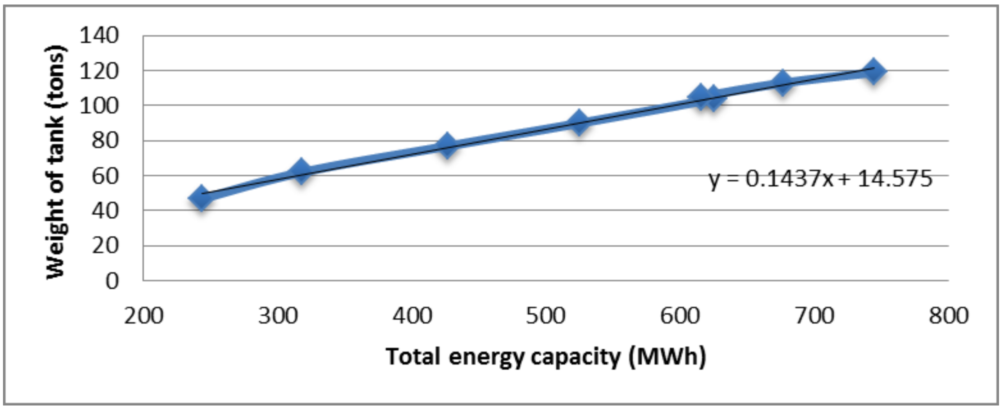


Figure 26 Weight of LNG fuel tank

5.2.2. Weight Impact of Methanol

From the table in 5.1.2, the low heating value of methanol is only half of HFO. Due to the small low heating value of methanol, the weight of required fuel would be twice as HFO when using methanol. Depends on the routes and the purpose of vessels, according to the design criteria. The different fuel consumption rate and the maximum cruising period would change the required fuel tank capacity. Therefore the losses of freight vary from 5% to 15% of deadweight.

5.2.3. Weight Impact of Scrubber System

The additional equipment of scrubber system mentioned in 5.1.3 is also come with impact on weight. Net weights of Wartsila WM series close loop wet scrubber system are shows in following figure.

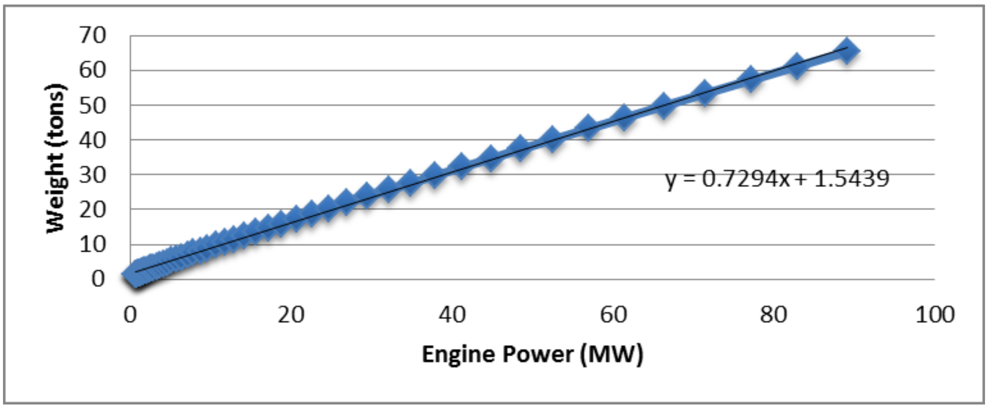


Figure 27 Weight impact of scrubbers

Weight impact is proportional to engine power, and can be express as (8)

$$Weight(ton) = 0.7294 \times Engine\ Power(MW) + 1.5439 \quad (8)$$

This weight is not including the freshwater and NaOH consumption, so the total additional weights can up to 100 tons.

The position of scrubber may above upper deck. High location of masses will reduce the stability of a vessel. Designers must consider the position of scrubber carefully.

5.3. Energy Consumption

To power the equipment of alternative methods, the electrical loads consume energy generated by engines. For example, using LNG as a fuel needs to store the fuel in specific tank with monitoring system and fuel supply system. The greatest amount of energy consumption of scrubber system is the operation of pumps. These energy cost are assumed in a 0.1%~1% range of total engine power by makers and research organizations.

So far only DNV specified that all tanks containing low flash liquid shall be inerted. That means the vessels are to be equipped with inert gas system to prevent explosion. In this condition, the load of inert gas system is also 0.1%~1% of total engine power.

In LCCA calculation the costs of additional equipment will be taken into account by 0.1%~1% of the total fuel cost.

5.4. Crew Training

In order to utilize these alternatives, crews are the key component of the whole operation on the sea. With new types of engines or equipment, crews are to be trained to have enough knowledge and ability to operate the machines. Without the specific techniques and information will cause unpredictable incident. Therefore crews who work on these vessels should have specific training other than traditional diesel driven ship training courses.

Handling LNG or methanol safely is also important or preventing hazards. Crew should be trained thoroughly understand the properties and characteristics of LNG or methanol. Understanding how to control the flammability and toxicity of fuels to ensure a safe operation. Ship operator shall develop a bunker procedure for alternative fuels.

Risk assessments are to be carried out to establish the emergency procedure to minimize the damage during an incident. Crew should have training and drill according to the emergency procedure to have correct incident reaction.

5.5. Other Impacts of Scrubber System

Chemical usage onboard of scrubber system create two impacts, first is the space and weight occupied by the holding tank mentioned 5.2.3. The other is handling of chemical. The crews should have training described in 5.4 to keep ship's safety. The supply and availability in port is to be considered, the remaining chemical quantity on onboard should be controlled and managed to ensure scrubber is able to work when engage in SECAs.

For example, the chemical tank capacity should be considered according to the route of vessel, the distance between ports where can refill the chemical and the consumption rate. If a vessel runs out of chemical and the scrubber is not able to work in SECAs, ship owners may get a penalty from the local government after the regulations take effect.

Discharge of wash water in scrubber system is an impact to the environment; to avoid this pollution the IMO Exhaust Gas Cleaning System guideline regulated the dischargeable wash water. The wash water can be discharge overboard at sea only when the PH value and Polycyclic Aromatic Hydrocarbons (PAH) comply with the guideline. Otherwise the water should be store onboard and dispose to onshore facility.

Sludge disposal is another issue of environment. Typical sludge generated by diesel engine can be burned in incinerator onboard, but many manufacturers believe that the sludge generated by Scrubber system cannot be incinerated onboard. Scrubber sludge is also to be disposed to onshore recycle facility. To discharge those wastes also increase the cost in life cycle.

Regarding to the NO_x emission regulations, using scrubber can only reduce the SO_x emission, it's necessary to add a NO_x abatement equipment into the system. This cost should count into the initial cost.

6. ASSUMPTIONS AND CASES SELECTION

In order to compare the LCC of alternatives, this chapter defines the cases for performing LCCA and assumptions of parameters. Four types of vessels were selected as a new build project completed on 2015 and start running in service. The ships refer to current existing vessels that navigate in Baltic Sea, North Sea and other SECAs frequently. There are one Ro-Pax, one Cruise passenger ship, one short sea container vessel and one small ferry that sails between islands. These ships have the same character that they all berth frequently and sail in fixed routes.

6.1. Assumptions for LCCA Parameters

A commercial vessel usually designed to service about 20~25 years, depends on vessel types and owner's strategies will be small difference. In this study, the life period were selected as 15 years for each types of ship.

The annual discount rate used in LCCA is assumed a constant 10% during the life period. Fuel escalation rate is count 5% annually (1980~2010 average) and keep the same growth rate in 15 years. Discount rate and escalation rate are used to calculate the cost present value correspond to each year. Here the inflation is neglected.

The cost of LNG/Methanol fuelled engine is estimated 25% more expensive than conventional diesel engine. LNG storage tank and other equipment including piping system installed onboard are very different and depended from size, location and total energy required in maximum continuous operation. The price of LNG tank is estimated from manufacturer's experience data. Due to the limitation of using open loop scrubber system in Baltic Sea region, close loop wet type scrubber system were selected as an alternative in the comparison. The cost of close loop wet type scrubber system and SCR NO_x abatement system is shown in follows, and the cost of different engine power in LCCA is computed by interpolation and extrapolation.

The price of MGO and HFO varying day by day and rushingly, the price given in table 8 is using in LCCA to evaluate fuel cost. Cost of LNG and methanol is selected the median value to assess LCCA. All of these alternative fuels will be given an uncertainty range to analyze the sensitivity and the influence to the result of LCCA.

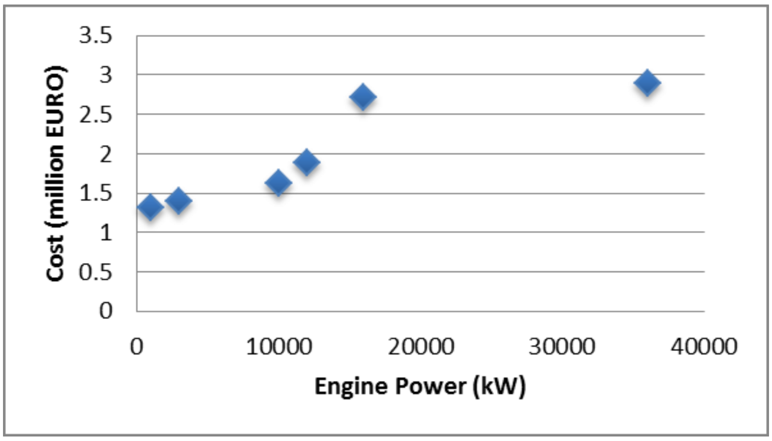


Figure 28 Cost of close loop scrubber system (NOx)

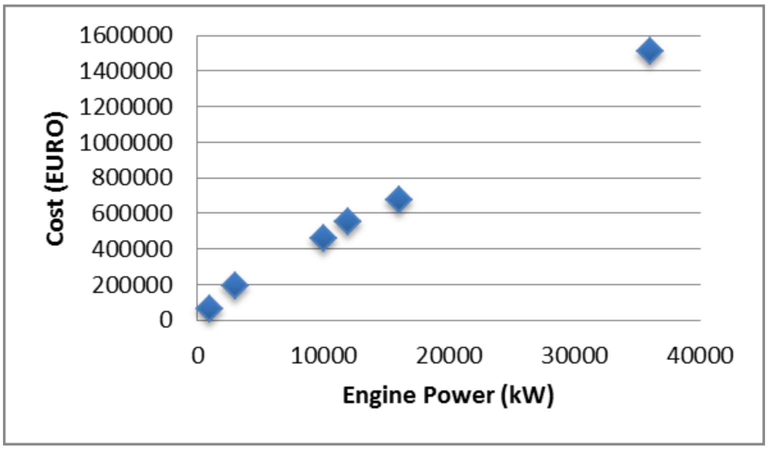


Figure 29 Cost of SCR system (SOx)

There are different views on maintenance cost of engine and equipment. Because the long-term experience is still limited for alternatives, in manufacturer's view it has no significant difference between different types of engines.

The costs on hull construction for a vessel with different alternatives are considered equally, thus these cost are neglected in LCCA calculation. As mentioned in Chapter 5, each alternative has impacts to space and weight, but designer can modify the arrangement or change the hull form to avoid cargo loss for new build vessel. In next Chapter the cargo loss will not be considered in LCC calculation, but for retrofit project, cargo loss should be taken into account carefully.

