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SCHOOL OF BUSINESS

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MASTER OF SCIENCE (MSc) IN **INTERNATIONAL SHIPPING, FINANCE & MANAGEMENT**

The 2020 Global Sulfur Limit and a Financial Investment Analysis around the Alternative Fuels and Solutions used in the Maritime Industry

by

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A thesis submitted to the Secretariat of the MSc in International Shipping, Finance and Management of the Athens University of Economics and Business, in partial fulfillment of the Requirements for the Master's Degree in International Shipping, Finance and Management.

Athens

30/10/2020

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CERTIFICATION OF THESIS PREPARATION

"I hereby declare that this particular thesis has been written by me, in order to obtain the Postgraduate Degree (MSc) in International Shipping, Finance and Management, and has not been submitted to or approved by any other postgraduate or undergraduate program in Greece or abroad. This thesis presents my personal views on the subject. All the sources I have used for the preparation of this particular thesis are mentioned explicitly with references being made either to their authors, or to the URL's (if found on the internet)."

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Abstract

The purpose of this paper is to demonstrate the radical changes in the Shipping industry in terms of emission limitations. In addition, we focus on the most promising solutions for the shipowners in order to be compliable with the new regulations set by the International Maritime Organization. Extensive reference is rendered in the dilemma between the Exhaust Gas Cleaning Systems (Scrubbers) and the use of low sulfur fuels like Marine Gas Oil (MGO) or Liquefied Natural Gas (LNG). There is also an emphasis in the alternative fuels providing information based on 8 criteria (Price, Infrastructure, Technology, Regulations, Scalability, Environmental Impact, CAPEX, OPEX). The approach of our study is technical but concurrently there is also a financial analysis for identifying the most cost-efficient solutions for the shipowners.

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INTRODUCTION

1) General Overview, background that led to the environmental limitations

Over the last decades, the landscape of the Shipping industry has changed dramatically. Shipowners seem to be on the spotlight and concurrently under pressure because of the massive emissions' reduction that is scheduled by the IMO. These limits are expected to contribute to a scalable wave of new technology developments of low carbon-fuels. The ramifications of atmospheric emissions (in specific NO_X, SO_X and Particulate matter) in the environment are investigated quite intensively by the experts.

The impact could be severe in both the climate but also in people's health. Acid rain, respiratory illnesses and premature deaths are only some of the consequences that have driven the authorities to render the regulations more stringent.

Since 2005, with the Annex VI of the International Convention for the Prevention of Pollution from Ships (known as the MARPOL Convention), the Sulfur Oxides regulations commenced to turn into tighter.

Regulation 14 to Annex VI introduced a worldwide limit on the sulfur content of marine fuels of 4.5 percent and a limit within designated SO_X emission control areas (SECA) of 1.5 percent. The Baltic Sea was the inaugural SECA (Baltic and North Sea) adopted under the Annex and was followed by the North Sea/English Channel SECA on November 22, 2007. In 2015, with the revised regulations the limit in SECA and ECA (North America and Caribbean Sea) areas was diminished to 0,1%. However, the 'moment of truth' for the shipowners was the 1st of January of 2020, when the sulfur limit is to be decreased to 0,5% globally.

The shipping industry as a transport solution is facing a serious crossroad as new technologies and challenges have emerged to contribute to the compliance with the regulations. In the future, a broader range of fuels types is expected to cover the propulsion solutions or even brand-new technologies.

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In the current thesis we have rendered a thorough investigation around the possible and feasible options for the shipowners in order to overcome the IMO obstacles.

2) a) Dilemma between Low Sulfur Fuels and Scrubbers

The major couple of options for the shipowners are the solution of switching the burning fuel into low-sulfur type like Low-Sulfur Fuel Oil or Marine Gas Oil (MGO) and the second which is the installation of Exhaust Gas Cleaning System (Scrubbers).

Nowadays, the current fuels used in the shipping industry are distilled products from crude oil. The Heavy Fuel Oil (HFO) is the most widely available fuel, but the problem is that burning HFO through the conventional combustion engine releases serious amounts of the Sulfur Oxides in the atmosphere. Nevertheless, the alternative solution is to turn into the Low Sulfur Fuels (produced with desolation process) which can provide the requested limit compliance. However, these fuels are massively more expensive than the conventional fuels that already used. Apart from the price, Low-Sulfur fuels have a scattered availability which troubles the vessels bunkering.

The other option-solution is the installation of a Scrubber device which can edit the transferred exhaust and deliver the SO_X in plummeted amounts in the atmosphere. Scrubber industry is a new emerged market with several makers and technology types (Open-loop, Closed-loop, Hybrid). Although, the EGCS option was advertised and commercially launched through shipowners, only a tiny percent of vessels has proceeded with the device installation. There are several reasons behind that fact, like the age of the ship or the high cost of the system which will be examined in the thesis main body in more detail. All in all, the most essential point behind the decision between the two solutions is the pricedifference among the low-sulfur fuels and the conventional ones. We will examine the cost-efficiency of four Panamax and four VLCC vessels and compare their characteristics which will enable us to provide a clear result for the best decision for the owner.

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b) <u>Alternative Fuels or Technologies</u>

The discussion around alternative fuels continues to rise as infrastructure and technologies flourish. LNG, LPG, Methanol, Biofuels, Hydrogen and the promising technologies of Batteries and Fuel Cells are the most overviewed now. Looking at the IMO standards, our study is based upon 8 basic criteria: Price, Infrastructure, Scalability, Technology, Environmental Impact, Regulations, CAPEX, OPEX. These criteria are also prerequisites for introducing a new alternative fuel in the shipping industry. As a final content of our study we will compare the most promising solutions based on our opinion in a small case study.

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MAIN BODY

1) Scrubbers vs Low Sulfur Fuels

Nowadays, Heavy Fuel Oil (HFO) and Marine Gas Oil (MGO) are the most common and widely used fuels in shipping industry. HFO contains 3,5% sulfur (mass) and the MGO 0,1%. With the implementation of the IMO 2020 regulation (1st of January) the vessels burning HFO should install the SO_X Scrubbers for being compliable with the regulations. However, the market penetration of Scrubbers and the stringent sulfur limitations will have a severe impact in the HFO prices causing the inevitable plummeting.

Price Spread

Since the IMO regulation about the lower Sulfur Cap of shipping fuels was announced, the shipowners came across two main different decisions or strategies in order to proceed with the implementation of the regulation. Switch to burning compliant 0.5% sulfur content fuel or continue using HSFO with Scrubbers installed to bring down the sulfur content of the fuel.

The global collapse of marine fuel prices has tremendously contracted the spread between Very Low Sulfur Fuel Oil (VLSFO) and High Sulfur Fuel Oil (HSFO), setting in doubt the financial aspect of Scrubber option. The bunker prices have followed the plummeting of crude oil prices and recorded significant decline.

What does the lower price spread for VLSFO means?

According to analysts, the lower price spread for VLSFO will hit the vessel operators from two sides. Firstly, the investment cost of Scrubbers (Capital Expenses, installation etc.) will take much longer to be recovered and in addition the charter rate premium will be dramatically decreased.

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<u>COVID-19</u>

The worldwide phenomenon of Coronavirus has struck the oil industry with great force causing countless damage. The extremely rapid spread and the restrictions on travel and transport on a global scale, has abridged oil demand for 2020 for the first time since the 2009 financial crisis, according to the International Energy Agency (IEA), pointing to anticipated low crude and bunker prices. The flattened curve of oil demand is the reflection of the impact from the Coronavirus on transport. China was the first country to face the virus and as a key source of demand plays a vital role in the supply chain.

<u>EGCS</u>

What is a Scrubber?

The Scrubber is a system or a device which is installed in the exhaust system of the vessel and modifies the exhaust gas with many substances. Some of them may include seawater or freshwater or even dry substances depending on the technology of each Scrubber maker. The general outcome is to release the modified exhaust in the atmosphere as a compliant one.

<u>Wet Scrubbers</u>

There is chemical reaction between the exhaust gas and the wash liquid in order to remove the SO_X compounds from the gas.

System types:

1) Open loop
2) Closed loop
3) Hybrid (both open and closed)

The exhaust gas is chemically treated either with seawater or freshwater. The seawater contains high sodium chloride content and it is mainly used in the open loop technology. On the other hand, the closed loop tech uses the freshwater with a few exceptions.

<u>Open Loop Scrubbers</u>

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The open loop technology uses the seawater (seawater is sourced outside from the vessel and it supplied through a dedicated pump) to clean the exhaust from the SO_X. The water alkaline is a key point to the effectiveness of the open loop Scrubber. In some cases, the river water alkalinity is higher than seawater, but the essential note is that the Scrubber makers need to know the alkalinity of the water which will be used to treat the exhaust.

As a result, the effectiveness of the open loop Scrubber technology depends upon the chemistry of the water that will be used. In case the water is not alkaline which means that the pH is very low, the Scrubber unit will not meet the expectations and the vessel will have to burn low sulfur fuel in order to comply with the regulations.

Open Loop Scrubber ABS Source:

1) Scrubber Salt Wash-water Pump
2) Scrubber Effluent Dilution Pump
3) Effluent Water Discharge Pump
4) Scrubber Salt Wash-water Monitor
5) Effluent Water Monitoring
6) Oil and Soot Separator
7) EGC Residue Tank
8) Sludge Separator
9) Deareation Unit
10) Exhaust Gas Inlet
11) Scrubber
12) Exhaust Fan
13) Control Cabinet
14) Monitoring and Alarm Cabinet
15) Exhaust Gas Outlet

<u>Closed Loop Scrubbers</u>

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There are many similarities between the open and the closed loop type Scrubber, especially in the chemical processes. The wash-water which moves continuously around the system is preserved to be suitable for recirculation. This is the significant difference of the closed loop system type. The water used can be either fresh or salty, but this might depend on the customized Scrubber design.

Closed Loop Scrubber ABS Source:

1) Scrubber Cooler Seawater Pump
2) Scrubber Wash-water Supply Pump
3) Effluent Water Recirculation Pump
4) Oil and Soot Separator
5) Alkali (NaOH) Unit
6) EGC Residue Tank
7) Sludge Separator
8) Deareation Unit
9) Wash-water Cooler
10) Exhaust Gas Inlet
11) Scrubber
12) Exhaust Fan
13) Control Cabinet
14) Monitoring and Alarm Cabinet
15) Exhaust Gas Outlet
16) Bleed-Off Treatment Unit
17) Holding Tank
18) Effluent Water Monitoring
19) Scrubber Wash-water Cooling Monitor

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Hybrid Scrubbers

Hybrid Scrubbing system type is basically the combination of both an open and a closed-loop type system with the aim of achieving the best result by exploiting the advantages of both system types. To be more specific, the system can be operated as an open loop type in the open ocean and as a closed one in a low alkalinity area.

Procedures to changeover:

1) Change circulating pump suction from seawater to circulating tank.
2) Change the wash-water discharge from the overboard discharge to the circulating tank.

Hybrid Scrubber ABS Source:

1) Scrubber Salt Wash-water Pump/Scrubber Cooler Seawater Pump
2) Scrubber Effluent Dilution Pump/Scrubber Wash-water Supply Pump
3) Effluent Water Discharge Pump/Effluent Water Recirculation Pump
4) Scrubber Cooler Seawater Monitor
5) Effluent Water Monitoring
6) Oil and Soot Separator
7) Akali (NaOH) Unit
8) EGC Residue Tank
9) Sludge Separator
10) Deareation Unit
11) Wash-water Cooler
12) Exhaust Gas Inlet
13) Scrubber
14) Exhaust Fan
15) Control Cabinet
16) Monitoring and Alarm Cabinet
17) Exhaust Gas Outlet
18) Bleed-Off Treatment Unit
19) Holding Tank

Effectiveness of Wet Scrubbers

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Wet Scrubbers, either open-loop or closed-loop, must provide for a clean exhaust gas, plummeting the SO_X numbers to be compliable with the regulations. In the closed-loop, the alkalinity can be controlled by interfering into the wash-water. However, the open-loop technology is highly based on the alkaline substances in the water. Therefore, the success and the effectiveness of the Scrubber unit will be diminished if the vessel will operate in freshwater with low pH. A higher pH guarantees a higher possibility for SO_X removal.

Scrubber Performance Factor	Rate %	Remark
SOx Removal required	97.10	Makes 3.5% S Fuel equivalent to 0.1% S Fuel
Expected SOx removal Rate	>96	Depends on the alkalinity of the water
Typical Particulate Removal Rate	30-60	When using heavy fuel, particulates emissions are higher than for 0.1% S distillate diesel fuel

EGCS	Advantages	Disadvantages	Application
Open Loop	Seawater using, no storage, no dangerous chemicals handled. Relatively friendly-user system, less equipment. Low CAPE & OPEX.	High demand of water. Not applicable in low Ph waters (fresh). Port areas restrictions for discharging water.	Ocean operating vessels. Vessels that do not enter discharge water restrictions ares.
Closed Loop	Full control of alkanility of the water, no restriction areas or limited operating areas. Effluent stored onboard.	Complex system. Additional equipment for water-treatment. Requires more space. NaOH substance needs special handling for its' hazardous properties. Effluent tank size limiting the operation time. High CAPEX. High OPEX due to NaOH handling.	Vessels trading in areas with low alkalinity water or port restrictions for discharging water.
Hybrid	Important flexibility to operate in all areas. Effluent stored onboaard.	Sophisticated system. Space required. Danger due to NaOH handling. High CAPEX. High OPEX due to NaOH.	Ocean open sea & in restricted discharge areas.

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Figure 1.1 Exhaust Gas Cleaning System

Scrubber Regulations

EGCS Guidelines

The International Maritime Organization (IMO) already incorporated regulations for wet scrubbing in specific. Shipowners who intend to install EGCS systems on their vessels must comply with National and Local regulations. The original regulation for EGCS is 14.4 (b) to MARPOL Annex VI. Eventually, the SO_X emissions could be count down to 6.0g/kWh for the systems which met the requirements.

Developed Guidelines:

MEPC.130 (53), MEPC.170 (57), MEPC.184 (59) 2009, MEPC.259 (68) 2015

The top goal is to monitor the SO_2/CO_2 emissions for the exhaust gases and then provide or guarantee compliance with the sulfur limits by the regulations 14.1 and 14.4.

In 2008, MARPOL Annex VI removed the EGCS from regulation 14 and the approval is now reported in regulation 4 of Annex. The guidelines must be contemplated by the Flag State of each vessel, render an assessment and then inform the IMO accordingly. EGCS retrofits following these guidelines will be acknowledged by the authorities' case-by-case.

In the 2015 Guidelines, there is an analysis of the different approaches for the determination of the pH value of wash-water discharge. The determination can be performed either by direct measurement or by calculation-based methodology and then approved by the administration authorities. The assemblage of data from wash-water is also endorsed to the IMO administrations to Appendix 3 of 2015 Guidelines and also get admonished by the GESAMP (Group Experts on Scientific Aspects of Marine Environmental Pollution).

There are two basic schemes to use in the preference of the maker in order to be compliable with the regulations. The approval will be issued by the Classification Society, on behalf of the Flag State and in accordance with the ongoing survey requirements of the guidelines.

<u>Scheme A</u>

Demonstration of the initial emission certification, along with continuous investigation of operation and daily supervision of the emissions.

Regarding approvals for Scrubbers: They must be certified to meet the SO_X limit. There is also continual operation with fuel oils by the manufacturer specified max SO_X into the range of allowable exhaust gas mass rates. The manufacturer will acquire the product range approval for the same EGCS design to test emissions at the highest, average and lowest capacity ratings. The certification can be issued prior or after the installation of the system. It is approved with a serial number for each vessel and SO_X Emissions Compliance Certificate (SECC). The technical manual of the system will also be provided to the customer-shipowner by the manufacturer for maintenance, survey procedures and operation. In addition, a survey must be performed after the installation to guarantee that the system is complied with ETM-A and has also the approved SECC. The certificate can be modified by the MARPOL Annex VI and IAPP in order to reverberate the installation. It is necessary for the

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system to be checked and monitored in daily basis and annual surveys onboard have to be executed to guarantee excellent operation.

Last but not least, the EGCS record book must be maintained by the shipowner because every survey or attendance for the maintenance of the system should be reported.

Scheme B

Unceasing exhaust emission monitoring and daily check of operation.

The Scheme B does not require pre-certification. Nevertheless, the system must be compliable with the sulfur limit requirements 14.1 and 14.4 of MARPOL Annex VI regulation at any port of loading. The manual (ETM-B) must also be provided with detailed analysis of EGCS operating parameters and limits. As Scheme A, the system must be surveyed after the installation with the same MARPOL Annex VI Annual and IAAP. The monitoring of the system should be regular, and the exhaust emissions must be under control. The Record Book is also necessary as in the Scheme A.

Documentation:

The shipowners who intend to proceed with an EGCS installation to comply with 14 regulation of MARPOL, a SO_X Emissions Compliance Plan is necessary (SECP) to be approved. In addition, the detailed method for all fuel combustion should be provided and an approved Onboard Monitoring Manual (OMM) is requested onboard.

OMM:

Must be approved by the Flag State of the vessel and should include:

- Data on the sensors used, service, maintenance, calibration.
- Positions where wash-water and exhaust measurements to be extracted.
- Data on the analyzers
- Other info
- Details on how the monitoring systems are to be surveyed.

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EGCS Approval

1) Statutory MARPOL Approval process covering the environmental performance aspects.
2) Class approval to the individual society rules

Operators who have chosen to install Scrubbers on their ships are betting on a wide price spread between VLSFO and HSFO in order to shorten the payback time of Scrubber cost, which can be a million dollars or more per ship.

Robert Hvide Macleod, chief executive of Frontline Management, had reportedly said in December 2019 that Scrubbers costing the company between $2-4m per ship would need a payback on the investment over nine to 18 months. That was based on price difference of about $285 between HSFO and VLSFO.

Adrian Tolson, director at BLUE Insight, noted that Scrubbers are still considered a viable option now despite the narrower spread. Retrofitting a Scrubber on a 18,000-teu containership, for instance, had a payback of 1.5 years based on January price spread, and at today's prices it could be 2.5 years, Tolson said, adding that there is still commercial sense especially for large-sized ships.

Apart from the issue of price spreads, the use of Scrubbers has also been surrounded by some doubts in particular over the use of open-loop Scrubbers as some countries and regions have banned the discharge of wash water in territorial waters from the open-loop system.

In addition, the coronavirus has disrupted normal operations at Chinese shipyards, leading to lengthier time needed to complete the retrofitting of Scrubbers on the vessels.

Most famous fuels worldwide:

IFO 380 - Intermediate fuel oil with a maximum viscosity of 380 centistokes (<3.5% sulfur)

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IFO 180 - Intermediate fuel oil with a maximum viscosity of 180 centistokes (<3.5% sulfur)

LS 380 - Low-sulfur (<1.0%) intermediate fuel oil with a maximum viscosity of 380 centistokes

LS 180 - Low-sulfur (<1.0%) intermediate fuel oil with a maximum viscosity of 180 centistokes

MDO - Marine diesel oil

MGO - Marine gasoil

LSMGO - Low-sulfur (<0.1%) Marine Gas Oil - The fuel is to be used in EU Ports and Anchorages. EU Sulfur directive 2005/33/EC

ULSMGO - Ultra-Low-Sulfur Marine Gas Oil - referred to as Ultra-Low-Sulfur Diesel (sulfur 0.0015% max) in the US and Auto Gas Oil (sulfur 0.001% max) in the EU. Maximum sulfur allowable in US territories and territorial waters (inland, marine, and automotive) and in the EU for inland use.

<u>Scrubbers CAPEX OPEX</u>

Below we can find an indicative paradigm from Alfa Laval, a famous Scrubber supplier demonstrating the general picture of the cost of installing a Scrubber (Closed-Loop).