To assess the annual fuel cost, the power consumption of main and auxiliary engines are to be computed. However, for different type of vessel and different working condition, the engines have different percentage of load. Based on the operation characters of vessels to calculate the daily average working load for main and auxiliary engines. Use this daily average working load to perform annual power and fuel consumption. Following sections shows the calculation of average working load for different types of vessels in detail.

6.2. Stena Germanica

M/V Stena Germanica is a Ro-Pax ferry owned by Stena Line on the route from Kiel to Gothenburg, from Germany to Sweden and the largest ferry in the Nordic region. It was built in 2001 by Astilleros Espanoles shipyard, rebuilt at Lloyd Werft yard in 2007 and underwent an extensive refit at Remontowa shipyard in 2010.

The Stena Germanica can carry maximum 1300 passengers and 300 cars, one trip from Kiel to Gothenburg or Gothenburg to Kiel everyday. Around 14.5 sailing hours between this two ports.

This vessel is propelled by four main engines with rated power 6000 kW for each and also equipped five auxiliary engines for electric power. In general condition, the power consumption of electric is assumed to be 2000 kW. And the service speed is use the 90% of maximum engine continuous rating.

Use the above data to simulate the LCC of a new build Ro-Pax ship project and delivery on 2015 and the vessel will navigate in Nordic region with four different solutions for SECAs limitation. Following table shows the detail particular of this vessel.

Table 10 Particulars of M/V Stena Germanica

Type	Ro-Pax		
Name	Stena Germanica	Fuel consumption rete	173 g/kWh
LOA	214.26 m	Days of operation/yr	300
LBP	223.11 m	Averaged total power / day	422 MWh
Breadth	28.7 m	Sailing in SECA	100%
Depth	9 m	Total energy consumption/yr	126,530 MWh
Draught	6.3 m	Continuous Sailing days	3
Gross Tonnage	51837	Total fuel used	21889 MT
Net Tonnage	23007	Engine cost diesel	€ 10,131,200
Deadweight	10670 MT	Engine cost LNG/methanol	€ 12,664,000
Main Engine Power	26000 kW	Cost of LNG tank	€ 5,130,576
Auxiliary Engine Power	5660 kW	Scrubber cost	€ 2,800,752
Averaged M/E load	54%	SCR cost	€ 1,092,000
Averaged A/E load	62%	Class	LR

Figure 30 M/V Stena Germanica
[http://www.motorship.com/__data/assets/image/0006/472497/germanica200811_Print.jpg]

The working hour based on the schedule of Stena Germanica, the vessel sails one voyage per day. In port operation required electric power supply only for crew's accommodations, restaurants and other activities. For this route, the passengers not stay onboard when vessel mooring along the pier.

Table 11 Average working load of Ro-Pax vessel engines

Ro-Pax

Main Engine	In port	Departure & Arrival	At Sea
Working hour	8 hr	2 hr	14 hr
Working load	0%	20%	90%
Average daily working load			54%
Aux. Engine	In port	Departure & Arrival	At Sea
Working hour	8 hr	2 hr	14 hr
Working load	5%	90%	90%
Average daily working load			62%

6.3. Crown Princess

The Crown Princess grand class cruise ship operated by Princess Cruise Line. It began operation in 2006 and sail in America coast and Europe. From October to March, the ship voyages in between South America and Eastern/Southern Caribbean. And from April to September she sails around Northern Europe and the Mediterranean.

She has total 19 decks (14 passenger decks) with 1538 passenger cabins that capable of 3080 passengers. 2 fixed pitch propellers, each driven by a Siemens electric propulsion motor of 19 Megawatts maximum output. Propulsion and ship's service power supply from six generators, four of 11520 Kilowatts and two of 8640 Kilowatts. Total engine rated power is 63360 Kilowatts.

The model of LCCA is assumed this vessel operated 330 days per year and averaged 18 hours per day. According to the sailing routes, assuming 80% of path is in SECAs. Start operation from 2015 with 15 years life cycle. Due to the limitation of SO_x out of SECAs takes effect in 2020. From 2015 to 2020 only use alternatives in SECAs and out of SECAs keep using HFO but after 2020 use alternatives in all areas. Next table shows the detail information of Crown Princess.

Table 12 Particulars of M/V Crown Princess

Type	Cruise		
Name	Crown Princess	Fuel consumption rete	173 g/kWh
LOA	288.63 m	Days of operation/yr	330
LBP	242.36 m	Averaged total power / day	1,104 MWh
Breadth	36.009 m	Sailing in SECA	80%
Depth	11.394 m	Total energy consumption/yr	291,393 MWh
Draught	8.5 m	Continuous Sailing days	7
Gross Tonnage	113561	Total fuel used	50410 MT
Net Tonnage	83977	Engine cost diesel	€ 21,504,000
Deadweight	13294 MT	Engine cost LNG/methanol	€ 26,880,000
Main Engine Power	50400 kW	Cost of LNG tank	€ 28,218,168
Auxiliary Engine Power	16800 kW	Scrubber cost	€ 3,151,880
Averaged M/E load	61%	SCR cost	€ 2,661,120
Averaged A/E load	90%	Class	LR

Figure 31 M/V Crown Princess
[http://www.seadogs-reunited.com/crown%20princess.jpg]

The sailing range of cruise vessel is longer than the previous vessel, and berth every one or two days. Thus, the duration of in port and departure/arrival condition is shorter and longer at sea. Different to last vessel, the electric power supply to passenger's cabin, restaurant and all the entertainment activities onboard in all condition. And those electric load consumed a lot of energy, so it should be considered carefully in LCCA.

Table 13 Average working load of cruise vessel engines

Cruise

Main Engine	In port	Departure & Arrival	At Sea
Working hour	7 hr	1 hr	16 hr
Working load	0%	30%	90%
Average daily working load			61%
Aux. Engine	In port	Departure & Arrival	At Sea
Working hour	7 hr	1 hr	16 hr
Working load	90%	90%	90%
Average daily working load			90%

6.4. Rijnborg

M/V Rijnborg is a new generation of container feeder vessel owned by a Dutch shipping company Wagenborg Shipping B.V. She is a 1700 TEU open top container carrier service in the Baltic's main ports and pass through the Kiel Canal to North Sea.

The Rijnborg was built at IHC Holland Kinderdijk yard in 2007. Compare to general 500 to 1000 TEU container feeder in Baltic Sea, Rijnborg is a large feeder. With twin engine propulsion and unusual forward deckhouse. All holds follow an open-top design. In order to sail year-round without problem in this area, she was built to very high ice class standards.
To pass through Kiel Canal maximum draught does not exceed 9 meters.

In this study, the same vessel is assumed to be delivered in 2015 and start operation in same area. The ship will sail around Baltic Sea and North Sea 350 days per year, 18 hours a day. Detail specification described in follow table.

Table 14 Particulars of M/V Rijnborg

Type	Container		
Name	Rijnborg	Fuel consumption rete	173 g/kWh
LOA	176 m	Days of operation/yr	350
LBP	166.75 m	Averaged total power / day	246 MWh
Breadth	23.7 m	Sailing in SECA	100%
Depth	14.25 m	Total energy consumption/yr	86,100 MWh
Draught	7.7 m	Continuous Sailing days	5
Gross Tonnage	16506	Total fuel used	14895 MT
Net Tonnage	8084	Engine cost diesel	€ 5,280,000
Deadweight	14850 MT	Engine cost LNG/methanol	€ 6,600,000
Main Engine Power	15000 kW	Cost of LNG tank	€ 5,130,576
Auxiliary Engine Power	1500 kW	Scrubber cost	€ 2,500,000
Averaged M/E load	61%	SCR cost	€ 642,000
Averaged A/E load	73%	Class	BV

Figure 32 M/V Rijnborg
[http://www.marinetraffic.com/nl/photos/of/ships/photo_keywords:9355812/ship_name:RIJNBORG]

Compare to general cargo ship, container vessel berth to different port frequently and departure the ports after quickly cargo loading/unloading process. This vessel assumed berth in port every 2 or 3 days, and stay in port 15 to 20 hours. In departure/arrival condition, running bow thruster requires huge power, and in other operation the main power consumption is from reefer containers. The reefers running 24 hours and assumed take constant 40% of the total generated power.

Table 15 Average working load of container vessel engines

Container vessel			
Main Engine	In port	Departure & Arrival	At Sea
Working hour	6 hr	1 hr	17 hr
Working load	0%	20%	85%
Average daily working load			61%
Aux. Engine	In port	Departure & Arrival	At Sea
Working hour	6 hr	1 hr	17 hr
Working load	50%	90%	80%
Average daily working load (with reefer)			73%

6.5. B-164 (Under construction)

On 18th of March 2013 the Board of REMONTOWA SHIPBUILDING S.A. singed a new contract for building modern, double-ended, car-passenger ferry with Gas-Electric propulsion. This project is from the Danish local government authority Samso Kommune and designed in accordance with gererally accepted pro-environment policy by using Gas-Electric propulsion. The ferry will also meet high ecological requirement.

The vessel is designed for year-round sailing between islands and the Danish mainland. It will carry 600 passengers and 160 cars onboard. The ship has 100 meter length and equipped four LNG/MGO duel fuel engine to speed up maximum 16 knots.

Compare to the previous three vessels, this vessel is smaller and with less engine power. Daily running hour is shorter because of the short routes between islands. It shows different scenario and result in the comparison that performed in Chapter 7.

Table 16 Particulars of B-164

Type	Ferry		
Name	B-164(Hull No.)	Fuel consumption rete	173 g/kWh
LOA	99.9 m	Days of operation/yr	350
LBP	N/A	Averaged total power / day	35 MWh
Breadth	18.5 m	Sailing in SECA	100%
Depth	5.2 m	Total energy consumption/yr	12,159 MWh
Draught	3.2 m	Continuous Sailing days	1
Gross Tonnage	N/A	Total fuel used	2103.507 MT
Net Tonnage	N/A	Engine cost diesel	€ 1,216,000
Deadweight	650 MT	Engine cost LNG/methanol	€ 1,520,000
Main Engine Power	3000 kW	Cost of LNG tank	€ 973,331
Auxiliary Engine Power	800 kW	Scrubber cost	$1,390,977
Averaged M/E load	36%	SCR cost	€ 192,000
Averaged A/E load	45%	Class	DNV

Figure 33 Vessel “B-164”
http://www.maritimejournal.com/news101/lng/trend-setting-danish-ferry [

The ferry service in short routes between islands and Danish mainland, the ferry only sails in daytime. During the nighttime, electric load supplied by shore power so the auxiliary engine working load was selected 0% here.

Table 17 Average working load of small ferry engines

Small ferry			
Main Engine	In port	Departure & Arrival	At Sea
Working hour	12 hr	3 hr	9 hr
Working load	0%	20%	90%
Average daily working load			36%
Aux. Engine	In port	Departure & Arrival	At Sea
Working hour	12 hr	3 hr	9 hr
Working load	0%	90%	90%
Average daily working load			45%

7. LIFE CYCLE COST ANALYSIS

Four different types of vessels mentioned in previous chapter with different routes, engine size and continuous working days/hours combined with different technologies are picked up the impacts in the life cycle cost analysis. The impacts of alternatives are coupled with the features of vessels; there is no specific best solution for all ship. This chapter introduced the baseline scenario, the detail calculation and performed the result of this study.