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	Supplier / contractor	Cost in USD
PureSOx EGC scrubber system 1) Exhaust Gas Cleaning Unit 2) Valves and sensors required for regulation 3) Control and data logging system 4) Water cleaning system 5) Caustic soda dosing system 6) Commissioning and support	Alfa Laval	1.575.000
Modification of funnel Cutting app. 3x3 meter hole in casing hull, movement of existing installations, enforcements, foundations, installation of scrubber, closing of casing, painting of casing according to yard standard, incl. scaffolding Fabrication and mounting of necessary exhaust pipe pieces, expansion joints, and exhaust gas dampers Fabrication and mounting of steel pipes for caustic soda (NaOH	Orskov yard	750.000
Electrical cabling and connection	Estimated	177.000
Exhaust gas dampers and entire cross-over (with sealing air)	Kolster Hesa-tek A/S	29.000
Drawing work	Hauschildt Marine	27.000
Not included / Unforeseen	25%	640.000
Total investment costs		3.199.000

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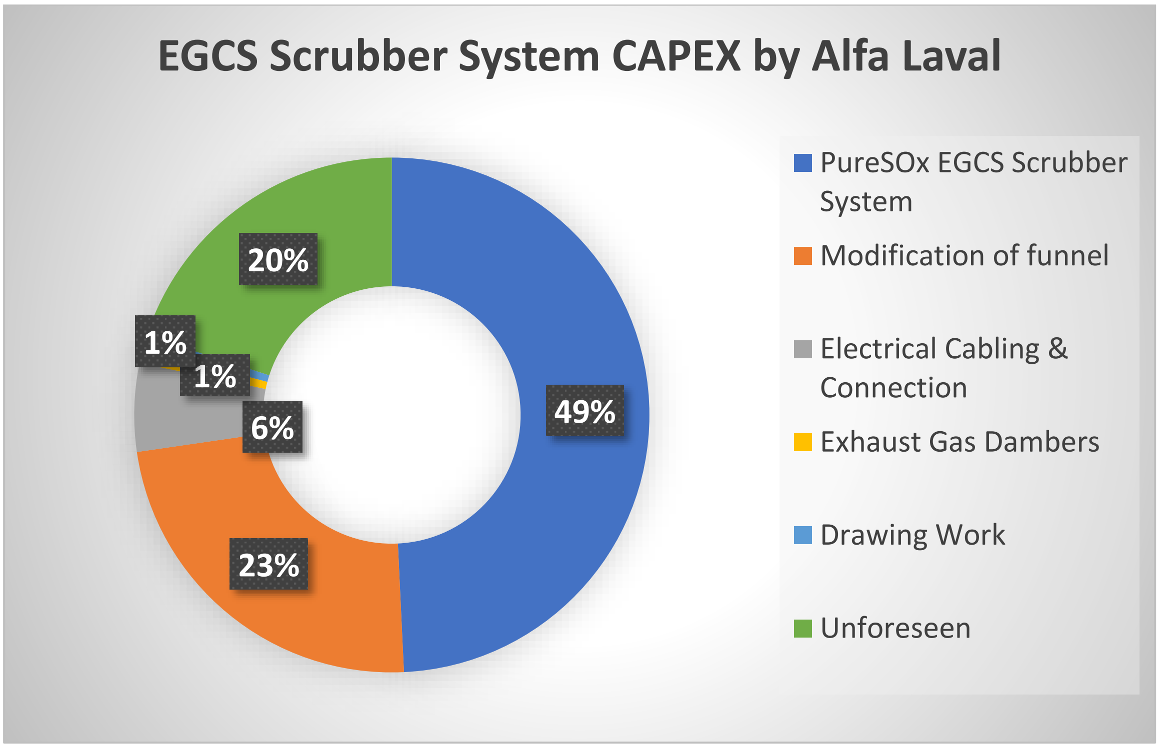

Figure 1.2 EGCS Scrubber CAPEX by Alfa Laval

<u>OPEX and payback period</u>

The savings in OPEX are strongly related to the fuel oil prices, i.e. the difference between high Sulfur HFO and low Sulfur MGO. The average price (Rotterdam) of a 380ct HFO (high Sulfur) for the last 6 months (Dec 2012 – May 2013) has been 624 USD/ton and that for MGO (low Sulfur) has been 952 USD/ton.

The total investment (CAPEX) will be paid back after approximately 15,000 hours of operation. Assumptions: 90% engine load (MCR), specific fuel oil consumption = 184 kg/MWh, 1.5% increase in fuel consumption due to running the Scrubber pump and increased back pressure on the engine.

Fuel Consumption is related to speed.

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The Cube Rule F=Fd (S/Sd)^3

The table below demonstrates how speed affects fuel consumption for a Panamax vessel. (This table is indicative because the consumption depends also on the engine of the vessel).

Speed Knots	Main Engine fuel consumption tons/day
16	44
15	36
14	30
13	24
12	19
11	14

<u>Options and subcategorizes to analyze</u>

In the below study, there is an analysis in two options based on the size category of the vessel. Therefore, there is a Dry Bulk option of Panamax size between 60.000-80.000 Dwt and the Crude Oil Tanker option of VLCC size above 160.000 Dwt. In continuation, there were developed four subcategories for each option abovementioned based on the age of the vessel. The four subcategories are as per below charts, a New Building vessel, a 5-year old, a 10-year old and a 15-year old. For each one of the total eight options there will be a financial analysis regarding their CAPEX and OPEX for all technical solutions (Scrubbers, MGO, Alternative Fuels).

<u>CAPEX</u>

According to DNV-GL assessment, depending on the size of the engine, the investment costs for Scrubber's range between 650 USD/kW (5,000 kW engine) and 150 to 100 USD/kW (40,000 kW and larger engines).

	Company Name	Vessel's Name	Vessel Size	Engine
NB	Goldenport	GW Mathilde	Panamax	Mcr 8,050kW
5-year	Starbulk SA	Laura	Panamax	Mcr 8,050kW
10-year	Technomar	Bonneville	Panamax	Mcr 11,620kW
15-year	Empire Bulkers Ltd	Jasmine A	Panamax	Mcr 10,320kW

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	Company Name	Vessel's Name	Vessel Size	Engine
NB	Thenamaris	Diyala	VLCC	Mcr 26,890kW
5-year	Maran Tankers	Maran Apollo	VLCC	Mcr 25,330kW
10-year	Pantheon	Sea Leopard	VLCC	Mcr 29,260kW
15-year	Aeolos	Syfnos	VLCC	Mcr 25,090kW

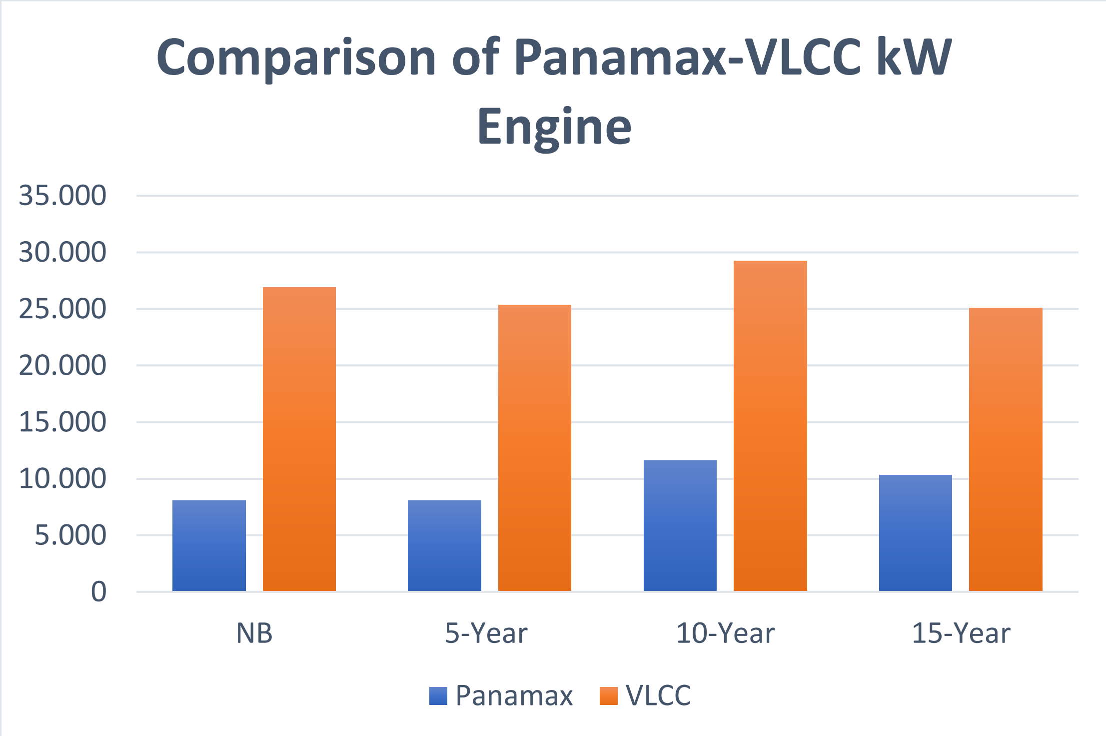

Figure 1.3 Engine Comparison between VLCC vessels

Based on the above, it is clear that the Panamax vessels with smaller kW engine power would require more USD for the Scrubber installation than the VLCCs. Therefore, from a macro perspective it seems more cost-efficient for the VLCC owners to invest in Scrubber installation than owners of smaller vessels.

<u>OPEX</u>

The OPEX without maintenance and spare parts is approximately equivalent to 0.6 to 0.7 per cent of the hypothetical fuel costs without the presence of Scrubber technology (according to MEPC 70-INF.9). The operational costs of Scrubbers are

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composed of the cost of maintenance and energy consumption. According to IMO MEPC 70/5/3, these amount to approximately 0.7 per cent of the total fuel costs.

	Company Name	Vessel's Name	Vessel's Size	Engine	Speed	Fuel Consumption
NB	Goldenport	GW Mathilde	Panamax	Mcr 8,050kW	14.40	24.90
5-year	Starbulk SA	Laura	Panamax	Mcr 8,050kW	14.40	24.90
10-year	Technomar	Bonneville	Panamax	Mcr 11,620kW	14.00	39.00
15-year	Empire Bulkers Ltd	Jasmine A	Panamax	Mcr 10,320kW	14.30	37.00

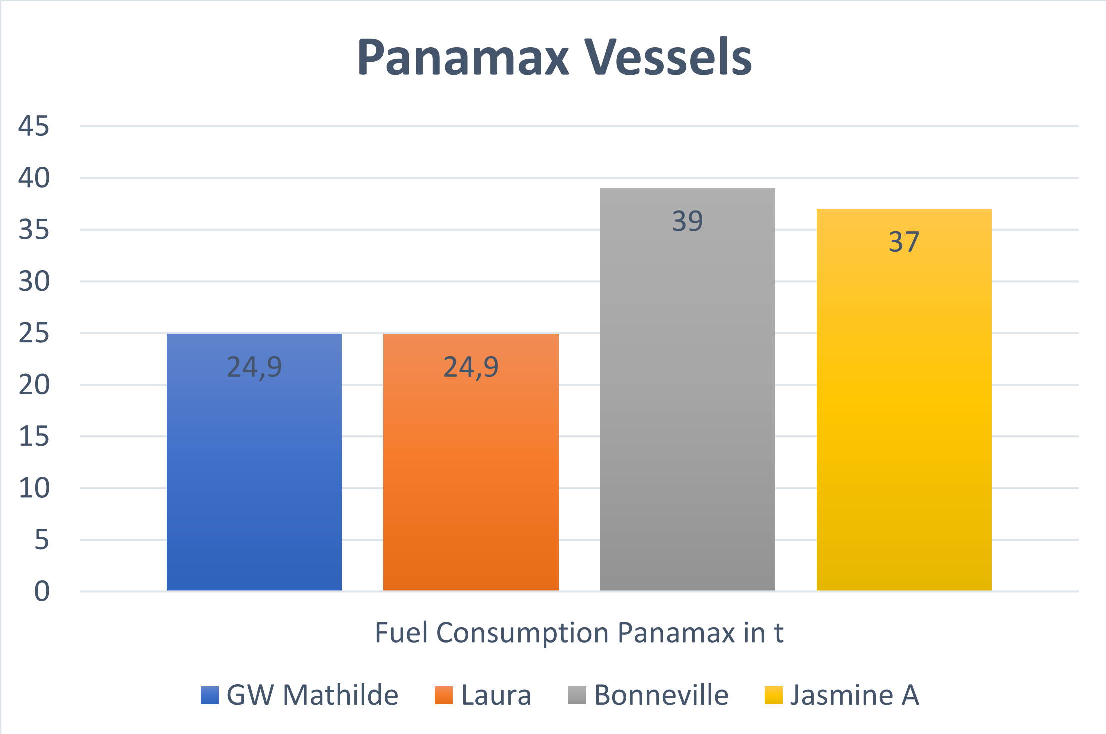

Figure 1.4 Fuel Consumption of Panamax Vessels

	Company Name	Vessel's Name	Vessel's Size	Engine	Speed	Fuel Consumption
NB	Thenamaris	Diyala	VLCC	Mcr 26,890kW	15.00	70.55
5-year	Maran Tankers	Maran Apollo	VLCC	Mcr 25,330kW	15.20	104.00
10-year	Pantheon	Sea Leopard	VLCC	Mcr 29,260kW	15.30	104.00
15-year	Aeolos	Syfnos	VLCC	Mcr 25,090kW	15.00	88.00

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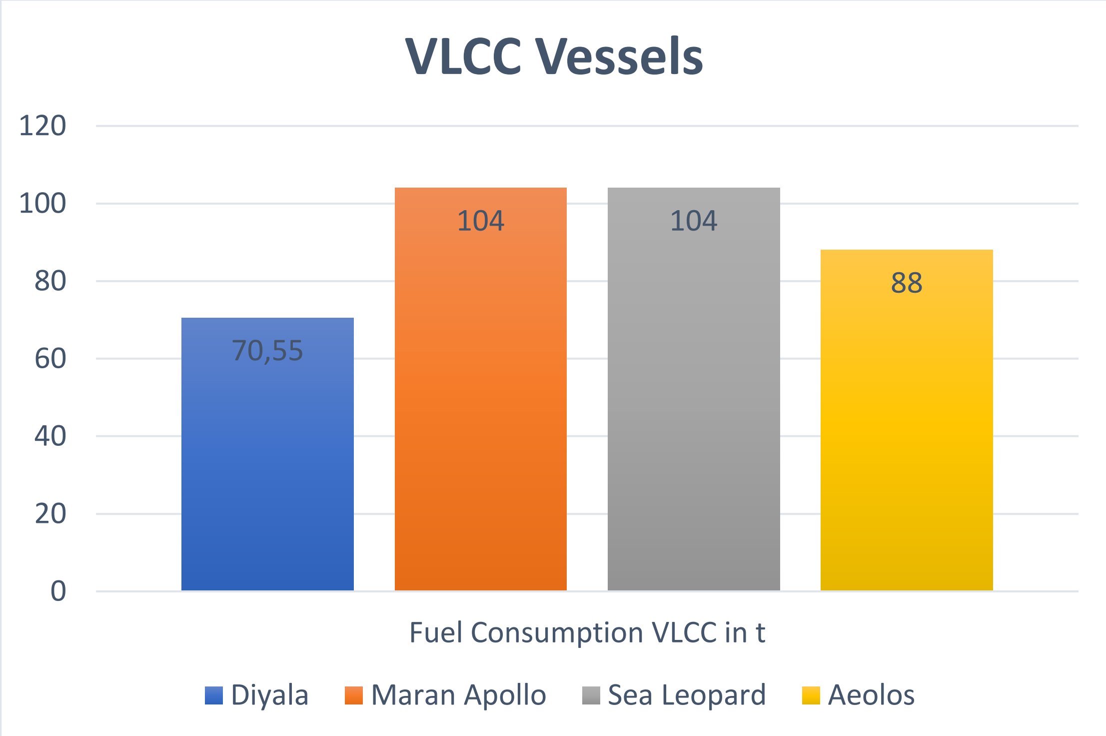

Figure 1.5 Fuel Consumption for VLCC Vessels

In the above tables we can identify the fuel consumption and the speed of each vessel according to Ihs maritime website.

Comparing the 2 categories (VLCC and Panamax), the most preferable for a Scrubber investment would be the VLCC category because of their size and engine kW and therefore fewer CAPEX. In the next step, when we study the subcategories, the Panamax category demonstrates significant differences between the vessels. For instance, the 10 and the 15-year old vessels consume higher volume of fuel increasing the OPEX and in addition they burn with a higher engine kW. The same differences are detected in the VLCC section where the fuel consumption seems to escalate while the age of the ship increases also. As a result, the best possible Scrubber investment concludes to the bigger vessel in size and the newest in age.

If we notice at the sample prices in the top critical bunkering places in the world, we will realize that the price gap between low and high Sulfur fuels has been diminished.

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Samples Prices	MGO	HFO/IFO380
LA, Long Beach	243	170
New York	238	166,5
Houston	232	139,5
Rotterdam	233,5	165
Fujairah	353	145
Hong Kong	255,5	207,5
Singapore	250	199,5

The average for MGO is 257,85 and for HFO is 170,43 USD.

	Company Name	Vessel's Name	Vessel's Size	Engine	Fuel Consumption	Trading Area last 12 months
NB	Goldenport	GW Mathilde	Panamax	Mcr 8,050 Kw	24,9	Far East - UK - Continent - Baltic
NB	Thenamaris	Diyala	VLCC	Mcr 26,890kW	70.55	Australasia - East & South Africa - Far East - Gulf - Red Sea - India - South East Asia - West Africa
5-year	Starbulk SA	Laura	Panamax	Mcr 8,050 Kw	24,9	Australasia - Caribbean - East & South Africa - East Coast South America - Far East - Gulf - Red Sea - India - South East Asia - US Gulf - West Africa
5-year	Maran Tankers	Maran Apollo	VLCC	Mcr 25,330kW	104.00	Australasia - Caribbean - East & South Africa - East Coast South America - Far East - Gulf - Red Sea - India - South East Asia - US Gulf - West Africa - Mediterranean - UK - Continent - Baltic
10-year	Technomar	Bonneville	Panamax	Mcr 11,620 Kw	39	Australasia - East & South Africa - East Coast South America - Far East - Gulf - Red Sea - India - Mediterranean - South East Asia - West Africa
10-year	Pantheon	Sea Leopard	VLCC	Mcr 29,260kW	104.00	Australasia - Caribbean - East & South Africa - East Coast South America - Far East - Gulf - Red Sea - India - South East Asia - US Gulf - West Africa
15-year	Empire Bulkers Ltd	Jasmine A	Panamax	Mcr 10,320 Kw	37	Australasia - Caribbean - East & South Africa - East Coast South America - Mediterranean - Far East - Gulf - Red Sea - India - South East Asia - US Gulf - US East & West Coast - West Africa
15-year	Aeolos	Syfnos	VLCC	Mcr 25,090kW	88.00	Australasia - East & South Africa - Far East - Gulf - Red Sea - India - South East Asia - West Africa

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Studying the above table, we can notice that except Goldeport's vessel, all other sample vessels of our research have crossed almost all major bunkering points that we have mentioned above. As we have already mentioned, if the annual operating costs of a Scrubber are close to 0,7% of the total fuel costs of the vessel then this number increases proportionally with the size and the engine of each vessel. According to Clarksons, the same relationship exists between voyage costs, operating costs and the age of the ship. For example, a 15-year old vessel would perform higher operational and voyage costs than a 10-year old. Therefore, it's unlikely a Scrubber investment in elder ships to pay back. We should always look at the price gap because the Scrubber investment has no meaning if the spread is zero. As it is already said Coronavirus has caused tremendous disaster in Scrubber investment because the gap is closing.

2) <u>Liquefied Natural Gas (LNG)</u>

With the Global Sulfur Cap 2020, the latest regulation adopted by the International Maritime Organization (IMO), merchant vessels' owners have to comply with new sulfur oxide emissions. Since January 1st 2020 the emissions must not exceed 0.5% worldwide, while the previous limit was 3.5%.

Liquefied Natural Gas (LNG) is a superior marine fuel that provides the best option to improve air quality and is the only adaptable marine fuel that accomplishes GHG's reduction objectives.The reductions that are accomplished through the utilization of LNG are more than 99% for sulfur emissions, 80% for nitrogen oxides and 26% for carbon dioxide compared to HFO. LNG is therefore considered as the greenest fossil energy, and a real technological breakthrough to reach compliance and maintain competitiveness at the same time.

The main component of LNG is methane (CH_4), the hydrocarbon fuel with the lowest carbon content and therefore with the highest potential to reduce CO_2 emissions. LNG has the same composition as natural gas used in households, for power generation and

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by the industry. The production process of LNG ensures that it is practically sulfur-free and as a result using LNG as a fuel does not produce any SO_X emissions. LNG must be stored in insulated tanks because its boiling point is approximately –163°C at 1 bar of absolute pressure.

The energy density per mass (LHV in MJ/kg) is approximately 18% higher than that of HFO, but the volumetric density is only 43% of HFO (kg/m^3). This volume accounts for roughly twice the same energy stored in the form of HFO. Regarding space requirements, cylindrical LNG tanks typically occupy three times the volume of an equivalent amount of energy stored in the form of fuel oil.

Price and Cost of LNG

Fuel is purchased on a dollar/tonbasis, but the transaction is really about buying energy. LNG offers a lower energy cost per ton, whenever priced against Heavy Fuel Oil (HFO) by nearly 24% because it contains more energy for a given mass: the energy that is provided by LNG as a marine fuel is 50GJ/ton, whereas HFO provides 40.5GJ/ton. 2,000 tons of LNG provides the same amount of energy as 2,469 tons HFO.

For the last ten years, hub prices of natural gas worldwide (except in certain parts of East Asia) have been below the price of HFO and crude oil. The delivered price of LNG fuel to ships must also take into account the liquefaction or break-bulk cost, distribution cost and applicable profit margins. Compared to other alternative fuels, LNG seems to have reached the most competitive feedstock price level historically among all alternativefuels. At this time the price level of LNG is competitive with MGO, but direct competition with HFO may be difficult.