7.1. Baseline Scenario

A baseline of life cycle cost is used to compare the performance of alternatives. The baseline in this study is defined as no extra new technology installation, propulsion and generator engines only fuelled by MGO in SECAs.

Follows table collect the baseline of life cycle cost for four different type of ship. The fuel consumption rate is assumed the same for different size of engine, and operation hours and days are defined according to ship’s routes. The initial capital cost is used to calculate payback time of extra initial investment and total life time cost is to compare which alternative can save more expense. The initial investment cost only considered the difference between alternatives mainly are engine and equipment cost, the hull part is neglected.

The total life costs on this table were sum of costs year by year, and exchanged to present value. Cruise vessel has largest engine power and fuel consumption, so she has highest initial and total life cost. Oppositely small ferry cost is much smaller than other three vessels.

In order to compare the economic efficiency between MGO and other alternatives, the return of investment (ROI) and total life cycle cost are set as the observe target. Here ROI means the return of extra investment of additional equipment installation cost such as LNG tanks, scrubber, engine prices etc. The equipment cost based on the assumption in chapter 6 and will be performed in next section.

Table 18 Baseline of four vessels

	Ro-Pax	Cruise	Container	Ferry
Main Engine Power	26000 kW	50400 kW	15000 kW	3000 kW
Auxiliary Engine Power	5660 kW	16800 kW	1500 kW	800 kW
Averaged M/E Load/24hr	54%	61%	61%	36%
Average A/E Load/24hr	62%	90%	73%	45%
Time in SECAs	100%	80%	100%	100%
Continuous Operation Days	3	7	5	1
Days of Operation (per year)	300	330	350	350
Life span	15 years	15 years	15 years	15 years
Date of starting operation	2015	2015	2015	2015
Engine fuel consumption	173 g/kW-h	173 g/kW-h	173 g/kW-h	173 g/kW-h
Total fuel consumption/year	21,890 MT	50,411 MT	14,895 MT	2,104 MT
Initial investment cost	€ 18.0 M	€ 38.7 M	€ 9.5 M	€ 2.3 M
Total life cycle cost	€ 168.9 M	€ 386.3 M	€ 112.2 M	€ 16.8 M

7.2. Life Cycle Cost Calculation-Initial Cost

The initial cost of a new build vessel is counted only costs before the vessel delivered. It includes costs of design, equipment, installation / commissioning and test / certify by classification society. Equipment includes main engine, auxiliary engine, LNG storage tank/Scrubber and other extra essential equipment for using the alternatives. The costs other than equipment cost can be simply estimated based on percentage of the equipment cost. In different country, the percentages are to be considered different value due to the big difference of labour costs in different countries.

In this study, the engineering design fee is 9 percent of equipment cost, installation and commissioning charges 50 percent and 1 percent for classification and inspection. Total capital expenses are 1.6 times of equipment cost shows in next table.

Table 19 List of initial investment

Total capital expense	Total	=	1.6A
Equipment	Equipment capital cost [€]	=	1.0A
Installation / Commissioning	Equipment capital cost [€]*Estimation percentage [%]	=	0.5A
Engineering design	Equipment capital cost [€]*Estimation percentage [%]	=	0.09A
Classification / Certification	Equipment capital cost [€]*Estimation percentage [%]	=	0.01A

The flowing four tables are the detail initial cost calculation of four types of vessels. Each one includes all alternative technologies and calculated based on above cost estimation.

Table 20 Initial cost calculation of Ro-Pax vessel

Ro-Pax vessel			LNG	HFO+Scrubber	Methanol	MGO
Equipment	=	A	€ 17.8 M	€ 14.0 M	€ 12.7 M	€ 11.2 M
Engineering design	=	0.09A	€ 1.6 M	€ 1.3 M	€ 1.1 M	€ 1.0 M
Installation	=	0.5A	€ 8.9 M	€ 7.0 M	€ 6.3 M	€ 5.6 M
Classification/test	=	0.01A	€ 0.2 M	€ 0.1 M	€ 0.1 M	€ 0.1 M
Total initial investment	=	1.6A	€ 28.5 M	€ 22.4 M	€ 20.3 M	€ 18.0 M

Table 21 Initial cost calculation of cruise vessel

Cruise vessel			LNG	HFO+Scrubber	Methanol	MGO
Equipment	=	A	€ 55.1 M	€ 27.3 M	€ 26.9 M	€ 24.2 M
Engineering design	=	0.09A	€ 5.0 M	€ 2.5 M	€ 2.4 M	€ 2.2 M
Installation	=	0.5A	€ 27.5 M	€ 13.7 M	€ 13.4 M	€ 12.1 M
Classification/test	=	0.01A	€ 0.6 M	€ 0.3 M	€ 0.3 M	€ 0.2 M
Total initial investment	=	1.6A	€ 88.2 M	€ 43.7 M	€ 43.0 M	€ 38.7 M

Table 22 Initial cost calculation of container vessel

Container vessel			LNG	HFO+Scrubber	Methanol	MGO
Equipment	=	A	€ 11.7 M	€ 8.4 M	€ 6.6 M	€ 5.9 M
Engineering design	=	0.09A	€ 1.1 M	€ 0.8 M	€ 0.6 M	€ 0.5 M
Installation	=	0.5A	€ 5.9 M	€ 4.2 M	€ 3.3 M	€ 3.0 M
Classification/test	=	0.01A	€ 0.1 M	€ 0.1 M	€ 0.1 M	€ 0.1 M
Total initial investment	=	1.6A	€ 18.8 M	€ 13.5 M	€ 10.6 M	€ 9.5 M

Table 23 Initial cost calculation of container vessel

Small ferry			LNG	HFO+Scrubber	Methanol	MGO
Equipment	=	A	€ 2.49 M	€ 2.80 M	€ 1.52 M	€ 1.41 M
Engineering design	=	0.09A	€ 0.22 M	€ 0.25 M	€ 0.14 M	€ 0.13 M
Installation	=	0.5A	€ 1.25 M	€ 1.40 M	€ 0.76 M	€ 0.70 M
Classification/test	=	0.01A	€ 0.02 M	€ 0.03 M	€ 0.02 M	€ 0.01 M
Total initial investment	=	1.6A	€ 3.99 M	€ 4.48 M	€ 2.43 M	€ 2.25 M

Next table and chart summarized initial capital cost of vessels with different alternative technologies; the result shows different scenarios in each vessel. Generally LNG has high initial cost because of the costly LNG storage tank. Except MGO, initial cost of methanol is less than others. Although the duel fuel engine is more expensive than conventional engine, but scrubber cost is more than the difference between two types of engines.

Table 24 Initial capital investment of different vessels and technologies

	Ro-Pax	Cruise	Container	Ferry
LNG	€ 28.5 M	€ 88.2 M	€ 18.8 M	€ 4.0 M
Scrubber	€ 22.4 M	€ 43.7 M	€ 13.5 M	€ 4.5 M
Methanol	€ 20.3 M	€ 43.0 M	€ 10.6 M	€ 2.4 M
MGO	€ 18.0 M	€ 38.7 M	€ 9.5 M	€ 2.3 M

It is easier to observe from below figure, except MGO methanol has less initial cost. Using LNG as a fuel cost most in Container, Cruise and Ro-Pax vessels, especially Cruise vessel has about double of initial cost, because of the longer cruising range and duration, the required numbers of LNG fuel storage tank cost huge amount of money. If the infrastructure of LNG available in most of ports, the fuel tank could be refilled in shorter duration, then the initial cost can be reduced but still more expensive than other alternatives.

Ferry has different scenario to other vessels, using scrubber technology unexpected cost more than LNG. There are two reasons, first is because the price curve of scrubber, from figure 26, the relationship between price and engine power is nonlinear, the lower engine power the higher unit cost per kilowatt. Ferry has small total engine power compare to other vessels, the relative cost of Scrubber is higher. Second reason is the short service routes; the ferry sails between island and back to mother port everyday, the fuel tank can be refilled frequently. So it need only small storage tank and it cost less. Based on these two reasons LNG has lower initial cost than scrubber when apply on ferry.

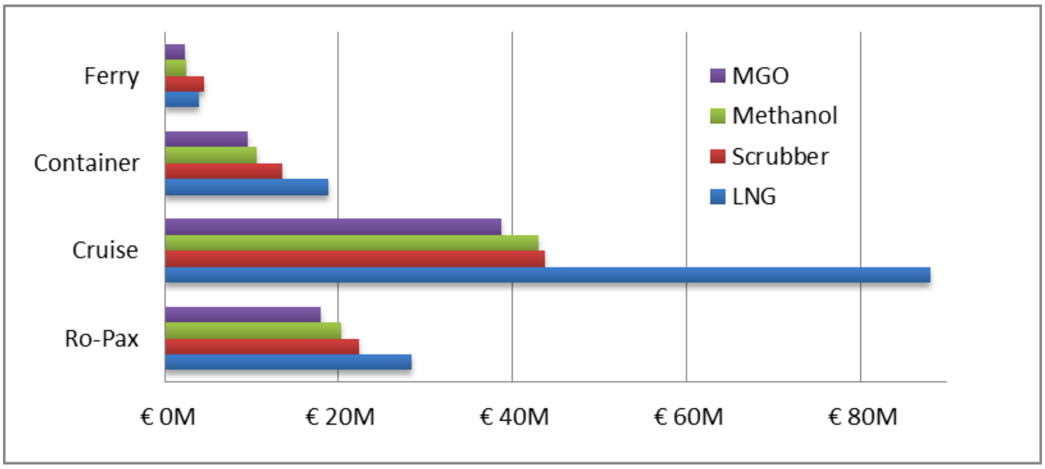


Figure 34 Initial capital investment comparison

7.3. Life Cycle Cost Calculation-Annual Cost

This section performs the calculation of costs after the ship start operation until the end of the life cycle. Operation costs include fuel cost, maintenance cost and labour cost. For scrubber system in addition, the consumption of caustic soda is to be taken into account. Maintenance costs and labour costs for alternative technologies are similar. Compare to fuel, the costs have only tiny influence to total life cycle cost. So in life cycle cost computation operation cost take only fuel and caustic soda cost, and assess annually with assumed escalation rate.

Estimation of future fuel price is very difficult and complicated. Here used the assumption in Chapter 6, the prices of four fuels follow the crude oil price fluctuation with the same escalation rate in 15 years. Following chart shows the tendency and price prediction in the future. MGO will rise to 1730 Euro/MT and the price spread between MGO and HFO/LNG reach about 600 Euro/MT in 2030. Methanol will be 150 Euro/MT cheaper than MGO. To have an integrated observation of life cycle cost, the other fuel price prediction scenarios will be performed in sensitivity analysis.