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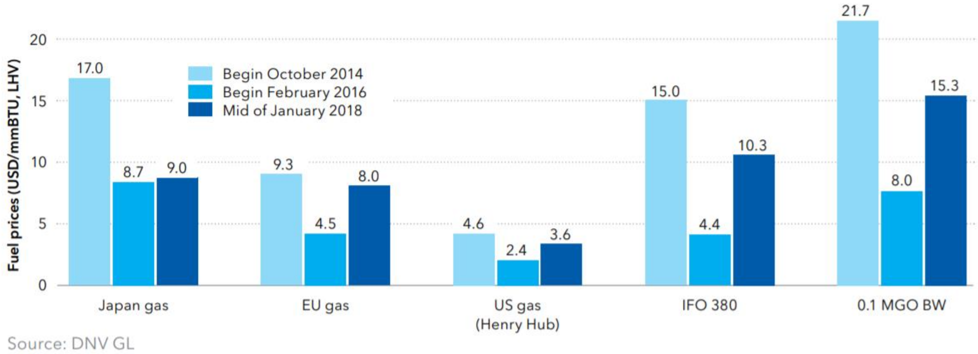

Figure 1.2.1 Fuel Prices

Since 2020, high-sulfur fuel oils (HFO), will not be permitted without a Scrubber system installed, and the price of low-sulfur fuel oils (LSFO) will be higher than HFO. Furthermore, the price of LNG is expected to be competitive with low-sulfur HFO. LNG can potentially compete with high Sulfur HFO and Scrubbers. In addition, the cost of LNG is comprised of the natural gas (about 25%), which has fluctuated little in recent history, together with a generally fixed liquefaction fee in order to cool the natural gas to a liquid state and the transportation costs that are usually contracted on a long term basis (about 75%). Therefore, the volatility of crude oil prices is reflected by the LNG pricing, which is more stable than traditional maritime fuels. Specifically, the underlying commodity of LNG forms a small portion of its price structure, while refining and distribution plays a disproportionately large portion. Consequently, LNG is relatively insulated against sharp commodity swings. At the same time, infrastructure and refining improvements have driven these incremental costs downward. As a result, LNG bunkers' cost remains less volatile compared to traditional oil based marine fuels.

<u>Infrastructure</u>

Nowadays, the dedicated LNG bunkering infrastructure for ships is improving rapidly. Due to bunkering technology improvements and more information about fuel prices, LNG availability grows rapidly. LNG bunkering and LNG distribution to bunkering locations is still taking place by road at a great share. Delivery by rail would be possible but is currently not practiced. LNG is traded globally, supported by local infrastructure in the major trading routes and most of the frequent bunkering

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ports offer relative fueling services. Vessels' managers or shipowners can choose the point of supply, where LNG's cost is most favorable.

LNG bunker vessels were delivered for operationin some key locations in 2017. These locations were: the North Sea, the Baltic Sea, the coast of Florida and the ARA Region (Amsterdam, Rotterdam, Antwerp). Locations for bunker vessels that are under development are: the Gulf of Mexico, the Middle East, the Western Mediterranean, China, Singapore, Japan and South Korea. These locations will possibly materialize in parallel with significant orders for LNG-fueled deep-sea ships within the next years.

In terms of LNG bunkering, there are three main types. The truck-to-ship bunkering, the shore-to-ship bunkering and the ship-to-ship bunkering which is the most preferable due to its flexibility method, as it can take place at anchor, at sea or along the quayside.

Figure 1.2.2: LNG Infrastructure [Source: DNV-GL – AFI presentation (01/10/2020) – "LNG bunkering infrastructure is being developed to supply the growing fleet" (page 9)]

Regulations

The mandatory IMO instrument that applies to all gases and other low-flashpoint fuels in shipping and to all gas-powered ships other than gas carriers, is the IGF Code (International Code of Safety for Ships which use Gases or other Low-Flashpoint Fuels).The IMO IGC Code (International Code for the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk) covers the gas-powered ships and their use of low-flashpoint fuels.

The IGF Code went into force on January 1st 2017 and has been adopted by IMO since June 2015 (MSC.391[95]).The IGF Code covers natural gas in compressed or liquid form (CNG, LNG) and it is necessary for all gaseous and other low-flashpoint-fuel ships. It also contains some obligatory provisions that are related with the arrangement, installation, controlling and monitoring of machinery, equipment and systems using low-flashpoint-fuels and initially focuses on LNG. Furthermore, all areas that need special consideration for the usage of low-flashpoint-fuels, are addressed by the IGF Code, with a goal-based approach. These goals and functional requirements specified for each section, aim to provide a basis for the design, construction and operation of ships using this type of fuel.

Nevertheless, other aspects like bunkering of LNG-fuelled ships are subject to national regulations and consequently they need to be evaluated on a case-by-case basis. For instance, local rules for LNG bunkering have been established to a limited number of ports. In addition, SGMF, IACS and ISO have developed some LNG bunkering requirements and guidelines.

Scalability

The availability of LNG as ship fuel is not expected to be limited for the foreseeable future, as there are no principal limitations to production capacities. The share that LNG has in the overall natural gas market is estimated at 10% approximately. LNG production capacity has increased significantly in the last three years. In 2016, the global LNG liquefaction capacity was approximately 320 mt/a. Around 42.5 mt/a of

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liquefaction capacity was brought online in 2019, increasing global liquefaction capacity to 430.5 mt/a. This represents 11% year-on-year growth from 2018, well above the growth rate from 2017 to 2018. As of January 2020, the global liquefaction capacity has increased to 435.6 mt/ (2020 World LNG report: International Gas Union [IGU]).

Technology

For decades, gas turbines, gas engines and LNG storage and processing systems have been possible for land installations. The transportation of LNG by LNG carrier has a history going back to the middle of the last century. Using LNG as a marine fuel in general shipping began early in the current century. Nowadays, the technology required for using LNG as ship fuel, as well as piston engines and gas turbines, several LNG storage tank types and process equipment are readily available.Furthermore, digitalization and big data analytics, machine learning and blockchain could have an impact on the LNG industry, particularly in deploying blockchain to facilitate trade. However, there is uncertainty in the industry of how to best adapt and deploy new technologies. This happens because there are both technical complexity and difficulty in generating consensus around a single system.

Environmental Impact

Nowadays, the cleanest fossil fuel available is the natural gas from LNG. It performs well from an emissions perspective as it emits zero sulfur oxides (SO_X) and particle emissions are very low. In comparison with other existing heavy marine fuels, LNG emits 90% less NO_X, and other emissions such as HC, CO or formaldehyde from gas engines are low and can be mitigated by exhaust gas after-treatment if necessary. By using the best practices and technologies to minimize methane leakage, realistic reductions of GHG by 10-20% can be achieved and there is a potential for up to 25% or more as technology develops in comparison with conventional oil-based fuels. LNG is a cleaner fuel, a clear winner when it comes to local emissions, and represents

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a significant step forward in the reduction of GHGs by meeting future carbon-related emissions targets.

CAPEX

Historically, a barrier to adoption was the high CAPEX for LNG engines and fuel tanks. Nevertheless, recent shipyard prices demonstrate substantially smaller LNG premiums above traditional vessels. This happens because of the current market conditions favoring newbuildings' buyers and due to the extensive LNG newbuilding experience and technology improvements that lead to shipyard efficiency gains. Also, the fact that there are various technology suppliers active in the market, indicates that LNG as a ship fuel is rapidly approaching the status of a fully developed technology. As applications increase and competition between suppliers is more intense, we can observe the CAPEX decreasing. In case of CAPEX costs for LNG systems, they are and will continue to be higher compared to the expenditures associated with using a Scrubber system with HFO.

OPEX

The OPEX costs for LNG systems on board ships are comparable with the OPEX of oil-fueled systems without Scrubber technology or an SCR (Selective Catalyst Reduction). The efficiency of gas-fueled engine systems is about the same as conventionally fueled systems. Consequently, the energy consumption of an LNG-fueled ship is roughly equivalent as that of an oil-fueled ship. Maintenance of a gas-burning engine may be cheaper thanks to cleaner fuel. Currently, the maintenance intervals of conventional and gas-fueled engines are typically the same, but they may be extended for gas engines, due to more operational experience to draw on. Also, the maintenance costs for the high-pressure gas supply system on board ships with high-pressure engines should be taken into account. Last but not least, number of ports offer discounts to LNG-fueled ships, thus in terms of cost-efficiency, it might be a favorable option.

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3) Case Study

MAIN ASSUMPTIONS		
Asia- US west coast Liner route	13,007nm	8% Spent in ECAs
Operational Condition	Strong Freight Markets	Weak Freight Markets
	High Demand	Low Demand
	20,5 knots speed	Slow Steaming
	$200 net loss per TEU	18 kn eastbound
		16 kn westbound

Finance Investement Hurdle Rate	
WACC 8%	Weighted Average Cost of Capital
Debit Loan Rate	6%
Portion	60%
Equity Return Rate	11%
Portion	40%
Tax Rate	0%

Formula:

WACC = Loan Rate × Debt Portion × (1-tax rate) +

Equity Rate × Equity Portion

In Values:

WACC = 6% × 0.60 × (1-0) + 11% × 0.4 = 8%

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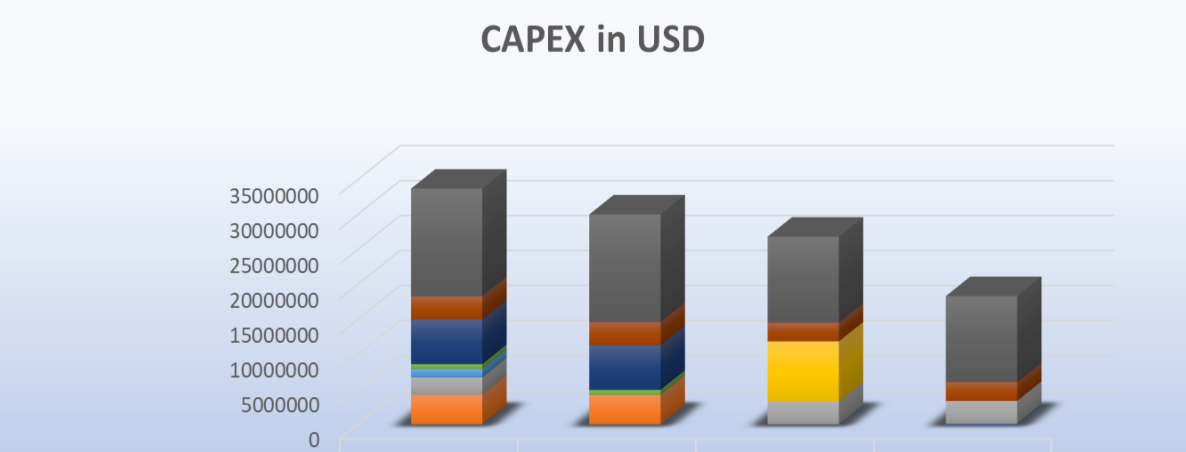
Investement Horizon Period	10 years
Inflation Rate	2,5% per year