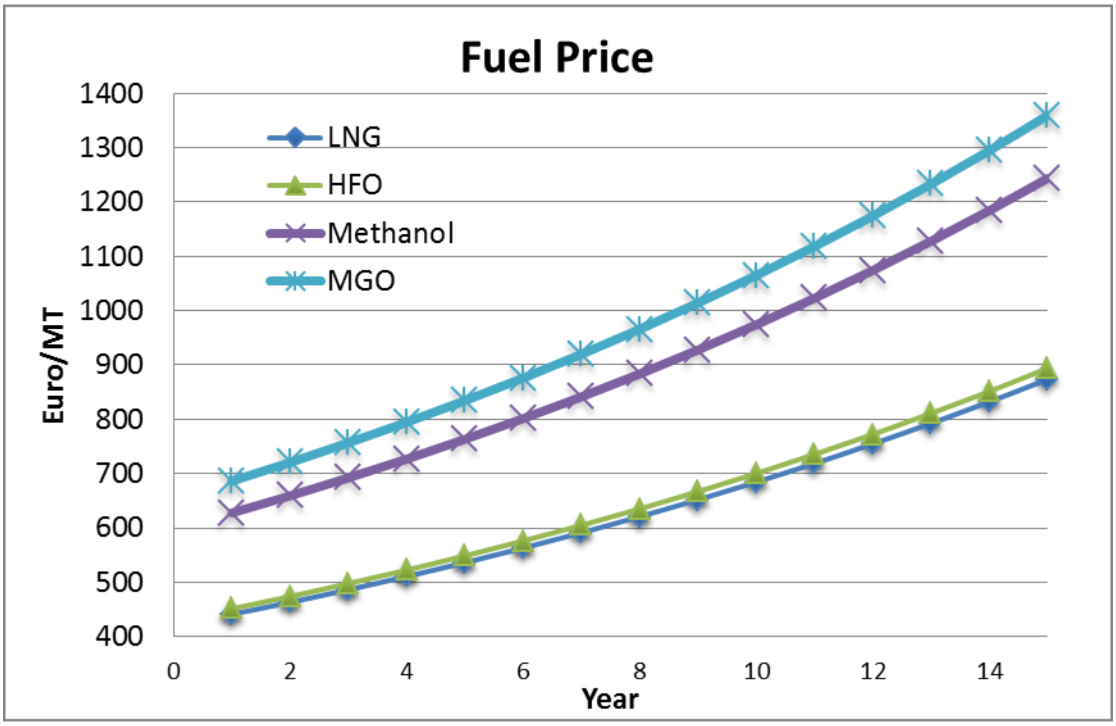


Figure 35 Fuel price estimation

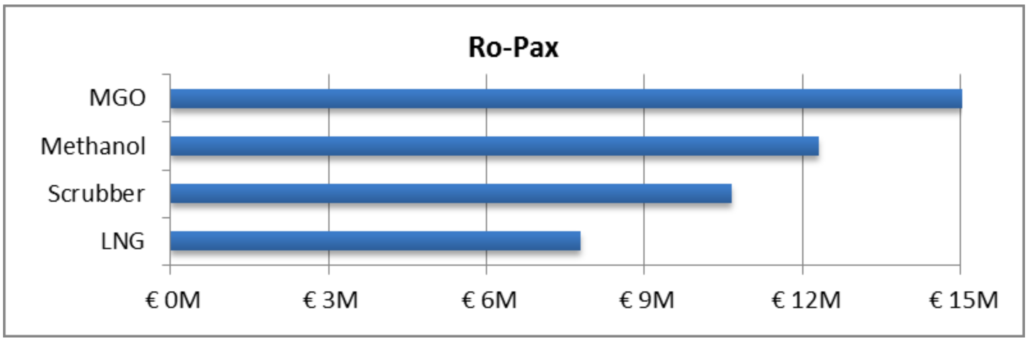


Figure 36 Annual cost (1st year) of Ro-Pax vessel

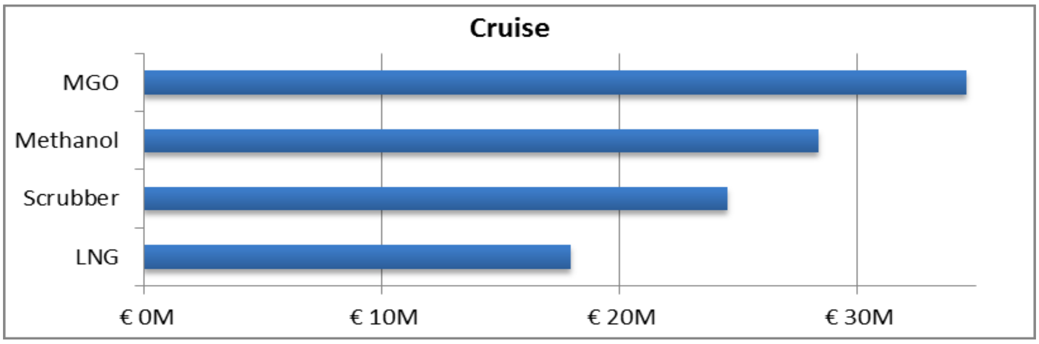


Figure 37 Annual cost (1st year) of Cruise vessel

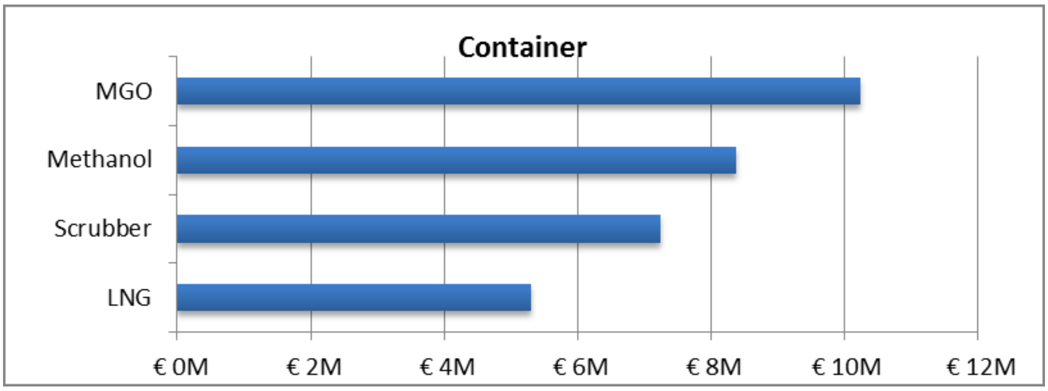


Figure 38 Annual cost (1st year) of Container vessel

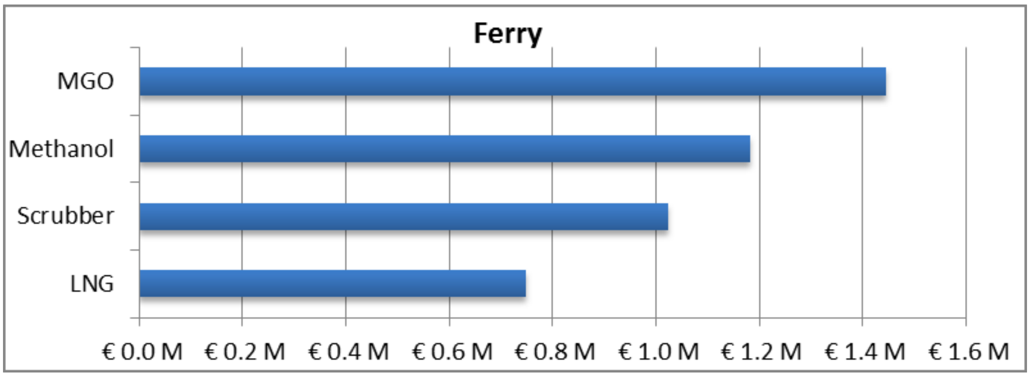


Figure 39 Annual cost (1st year) of Small ferry

As shown in figure 34 to 37 all vessels have the same ratio between different technologies' annual costs. The fuel costs difference between alternatives and MGO depending on the amount of fuel consumption. Table 25 lists the annual cost saving, with different technologies Ro-Pax vessel can save 1.28 to 5.37 millions of Euros in the first year. For Cruise vessel 2.95 to 12.36 millions of Euros, 0.87 to 3.65 millions for Container and 0.26 to 0.52 for small ferry.

Use those values with escalation rate and discount rate to obtain the annual cost saving in each year respect to present value.

Table 25 Cost saving in 1st year

	Ro-Pax	Cruise	Container	Ferry
LNG	€ 5.37M	€ 12.36M	€ 3.65M	€ 0.52M
Scrubber	€ 4.38M	€ 10.08M	€ 2.98M	€ 0.42M
Methanol	€ 1.28M	€ 2.95M	€ 0.87M	€ 0.26M

7.4. Life Cycle Cost Calculation Result

The life cycle cost of four ship/route combined with four types of technologies computed according to initial costs and annual costs listed in previous sections.

During 15 years lifetime, costs of each year is estimated and exchanged to present value by escalation rate and discount rate. The life cycle cost progression from year 0 to year 15 shows in follows.

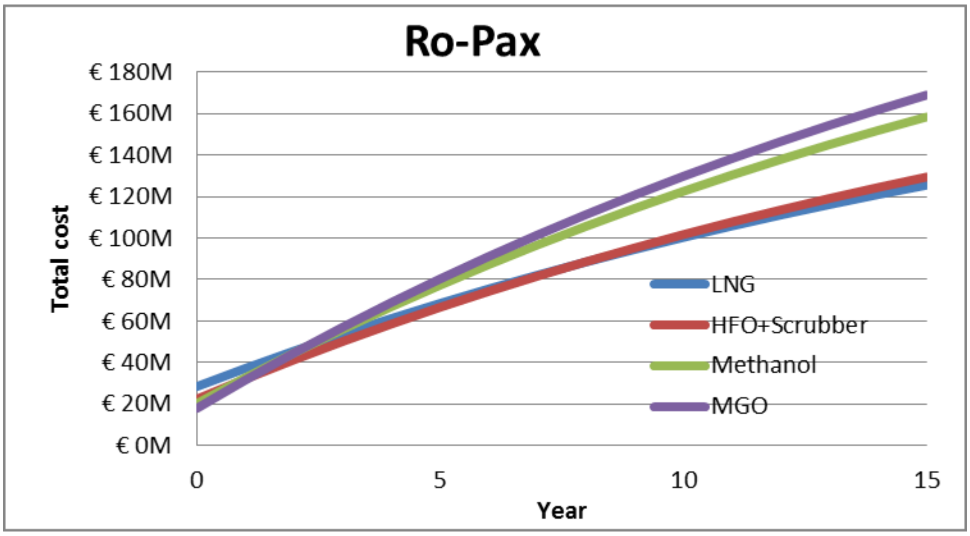


Figure 40 Life cycle cost progression of Ro-Pax

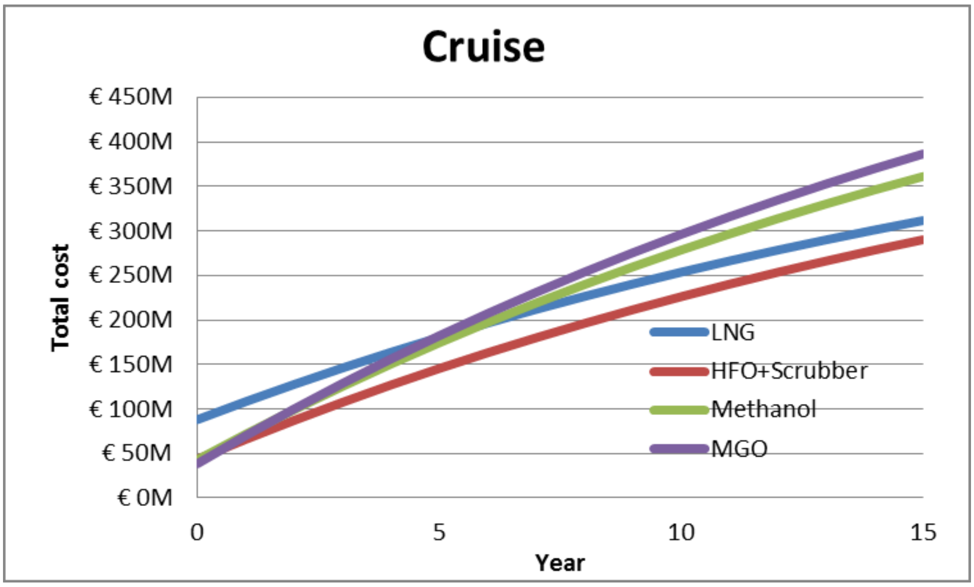


Figure 41 Life cycle cost progression of Cruise

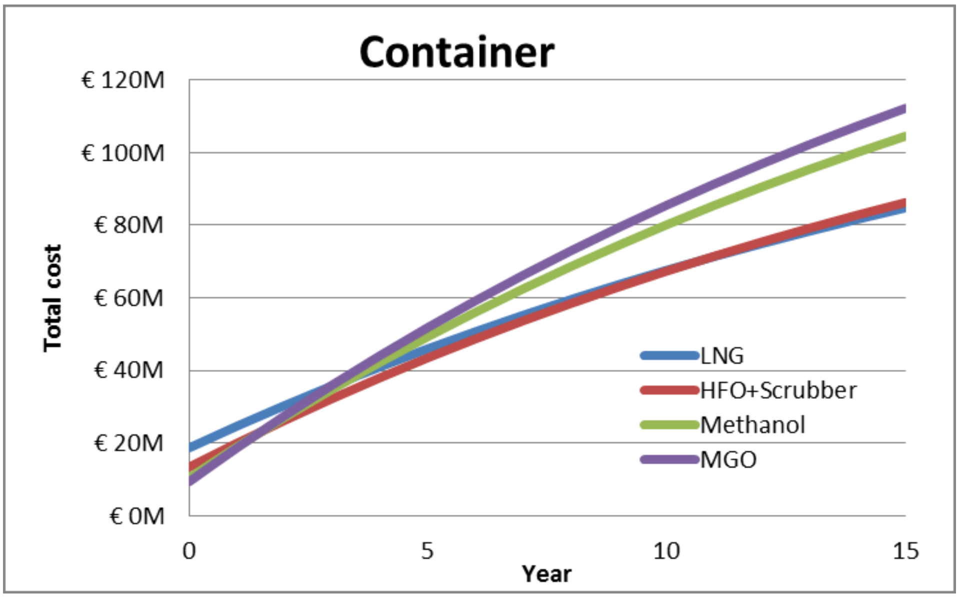


Figure 42 Life cycle cost progression of Container

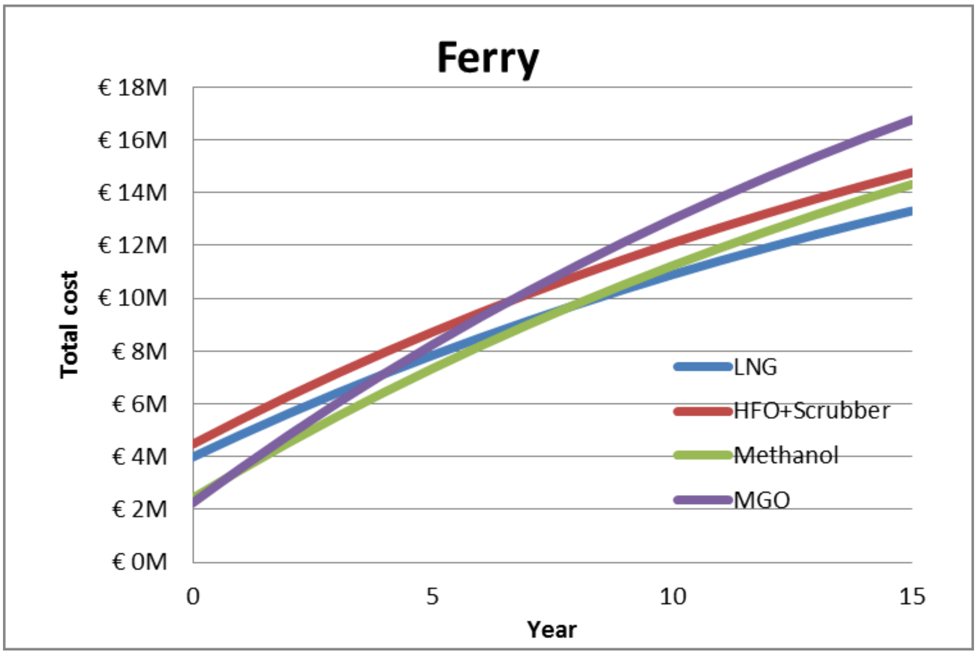


Figure 43 Life cycle cost progression of Ferry

Observe above charts, the cross between purple line and other colors means at that time alternatives has the same total cost with MGO. It also represents the moment of return of extra investment. In long period, LNG seems a most economical solution for Ro-Pax, Container and ferry such kind short shipping vessels. But for Ocean going Cruise vessel, due to the high initial cost of LNG, Scrubber is more competitive than others. But from the tendency shows on figure 39, the cost of scrubber will exceed the cost of LNG if the lifetime extended. Next figure points out the payback time of each vessel and alternative technology.

The extra investment of methanol only relates total engine power, so the payback time are more stable for four vessels.

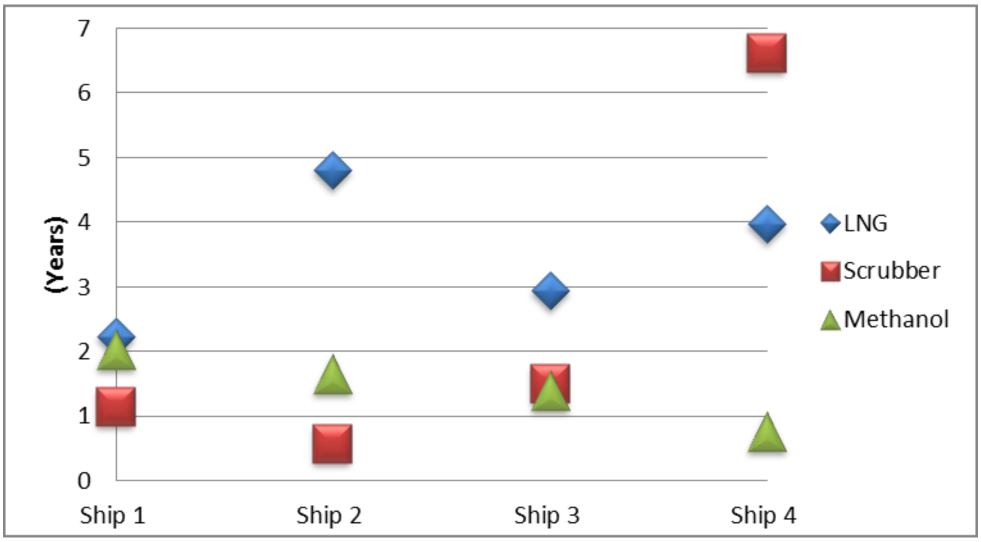


Figure 44 Payback time of extra investment

Total life cycle costs listed in next table, costs of each type of vessel with huge difference. Sizes, speeds, purposes and routes of vessels give every ship a feature of initial investment and annual fuel consumption. For ship 1: Ro-Pax vessel can save most expense when using LNG as fuel, scrubber cost about 4 millions EURO more and methanol also saves about 10 millions ERUO compare to MGO. For ship 2: Different to ship 1, Cruise vessel has economic efficiency with scrubber, it can save about 20 million more than LNG and 60 million than methanol. For ship 3: Container vessel has same order for alternatives with ship1, the differences between technologies are smaller. For ship 4: The total costs of Ferry are much smaller than other vessels. Unlike other vessels, scrubber cost more than methanol, but LNG saves 1 millions more than methanol.

Table 26 Total life cycle cost

	Ro-Pax	Cruise	Container	Ferry
LNG	€ 125.51 M	€ 311.63 M	€ 84.80 M	€ 13.31 M
Scrubber	€ 129.43 M	€ 290.11 M	€ 86.28 M	€ 14.76 M
Methanol	€ 158.37 M	€ 361.06 M	€ 104.54 M	€ 14.32 M
MGO	€ 168.93 M	€ 386.34 M	€ 112.21 M	€ 16.76 M