Types of Main Engines	2-S HP DF	2-S LP DF	Open Loop Scrubber System	Conventional Vessel
	MAN ME-GI	WinGD 9X-92DF Winterthur Gas & Diesel engines	Conventional diesel cycle with scrubber fitted	Conventional diesel cycle
	using 1.5% S pilot fuel with no methane slip	Otto Cycle Combustion 1% S micro pilot	SCR required 3,2 m $	SFOC: 170 g/kWh
	SFOC: 167,5 g/kWh	SFOC: 169 g/kWh	SFOC: 170 g/kWh	
	HP Gas System 1,2 m $	LP Gas System 700k $	2% fuel consumption penalty applied within 0.1%S ECAs and a 1% penalty within 0.5%S areas.	Add CAPEX of 120k $ for fuel chiller
	LP Gas System 700k $		No Sodium Hydroxide (NaOH)	



	2-S HP DF	2-S LP DF	Open Loop Scrubber	Conventional
Main Engine	15.396.552	15.396.552	12.317.241	12.317.241
Auxiliaries	3.327.600	3.327.600	2.662.080	2.662.080
LNG Tanks	6.382.837	6.382.837	0	0
LP Gas Supply	708.654	708.654	0	0
HP Gas Supply	1.190.621	0	0	0
Scrubber (inc. yard work)	0	0	8.620.560	0
SCR	2.495.700	0	3.260.340	3.260.340
LNG Yard Work	4.230.000	4.230.000	0	0
Fuel Chiller	0	0	0	118.000

Figure 1.3.1 CAPEX in USD.

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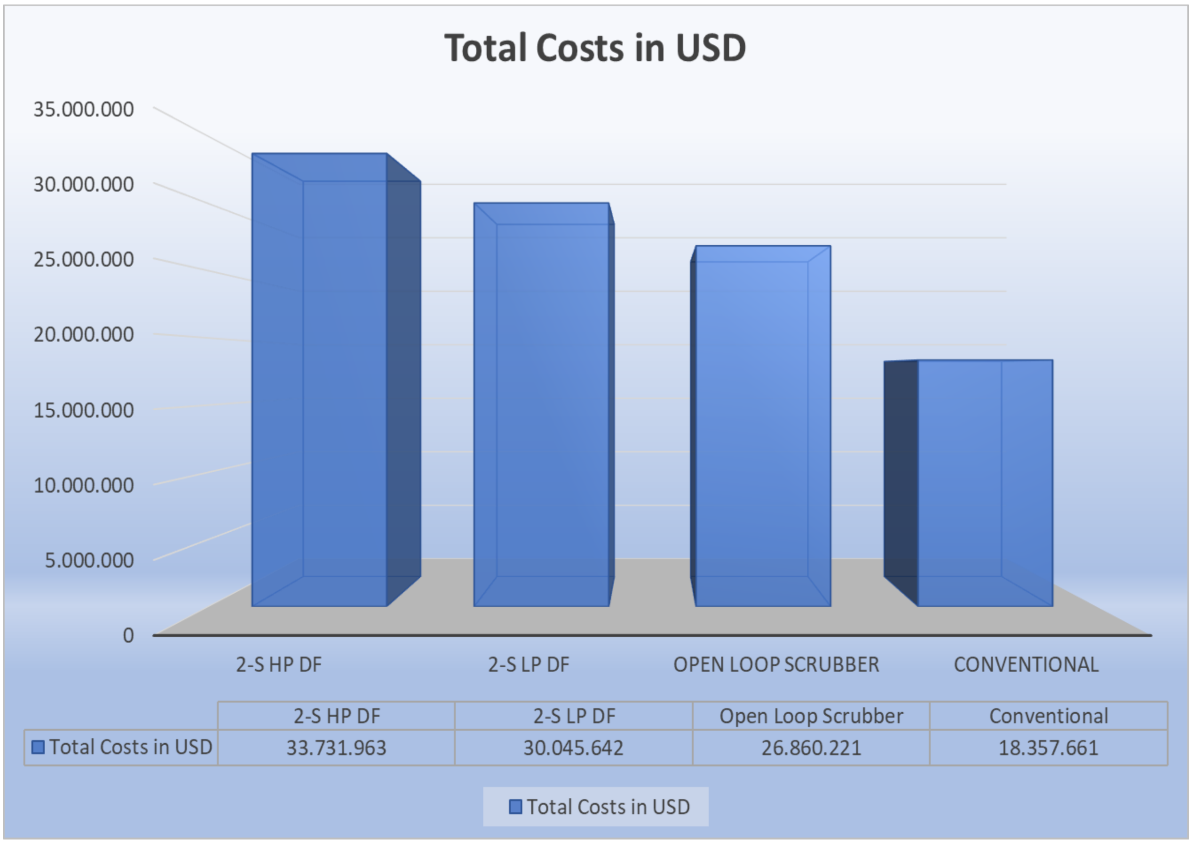

Figure 1.3.2 Total Costs in USD.

The CAPEX premium for LNG alternatives over a Scrubber with IMO 2020 0.5% compliance is \$6.87M for a 2-s HP DF M/E arrangement and only \$3.18M for a 2-s LP DF M/E.

<u>Fuel Consumption</u>

Based on the contract maximum continuous rating (CMCR) power and CMCR speed in all cases.

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	% rated speed at sea	% during idle in port	% during active operation in port
A/E Power	40%	30%	70%

Fuel Consumption summary for each engine.

Assumption of 20,5 speed knots eastbound.

Propulsion Technology	Design Consumption (tpd)				Energy Consumption [MMBtu/hr]	M/E SFOC[g/kWh]	A/E SFOC[g/kWh]
	LNG	HSFO	VLSFO	MGO			
2-S HP DF	122	2			240,9	168	180
2-S LP DF	123,6			1,3	242,8	169	180
Open Loop Scrubber		154,2			246,6	170	180
Conventional			145,9		244,1	170	180

<u>Fuel tank size impacts</u>

C-type tanks sized at 8,581 cubic meters.

For a 14,000 TEU vessel this study assumes the loss of cargo space equates to 300 TEUs or approximately 2% of capacity.

Propulsion Technology	Tank Sizes [m3]				TEU Loss
	LNG	HSFO	VLSFO	MGO	
2-S HP DF	8.581	304		59	300
2-S LP DF	8.581			75	300
Scrubber		4.866			
Conventional			5.234	733	

The profit impact of the lost cargo capacity is calculated on the displaced profit before tax per TEU basis multiplied by the number of round trips per year. $200 per TEU is assumed in a strong market and zero per TEU in a weak market, as the 14,000 TEU vessel is expected to be operating below 98% utilization and therefore incur no profit penalty.

Fuels Used:

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	Contain S
Fuels Used	
LNG Cleanest Fossil Fuel	Comply with 0,5%
Oil Derived	
HSFO	3,50%
MGO	0,10%
VLSFO	Comply with 0,5%

Scenarios	**Results**	**Results**	**Results**
Stranded Fuels	Initial drop of HSFO price due to IMO 2020	Transitional recovery years	
Business as Usual	Price remains as Q3 2018		
Tight Supply for Distillates	MGO 20% increase than Q3 2018 due to high demand for Low S Fuels	HSFO & LNG prices remain as Q3 2018	
LNG Economies of Scale	Liquefaction & delivery costs plummet 20% due to extend adoption & economies of scale		
LNG Liquefaction Technology	Liquefaction cost reduce 20% due to tech improvements		
Tight MGO, Unvavailable HSFO, Improve LNG	MGO 20% increase than Q3 2018 due to high demand for Low S Fuels	HSFO 20% increase in price because of no availability	LNG Liquefaction & delivery costs plummet 20% due to extend adoption & economies of scale

In the Stranded Fuels scenario, the HSFO price decreases after the implementation of the IMO 2020 regulation. Moreover, the recovery is expected to be slow because the market penetration of Scrubbers was very slight. A stronger penetration is expected in the next 5 or 6 years.

Common assumptions & fuel forecasts
HSFO, MGO, VLSFO Relative to Rotterdam Prices
LNG “Sabine Pass” liquefaction cost, estimated at $3.0/MMBtu (Ripple) for 2018
LNG logistics and bunkering estimated at $3.0/MMBtu (Braemar) for 2018
Conversion to LHV increases molecule cost by 10% to $3.54.
Base price of LNG at USGC is given by the sum of three quantities above: $3.54 + $3.0 + $3.0 = $9.54/MMBtu
Rotterdam HSFO for July 9 2018 $442/mt (Ship & Bunker)
Rotterdam MGO for July 9 2018 $644/mt (Ship & Bunker)
VLSFO 0.5%S price is obtained by adding 85% of the MGO price to 15% of the HSFO price.
Prices increase by 2.5% every year

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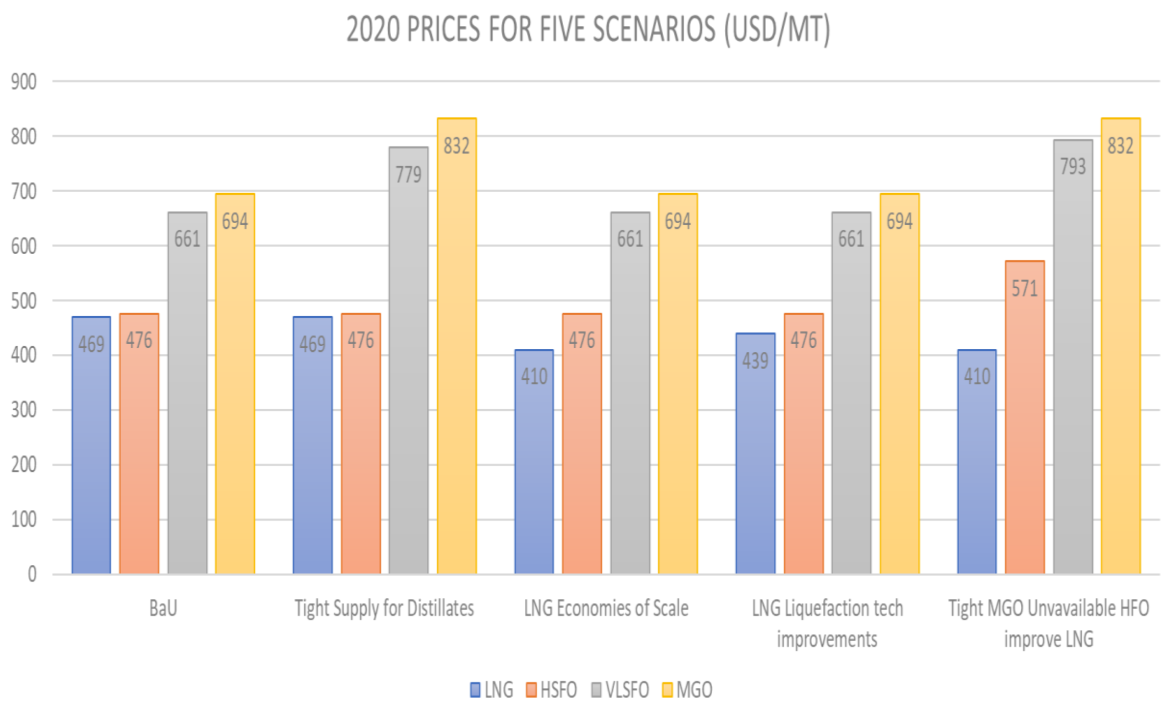