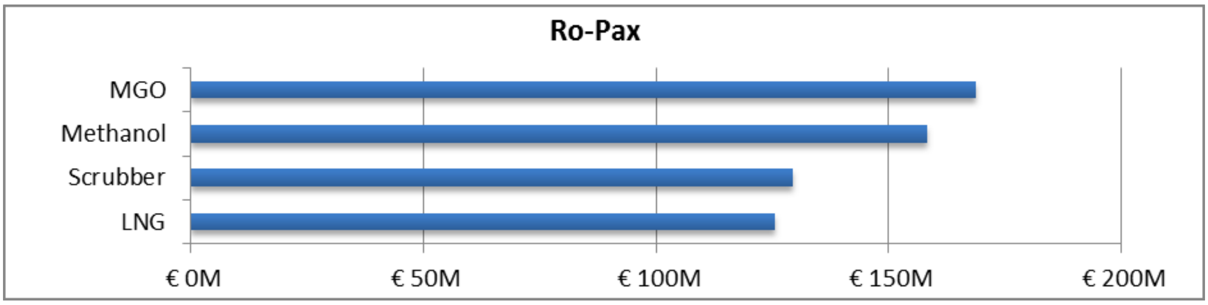


Figure 45 Total life cycle cost of Ro-Pax

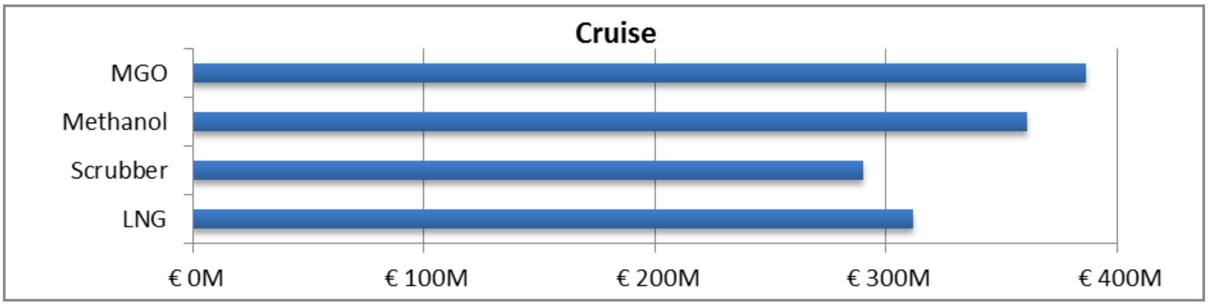


Figure 46 Total life cycle cost of Cruise

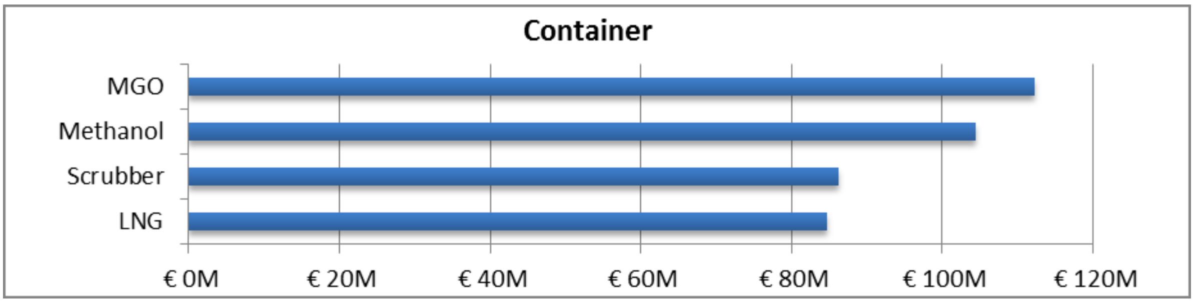


Figure 47 Total life cycle cost of Container

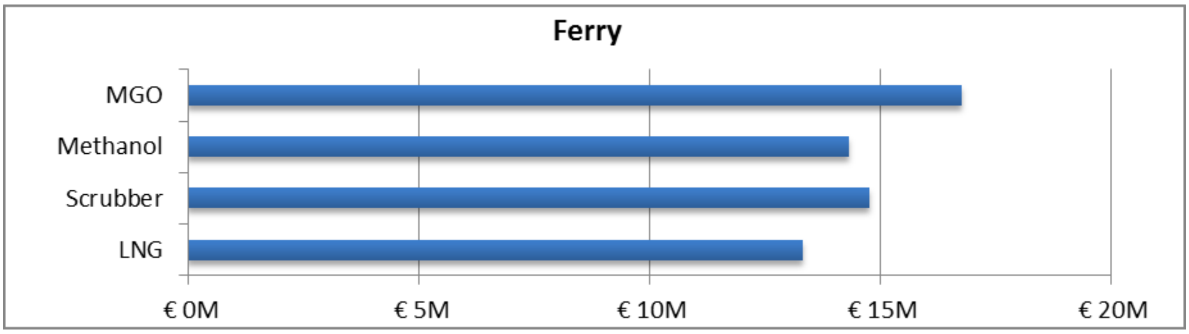


Figure 48 Total life cycle cost of Ferry

From above result, LNG is the cheapest solution for Ro-Pax and container vessel, but it only saves about 4 million and 1.5 million Euros more than scrubber for each vessel. Only 1 to 2 percent of total life cost of MGO saving in 15 years, ship owner must consider if it worth to take this risk to invest huge amount of money in the beginning.

Compare methanol and LNG as fuel for ferry, methanol cost 1 million more than LNG, about 6% of total cost of MGO. But the initial investment of LNG was 1.6 million more than methanol. It is not logical to spend 1.6 million to earn 1 million after 15 years.

For Cruise ship, it is obviously that scrubber is the best solution compare to other alternative. Less initial expense and saves most cost in the lifetime.

7.5. Sensitivity Analysis

Sensitivity analysis gives a general view of impact from parameters in LCCA. Besides running hour, operation days, engine power, amount of fuel consumption in SECA and other factors related to ship's operation, which are based on owners' statistics and experiences, the other parameters are difficult for owner to predict. Fuel cost takes up more than 50% of total life cycle cost in each case. Predicting fuel prices accurately is a mission impossible, especially with different fuel and long term period. Instead of make any prediction, the fuel price varied according to different scenarios to analyze the possible development in the future. Using parameters to give different relationships between fuels, first is the initial price, as mentioned in Table 8, the price of LNG and methanol were estimated in a range. The medina prices were considered in previous calculation. Here take the uppermost or lowermost price to assess the total life cycle cost.

Another parameter is the fuel prices growth tendency. MGO and HFO are produced from fossil oil, and LNG and methanol are from natural gas. Unlike previous assumption, here the fossil fuels and natural gas fuels growth with different rates. Combine a high or a low growing curves approached by natural logarithm with fuel prices to get an overall view.

7.5.1. Scenario I

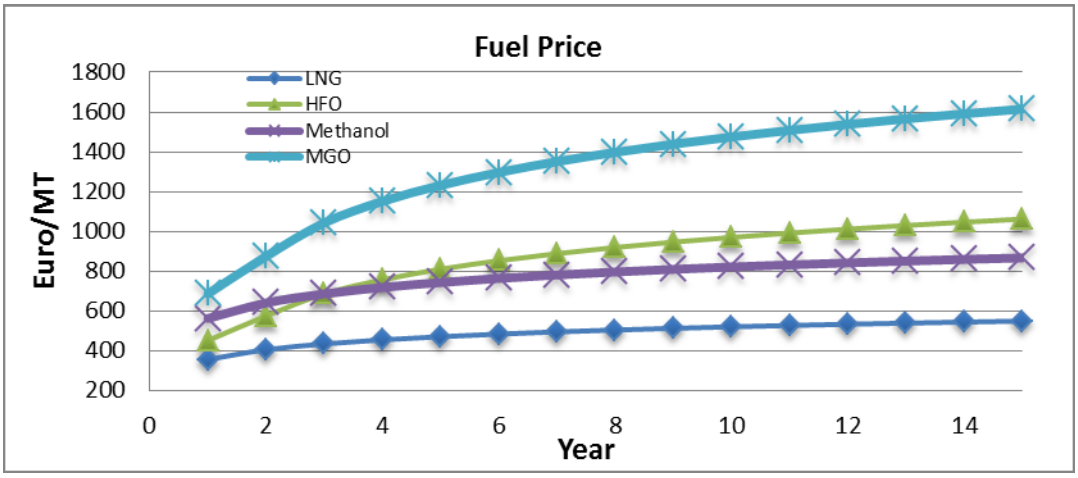


Figure 49 Fuel prices - Scenario I

In this case the LNG and methanol price are selected at lowermost points. Fossil fuels price used high growing curve. The 15 years fuels prices estimation shows in figure 49. From the fourth year, methanol price is lower than HFO. It represent fossil still the primary marine fuel on the market after 2015, not many ship owner switch to LNG or methanol. The demands of fossil oil push the prices rising. With technologies development, the production cost of LNG and methanol reduced, so the prices growth slowly in the future.

Table 27 Total life cycle cost – Scenario I

	Ro-Pax	Cruise	Container	Ferry
LNG	€ 106.28 M	€ 267.34 M	€ 71.71 M	€ 11.47 M
Scrubber	€ 165.42 M	€ 372.98 M	€ 110.77 M	€ 18.22 M
Methanol	€ 143.11 M	€ 325.91 M	€ 94.15 M	€ 14.24 M
MGO	€ 219.70 M	€ 503.28 M	€ 146.76 M	€ 21.64 M

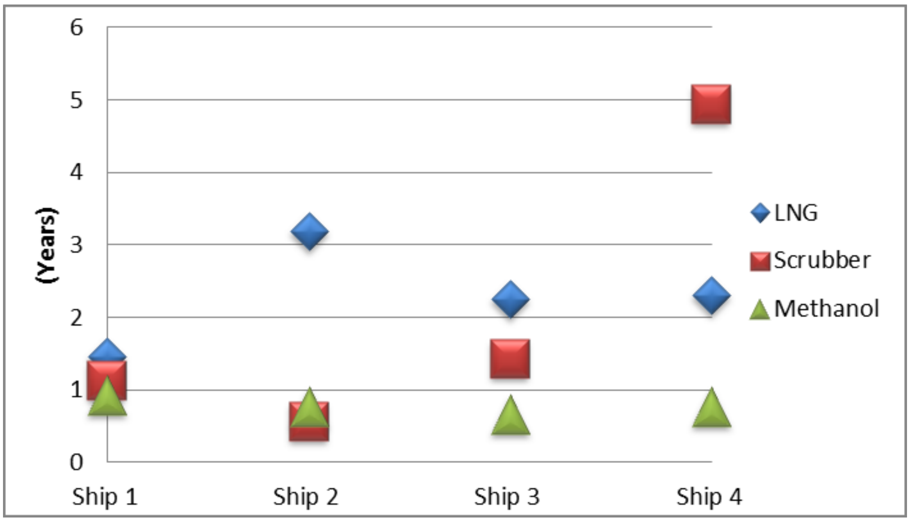


Figure 50 Payback time – Scenario I

Above figure and table show the result of this scenario, the appearance of figure is similar to the case in section 7.4 but payback time is shorter, it is because of the MGO will be more expensive in the future. Methanol still has stable performance for each vessel that can get payback around one year. LNG needs longer time for cruise vessel and scrubber need longer time for small ferry to retune the extra initial investment.

The sequences of total costs are the same for all vessels, LNG cost least expenses during whole life cycle. Methanol is a cheaper solution than scrubber, and all alternatives can save costs compare to MGO. In this case, LNG can really save a significant amount of money, especially for Ro-Pax and container vessels total life cycle costs of using LNG as fuel are less than 50% of costs of using MGO as fuel.

7.5.2. Scenario II

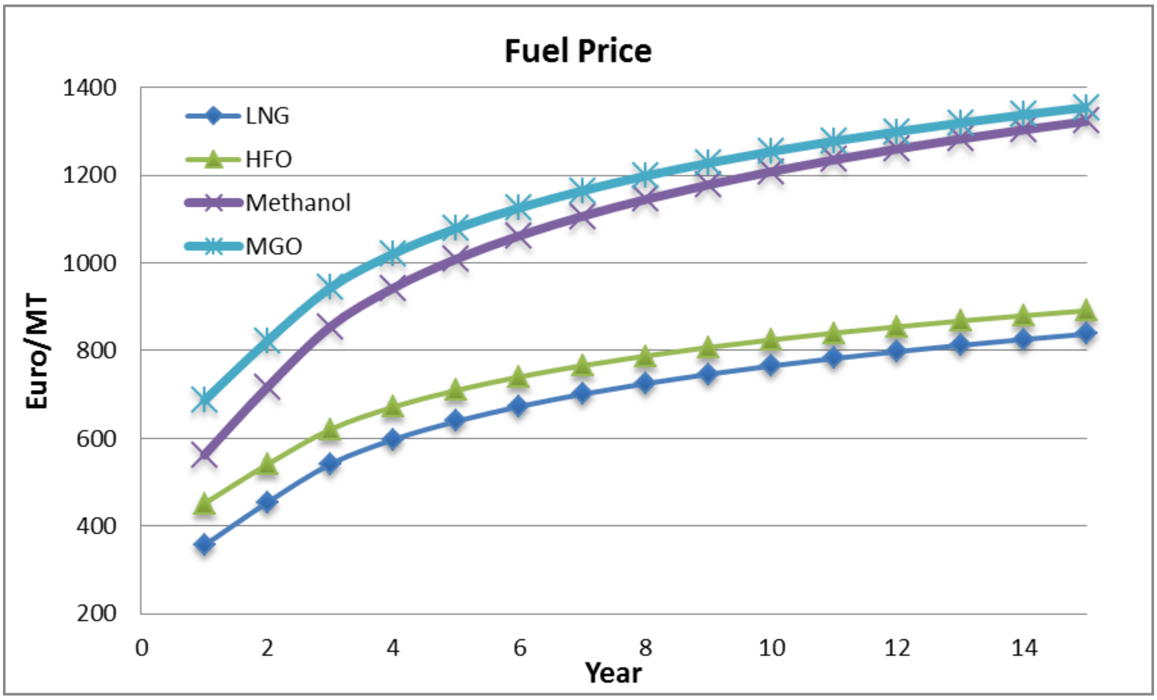


Figure 51 Fuel prices – Scenario II

In Scenario II, LNG and methanol has low initial price so some ship owner switch to operate their vessel with natural gas fuel. The demands of LNG and methanol boost the price rising fast; correspondingly the fossil fuels have a lower inflation curve due to the reducing of demands.