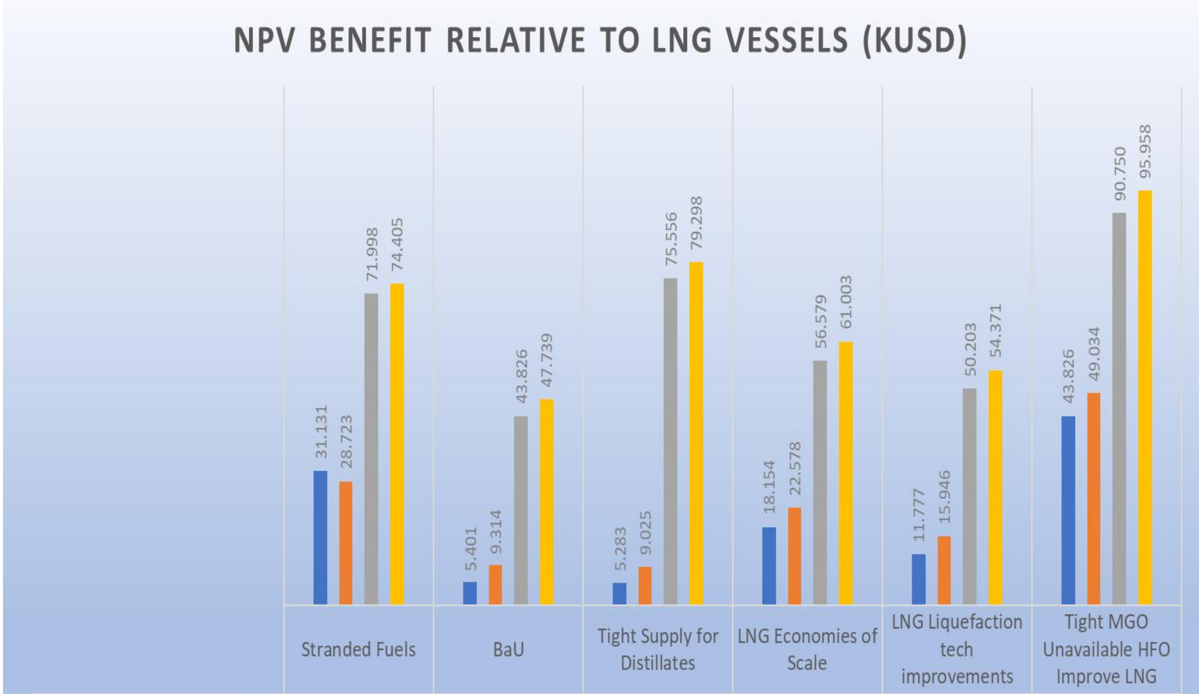
Figure 1.3.3 2020 Prices for 5 Scenarios.

<u>Results</u>

The result acknowledged by that small case study is that LNG arises as the most promising alternative fuel. More specific, it provides the best return on investment on NPV basis with this 10-year horizon and the fast pp period of 1-2 years. In addition, the LNG seems to be a better solution than open loop Scrubber in all scenarios except the first. On the other hand, Scrubbers are indicated as a high-risk investment in a very volatile market for HFO. Even though the market penetration of Scrubbers is quite promising within the next years, the evolution of new blends and the enhancement of infrastructure and availability of compliable fuels will drop the Scrubber option out of the game.

NET PRESENT VALUE COMPARISON

STRONG FREIGHT MARKETS, 20.5 KNOT VOYAGE



	Stranded Fuels	BaU	Tight Supply for Distillates	LNG Economies of Scale	LNG Liquefaction tech improvements	Tight MGO Unavailable HFO Improve LNG
Open Loop Scrubber vs HP DF	31.131	5.401	5.283	18.154	11.777	43.826
Open Loop Scrubber vs LP DF	28.723	9.314	9.025	22.578	15.946	49.034
Conventional vs HP DF	71.998	43.826	75.556	56.579	50.203	90.750
Conventional vs LP DF	74.405	47.739	79.298	61.003	54.371	95.958

Figure 1.3.4 NPV Benefit relative to LNG Vessels Strong Freight Markets.

NET PRESENT VALUE COMPARISON

WEAK FREIGHT MARKETS, 18KN EASTBOUND,

16KN WESTBOUND

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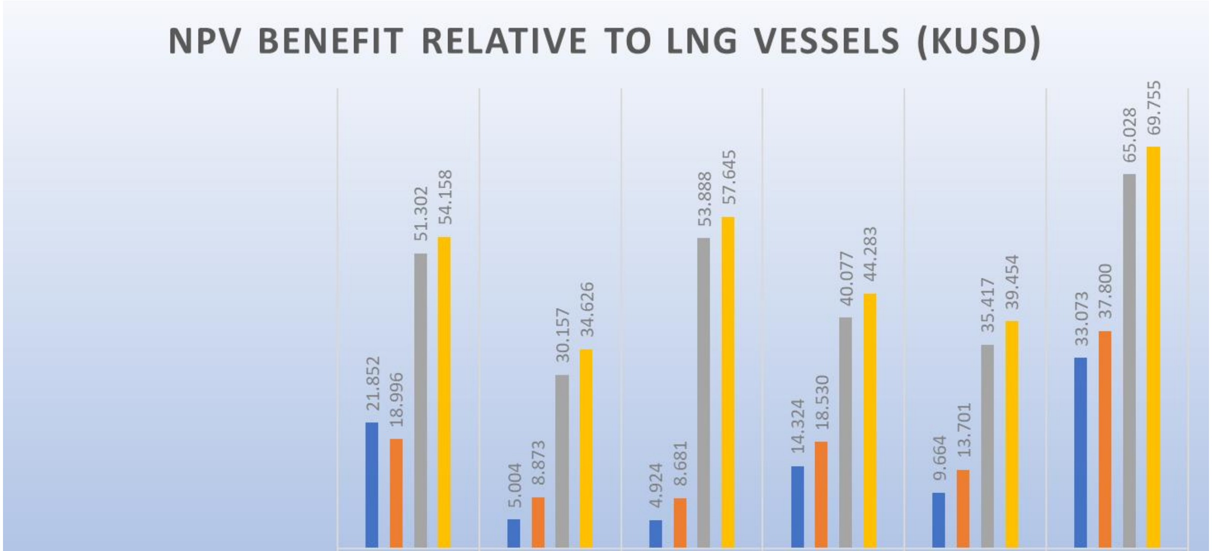

	Stranded Fuels	BaU	Tight Supply for Distillates	LNG Economies of Scale	LNG Liquefaction tech improvements	Tight MGO Unavailable HFO Improve LNG
Open Loop Scrubber vs HP DF	21.852	5.004	4.924	14.324	9.664	33.073
Open Loop Scrubber vs LP DF	18.996	8.873	8.681	18.530	13.701	37.800
Conventional vs HP DF	51.302	30.157	53.888	40.077	35.417	65.028
Conventional vs LP DF	54.158	34.626	57.645	44.283	39.454	69.755

Figure 1.3.5 NPV Benefit relative to LNG Vessels Weak Freight Markets.

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ALTERNATIVE FUELS

1) Liquefied Petroleum Gas (LPG)

Liquefied petroleum gas (LPG) is composed by any mixture of propane and butane in liquid form. LPG as a term is usually related to propane in the USA. In order to achieve desired saturation, pressure and temperature characteristics, specific mixtures of propane and butane can be used.

Since propane's boiling point is -42°C, it is gaseous under ambient conditions but can also be turned into liquid if moderate pressure is applied (8.4 bar at 20°C).Regarding butane, it can be found in two forms: n-butane with a boiling point of -0.5°C or iso-butane with a boiling point of -12°C. Both n-butane and iso-butane have higher boiling points than propane, so they can be liquefied at lower pressure. In case of land-based storage, it is necessary to keep the pressure below 25 bar and for this reason the propane tanks are equipped with safety valves to achieve it.Also, compared to oil tanks, LPG fuel tanks are larger than them, due to LPG's lower density.

Byproduct of oil and gas production and byproduct of oil refinery are the two main LPG sources, but can also be produced from renewable sources such as byproduct of renewable diesel production.

Price

In Figure 2.1.1 we can see that propane prices in USA were very close to those of Brent crude oil until 2010. Since 2011, due to increased LPG production as a byproduct of shale oil and shale gas the prices have decoupled, and USA became a net exporter of LPG in 2012. Nowadays, LPG is more expensive than LNG, but cheaper compared to VLSFO and low-sulfur fuel oils.

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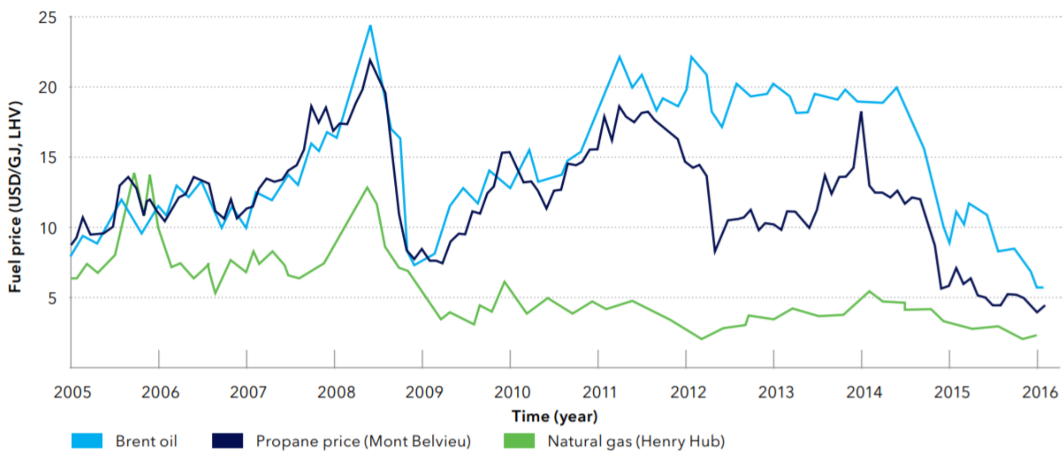

Source: DNV GL

Figure 2.1.1 Propane Prices

<u>Infrastructure</u>

The bunkering infrastructure at existing LPG storage locations or terminals can be easily developed, by adding distribution installations. Dedicated facilities or special bunker vessels are those that ensure distribution to ships. In Figure 2.1.2 we can see the extensive network of LPG import and export terminals in Europe.