Table 28 Total life cycle cost – Scenario II

	Ro-Pax	Cruise	Container	Ferry
LNG	€ 133.15 M	€ 329.23 M	€ 90.00 M	€ 14.05 M
Scrubber	€ 148.07 M	€ 333.02 M	€ 98.96 M	€ 16.55 M
Methanol	€ 185.54 M	€ 423.63 M	€ 123.03 M	€ 18.31 M
MGO	€ 195.22 M	€ 446.89 M	€ 130.10 M	€ 19.29 M

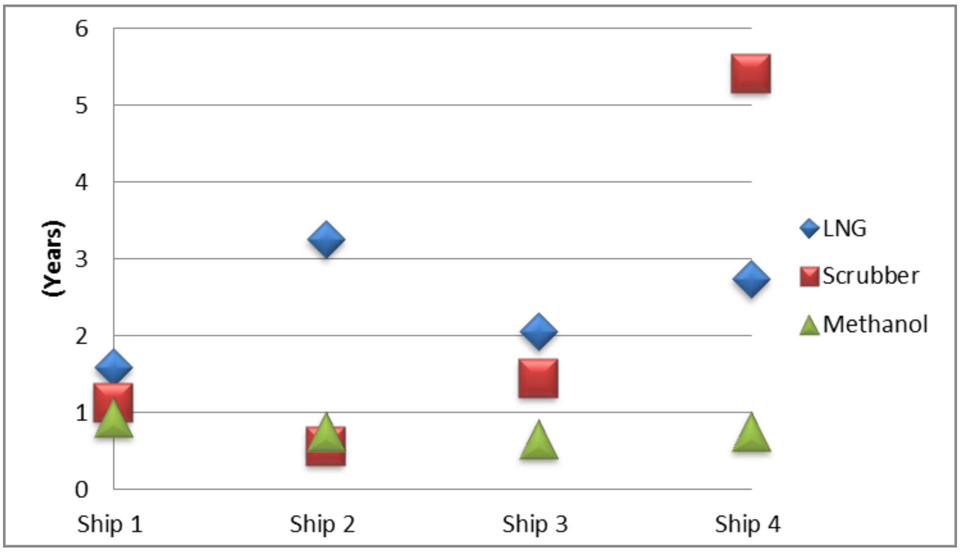


Figure 52 Payback time – Scenario II

LNG still has the best performance in this case, but scrubber is also has good performance close to LNG. For Ro-Pax and container vessels, scrubber cost about 7% of MGO total cost than LNG fuelled vessels. Less than 1% difference for cruise vessel and about 13% for ferry. Due to the fuel prices spread in beginning years are similar to scenario I, the payback estimation is almost the same to scenario I.

7.5.3. Scenario III

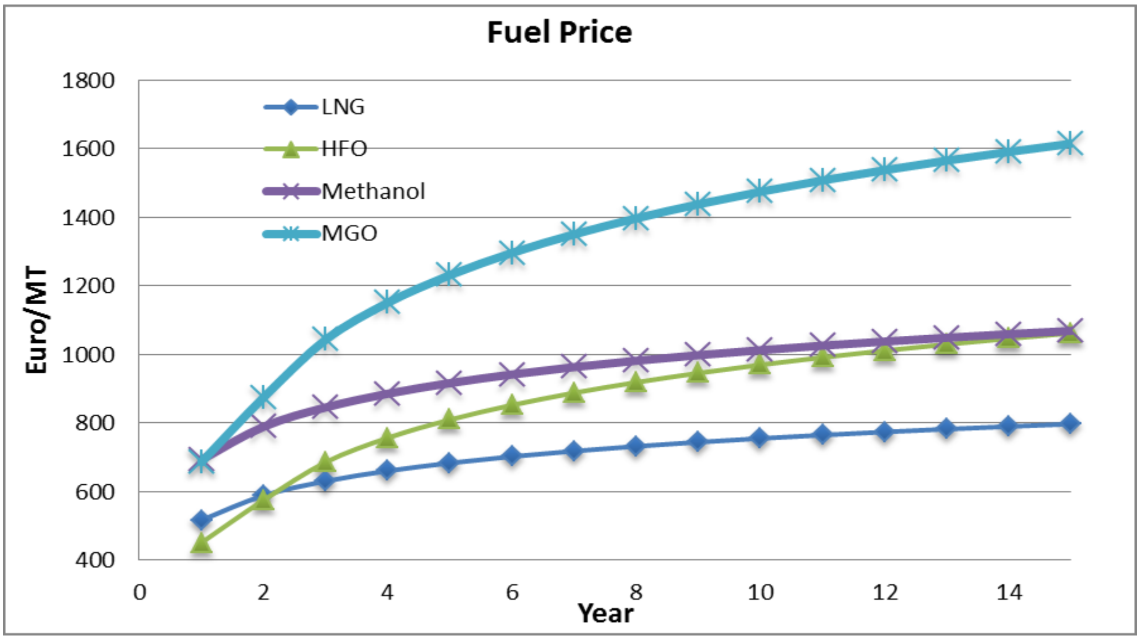


Figure 53 Fuel prices – Scenario III

In the third case, assuming LNG and methanol have uppermost prices at the start of life cycle. Therefore the initial HFO price is cheaper than LNG. Most of vessels keep using fossil fuels so the fossil fuels have high growing rate for the price and natural gas fuels prices grow slowly.

Table 29 Total life cycle cost – Scenario III

	Ro-Pax	Cruise	Container	Ferry
LNG	€ 141.46 M	€ 348.37 M	€ 95.66 M	€ 14.85 M
Scrubber	€ 165.42 M	€ 372.98 M	€ 110.77 M	€ 18.22 M
Methanol	€ 171.76 M	€ 391.91 M	€ 113.65 M	€ 16.99 M
MGO	€ 219.70 M	€ 503.28 M	€ 146.76 M	€ 21.64 M

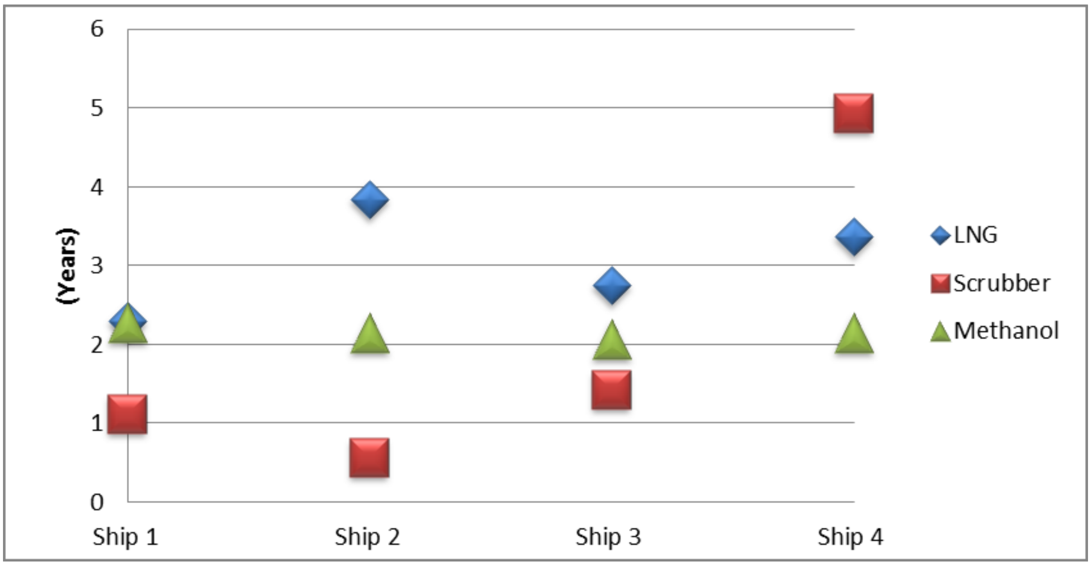


Figure 54 Payback time – Scenario III

Table 29 and figure 54 show the result of total cost during the life cycle, all alternatives can save some expenses compare to MGO and the extra initial investment can be payback less than five years. As scenario I and scenario II, LNG is still most economic fuel in all alternatives. Scrubber and methanol have different performance in different types of vessel, for ferry methanol cost less than scrubber, but for other three vessels scrubber have better performances. The payback time of methanol is stable for each type of vessel around two years.

7.5.4. Scenario IV

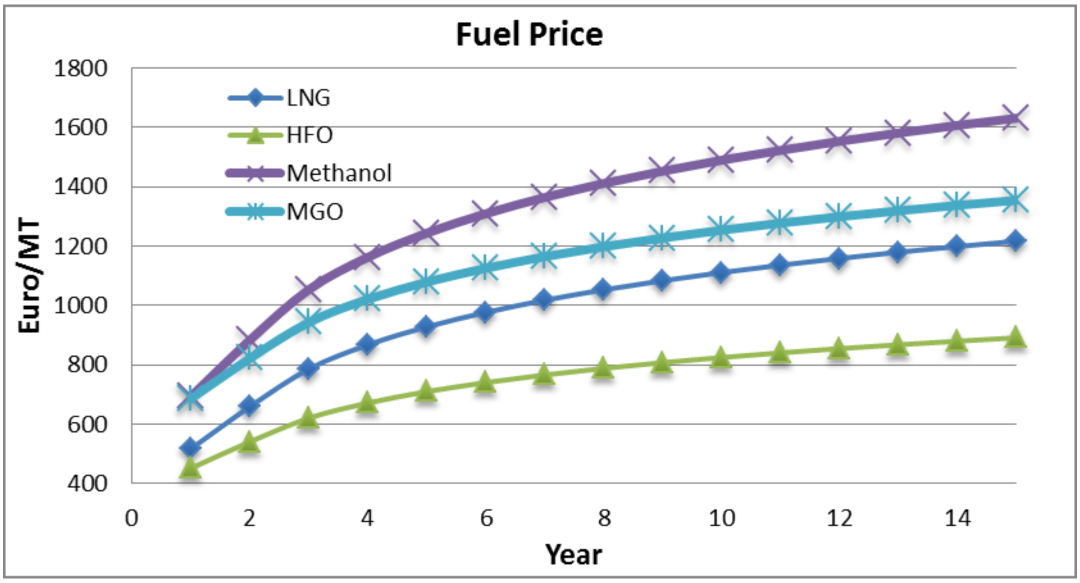


Figure 55 Fuel prices – Scenario IV

Last scenario considers a worst condition for natural gas fuel. In this condition, LNG and methanol prices at uppermost point at beginning. These fuels cost with higher price growing curve in the life cycle. Fossil fuels have lower growing rate of prices. The relationship and the history of fuel prices in the life cycle showed in above chart. Methanol is always cost more than MGO in this case.

Table 30 Total life cycle cost – Scenario IV

	Ro-Pax	Cruise	Container	Ferry
LNG	€ 180.49 M	€ 438.26 M	€ 122.22 M	€ 18.60 M
Scrubber	€ 148.07 M	€ 333.02 M	€ 98.96 M	€ 16.55 M
Methanol	€ 224.10 M	€ 512.43 M	€ 149.26 M	€ 22.02 M
MGO	€ 195.22 M	€ 446.89 M	€ 130.10 M	€ 19.29 M

Table 30 and figure 56 show the result of scenario IV, the methanol price cost more than MGO in the whole life period so methanol never get payback and the total life cycle costs are more expensive than other fuels. Total expenses of LNG are cheaper but close to MGO, the extra initial investment of LNG fuelled cruise vessel can be payback after 10.7 years. Under this fuel prices assumption, scrubber is the best solution for all vessels.

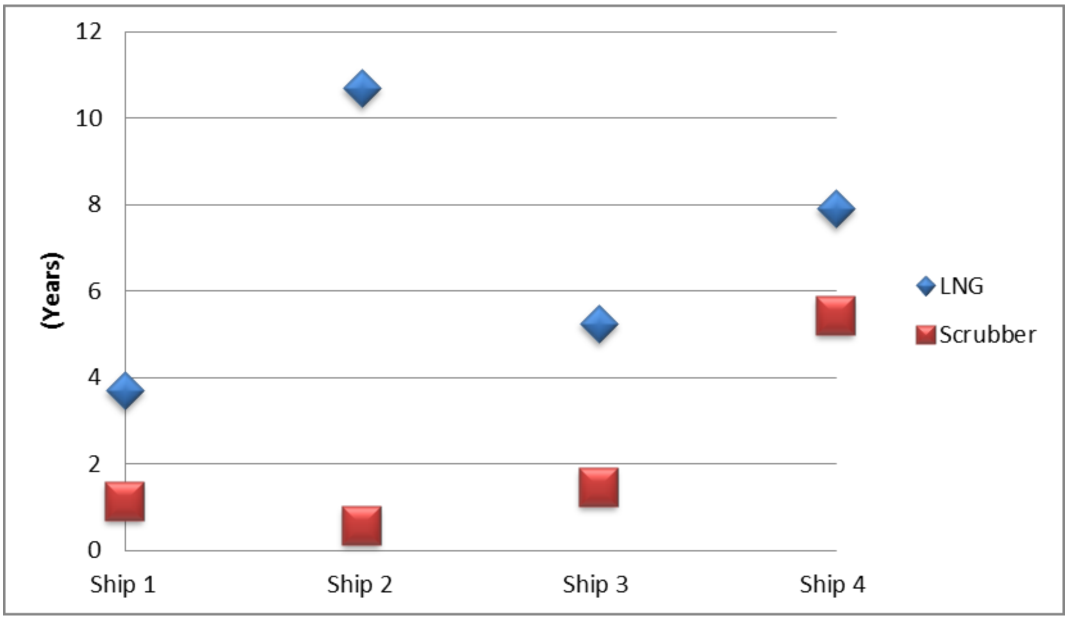


Figure 56 Payback time – Scenario IV

7.6 Retrofit Case

From the LCCA result in previous section, it is conclude that methanol might be a good solution for retrofitting project. The container vessel is picked up as a model in this part to carry out LCCA for comparing different alternative fuels retrofit project.

Different to new build projects, besides the modifications of engine, structure, new equipment installation, the loss from off-hire during the retrofitting is to be considered as an initial cost. And because of the cargo capacity of existing vessels is fixed, new installation will reduce the cargo space and weight. Cargo loss is to be considered as an operation cost in LCCA.

Following table shows the estimated costs of converting the engines and new equipment installations. The total capital investment of switching to methanol is obviously lower than others. Although the methanol fuel price is expensive than the other two, the difference of costs between methanol and others couldn't be payback in short lifetime, especially vessels sails in SECAs less than 50% of life time.

Table 31 Retrofit investment estimation

	LNG	HFO+Scrubber	Methanol
Equipment, modification of engines	€ 6.12M	€ 3.14M	€ 0.99M
Steel work and installation	€ 3.06M	€ 1.57M	€ 0.50M
Design costs	€ 0.61M	€ 0.31M	€ 0.10M
Off-hire cost	€ 0.68M	€ 0.34M	€ 0.34M
Total retrofit cost	€ 10.47M	€ 5.37M	€ 1.92M

Next figure performs a 10 years LCCA of a container vessel, which service in SECAs 30 percent of lifetime. It is assumed using HFO as fuel outside of SECAs and switch to alternatives when sails in SECA. The fuels price prediction is the same with the assumption in section 7.3. From the result, after second year the life cycle cost of methanol is less than MGO. At the tenth year, total cost of using scrubber system is close to methanol but still higher then it. It concludes that methanol is the cheapest solution in this case.

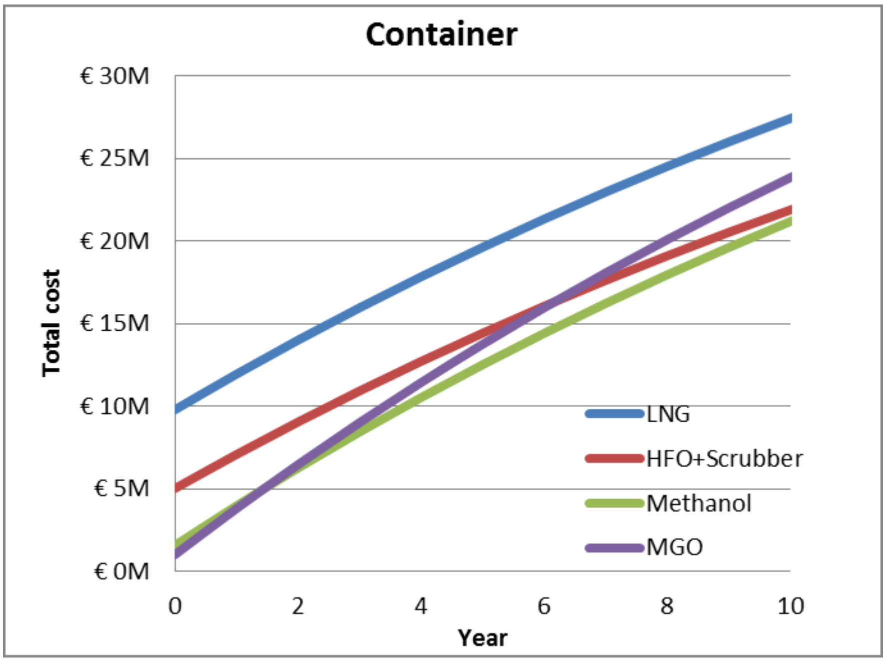


Figure 57 Life cycle cost for container sails 30% lifetime in SECAs

To have an integrated observation, next table lists the cheapest life cycle cost solution for a range of life cycle from one to ten years and duration in SECAs from 10% to 50 %. For container ship sails 10 percent of lifetime in SECAs and life cycle from one to ten years, switch to MGO directly without conversion is more economic. Scrubber system with burning HFO is good for vessel sails more than 40 percent of lifetime in SECAs and life cycle from 8 to 10 years or more. Methanol is suitable for period from 20% to 50% and life cycle around 5 years.

Table 32 Life cycle cost comparison for retrofit container

Life cycle	Period in ECA				
	10%	20%	30%	40%	50%
1 year	MGO	MGO	MGO	Methanol	Methanol
2 year	MGO	MGO	Methanol	Methanol	Methanol
3 year	MGO	Methanol	Methanol	Methanol	Methanol
4 year	MGO	Methanol	Methanol	Methanol	Methanol
5 year	MGO	Methanol	Methanol	Methanol	Methanol
6 year	MGO	Methanol	Methanol	Methanol	Methanol
7 year	MGO	Methanol	Methanol	Methanol	Methanol
8 year	MGO	Methanol	Methanol	Methanol	HFO+Scrubber
9 year	MGO	Methanol	Methanol	Methanol	HFO+Scrubber
10 year	MGO	Methanol	Methanol	HFO+Scrubber	HFO+Scrubber

8. CONCLUSIONS AND DISCUSSION

International trade is more and more important and develops fast in the past century. Marine transportation supports the international trade and economic evolution. Shipping industry obtained huge amount of energy to improve the technologies. But those technologies also accompany with some pollutions, after human have a more comfortable life they realize that environment protection is more and more important.

The MARPOL convention witch published by IMO has forty years history. Most of regulations are adopted and take effect in last decade and near future. Air pollution is becoming an important issue recently, regarding to the regulations in MARPOL, the new limitation of SOx emission in SECAs will take effect in 2015. The countries in SECAs are always the pioneers in environment protection field and also have advanced industry science and technology.

This study listed four possible solutions to achieve the restriction, LNG, Scrubber, Methanol and MGO. Those fuels and technologies are well discussed and have high possibility to be commercialized. LNG and scrubber have fuel price advantage, so the operation cost is lower. The advantage of methanol and MGO is low initial investment for the equipment.

The decision of using which technology onboard depends on various factors. One of the most important factors that ship owner also concern more is the expenditure of the vessel. The amount of expenditure affects the profit which ship owner can obtain from operating the vessel. A LCCA is performed in this study to provide the detail comparison between different technologies. Basically the costs occur during the life cycle of the vessels can be simply classified to initial investment and operation cost. Initial investment related to the price of the equipment and machinery required by different technologies. Operation cost mainly comes from the fuel consumption.

According to the results of LCCA in section 7.4, all of the alternative fuels cost less than using MGO in the SECA area. The types and service routes affect the machinery cost, for example, cruise vessels have longer continuous operation days that make LNG fuelled vessels require more storage tanks. The LNG storage tank now is still expensive that’s why scrubber has better performance on cruise vessels. Oppositely, for small ferry it can refill the fuel everyday so it only needs one small storage tank and due to the price curve of scrubber, price per unit power of small scrubber is more expensive than large one. Therefore scrubber is not a very good solution for small ferry.

Fuel prices have huge impact to the total life cycle cost. Predicting the prices especially for duration longer than decade is extremely difficult. However, from the sensitivity analysis in sect 7.5, except scenario IV, LNG fuelled vessels has very good achievement compared to others and methanol has stable ROI for each type vessel. Ship owner can put their own fuel price forecast into this model to select their future fuel.

Although LNG is a green and cheap fuel, ship owner still need to consider the availability of LNG in their operation port. Currently only few ports built LNG infrastructure, ship owner must select their routes carefully. However, more and more LNG fuelled vessels on the market will encourage investment in infrastructure and the development of the supply chain.

Scrubber is a more safe solution for ship owner, compare to MGO it still reduce huge amount of cost no matter in which fuel price estimation. And the initial investment is far less than LNG except for small vessels, ship owner don't need to take much risk to fulfill the requirement in SECAs. But using scrubber system will generate waste and sewage that cannot be discharge into the sea. The handling and postprocessing are still cost money and energy. Although using scrubber system achieves the requirement, HFO is still not a clean energy for the future.

The advantage of methanol is low initial investment, quick payback time and the total cost is lower than others in five years. It might be a good solution for vessels, which service not only in SECAs with short life cycle. A retrofit example with LCCA was performed in section 7.6 to observe the feasibility of methanol fuelled vessel. The result shows that Methanol is suitable for vessels sailing period in SECA from 20% to 50% and remains life cycle around 5 years.

In conclusion, the regulations of MARPOL Annex VI are mandatory. It will impact the shipping industry in SECAs 2015 and in global area 2020 or 2025. The shipping industry must consider and face this challenge. As the LCCA result in this study, each alternative has its own advantages, depending different type, purpose, routes and life time, there is no best solution for all vessels. But it is obviously all alternatives are better than switch to MGO for short sea shipping vessels in SECAs. Due to those developments, the related international conventions and classification rules, which concerned about safety issues will also published in the near future. LNG, scrubber and methanol are mature technologies for the shipping industry.

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