Source: DNV GL

Figure 2.1.2 Overview of European import and export LPG terminals

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Regulations

The IMO IGF Code is mandatory for all gas and other low-flashpoint-fuel ships, but LPG is currently not included and is not in the agenda's near future. In order to be included, technical provisions will be needed to cover particular aspects of LPG fuel and the main safety concern has to do with the density of LPG vapors, which are heavier than air. Thus, leak detectors and special ventilation systems should be used. In case of LPG transportation by sea, it is subject to the IMO IGC Code, which also enables the use of LPG as fuel for gas carriers.

Scalability

Global LPG production in 2015 was 284 million tones, or 310 million tons of oil equivalent, which is higher than the global demand for marine fuel according to the World LPG Association. The annual increase in production is approximately 2% over the last decade.

North America and the Middle East are the continents that lead in terms of LPG production. LPG is used as a transportation fuel for road vehicles at 9%, while other uses of LPG include homes for heating and cooking, the refineries, and chemical and other industries.

Asia is the continent leader for the largest share of LPG consumption. Taking into consideration the current production level, the demand for shipping is expected to be safely covered until 2030, given the fact that demand for LPG as a ship fuel will initially grow slowly and remain at a moderate level.

Environmental Impact

LPG combustion results in CO_2 emissions which are approximately 16% lower compared to those of HFO. When accounting for the complete life cycle including fuel production, the CO_2 savings amount to roughly 17%.

The emissions of propane and butane as greenhouse gases, are three to four times higher than that of CO_2 and in terms of global warming potential, the issue of unburned LPG that potentially escaping to atmosphere (LPG slip), should be taken

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into consideration in order to address it. Meanwhile, by using LPG, sulfur emissions are virtually eliminated. Also, particular matter (PM) emissions are expected to be significantly reduced by the usage of LPG.

Furthermore, the technology applied is a factor that determines the reduction of NO_X emissions. For a two-stroke diesel engine, the NO_X emissions are expected to be reduced by 10% to 20% compared to HFO, whereas for a four-stroke Otto-cycle engine the expected reduction is greater and might not exceed Tier III NO_X limits. A two-stroke diesel-cycle engine would have to be equipped with EGR or SCR systems, in order to be compliant with these standards, while both solutions are commercially available.

<u>Technology</u>

LPG can be used as a ship fuel in the following three main options:

a) In a two-stroke diesel-cycle engine
b) In a four-stroke, lean-burn Otto-cycle engine
c) In a gas turbine

At this time, the MAN ME-LGI series is the only two-stroke diesel engine model which is commercially available. However, a Wartsila four-stroke engine was commissioned in 2017 for stationary power generation (34SG series).Therefore, in order to maintain a safe knock margin, the engine had to be derated.Wartsila offered an alternative technology that consists in the installation of a gas reformer which is able to turn steam and LPG into methane by combining them with hydrogen and CO_2. Furthermore, this mixture can then be used in a regular gas or dual-fuel engine without derating.

LPG can be preserved refrigerated or under pressure, although its temperature and pressure range might not always be the appropriate for a ship to handle. For this reason, it is important for the bunkering vessel and the ship to be bunkered, to carry the necessary equipment and installations for safe bunkering. Due to its simplicity the preferred solution is a pressurized LPG fuel tank, because by using either pressurized

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tanks or semi-refrigerated tanks the vessel can bunker more easily without major modifications.

<u>CAPEX</u>

Given the fact that pressurized type C tanks are used in both cases (LPG and LNG systems), the cost of installing LPG systems on board a vessel (e.g. internal combustion engine, fuel tanks, process system) is roughly half than of an LNG system. This is because there is no need for special materials that can handle cryogenic temperatures.

Between LPG and LNG systems on large ships the cost difference is lower, if the LPG storage takes place in pressurized type C tanks, which costs more than large prismatic tanks. An alternative solution is that LPG can be stored at low temperatures in low-pressure tanks, which require thermal insulation.

<u>OPEX</u>

The operational costs for LPG systems, excluding fuel costs, are expected to be comparable to those of oil-fueled vessels without a Scrubber system. Practical experiences are currently not available.

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2) Biofuels

Biofuel is a collective term for a range of energy carriers produced by converting primary biomass or biomass residues into liquid or gaseous fuels. The most promising biofuels for ships are hydrotreated vegetable oil (HVO), fatty acid methyl ester (FAME) and liquefied biogas (LBG), although other options are available, as well.

In order to achieve the goal of reducing greenhouse gases (GHG), the use of biofuels is significantly motivated. According to studies, sustainable biofuels are one of few options available for deep-sea shipping to achieve the IMO target of reducing GHG emissions by at least 50% by 2050 compared to 2008 levels.

The effective GHG reduction varies greatly depending on feedstock and production process. Other aspects of biofuel production are also controversial, including land use and socio-economic issues. Several standards and initiatives address these aspects. Biofuels from advanced processes utilizing sustainable feedstocks can achieve substantial GHG reductions while minimizing other effects. (The potential for GHG reduction when using biofuels is illustrated in Figure 2.2.1)

Price

HVO, FAME and LBG are currently more expensive than their fossil counterparts, but information on prices is still very limited because the market for these fuelsis immature. In addition, there are great local and regional variations in price and availability. Nevertheless, this market is expected to grow in the next years and the cost reduction can be achieved. Specifically, the potential for reducing production costs is expected to be higher for HVO than for FAME. Continuous process improvements, technological developments and scaling of production are the factors that will determine the cost reduction.

Infrastructure

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Currently, there is lack of global infrastructure and bunkering facilities for biofuels, while biofuel is available in specific ports (Netherlands, Australia, Norway).

HVO can in most cases be distributed using the existing MGO and HFO distribution systems, although modifications are sometimes required.

FAME's distribution through existing distribution systems is more difficult. Also, FAME storage for more than six months should be avoided, because of potential oxidation and sedimentation of FAME. Furthermore, FAME is hygroscopic and in case of tanks that contain MGO blended with FAME, efficient drainage systems are needed to drain water from the bottom of the tank in a regular basis.

On the other hand, LBG which is liquefied methane produced by biomass, can use LNG infrastructure, since methane is the main component of LNG. Thus, there is no problem in blending LBG with LNG.

<u>Regulations</u>

There are several standards covering biofuels addressing either technical or sustainability aspects. Among the former is ISO 8217:2017, a commercial quality standard for marine fuels which defines requirements for fuel used in marine diesel engines and boilers and their conventional treatment on board (sedimentation, centrifuging, filtering) before use.

Initially, ISO 8217:2017 did not allow FAME to be blended with regular marine distillate or residual fuels, but its sixth edition introduces the DF (Distillate FAME) grades DFA, DFZ and DFB. These grades allow up to 7% of FAME content by volume and are also covered by the European standard EN590, while the International Council on Combustion Engines (CIMAC) provides shipowners and operators with a guidelinefor managing these marine distillate fuels effectively. Apart from this aspect, all other parameters of these grades are identical to those of traditional grades.

In case of HVO, the limitations mentioned above do not apply to it, as it is classified as a DM (distillate) under the ISO standard, provided that certain conditions are met.

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Among the standards addressing sustainability of biofuels are the EU Renewable Energy Directive as well as ISO 13065, which specifies principles, criteria and indicators for the bio-energy supply chain to facilitate the assessment of environmental, social and economic sustainability aspects.

In addition, there are many sustainability questions regarding growing crops for liquid fuel production. The Roundtable on Sustainable Biofuels (RSB) has addressed these questions and has created tools and solutions for sustainability, such as the global certification standards for sustainable biomaterials, biofuels and biomass production. The Global Bioenergy Partnership (GBEP) defines sustainability indicators for bioenergy based on three pillars: environmental, social and economic feasibility.

Taking all the above regulations into consideration, we identify that standards do exist, but in terms of maritime industry there is lack of globally accepted biofuel standards. IMO is currently making references to technical ISO standards regarding fuels. Carbon intensity guidelines are one measure that is being considered in order to succeed in the recently adopted IMO GHG reduction strategy, however details are still to be discussed, while these efforts could entail looking at sustainability aspects of biofuels.

<u>Scalability</u>

Global production data indicate that 81 million tons of conventional transport fuel (which includes sugarand starch-based ethanol, oil crop biodiesel and HVO) were produced in 2017 (IEA, 2018). Over the next five years, this volume is anticipated to grow by 3% annually. To achieve the UN's Sustainability Development Goals for 2030, the use of biofuels would have to triple. Drivers of this development include falling costs, widespread sustainability governance, and increasing adoption by various industries such as shipping. The use of biofuels in shipping is currently very limited.

<u>Environmental Impact</u>

The use of biofuels is considered to be a solution for the GHG reduction target, but it does not reduce carbon emissions. The CO_2 that is added to the atmosphere from the

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combustion of biological materials is like those of fossil fuels. The difference though, is that the CO_2 emissions that come from biofuels are considered as part of the CO_2 emissions of the natural CO_2 life cycle. More specifically, this part of emissions is an equivalent amount of CO_2 that is captured from the atmosphere by the feedstock plants as they grow, and for this reason biofuels are considered as CO_2-neutral fuels.

The type of feedstock used, and the fuel production process are the factors that will determine the actual GHG emissions from a given biofuel. There are reports for a lot of biofuels, indicating that their GHG reductions range between 19% and 88% based on life-cycle assessments, but the credibility of these reports is debated. Consequently, it is necessary to define a classification system regarding biofuels in order to have a reliable data basis, which could be used safely in shipping. The Renewable Energy Directive (RED) specifies that biofuels should lower GHG emissions by at least 50% compared to fossil fuels; from 1 January 2018, the GHG emissions of biofuels produced in installations which began production on or after 1 January 2017 are to be at least 60% lower than those of fossil fuels.

HVO's reduction potential is higher than FAME's one, with a life-cycle emission reduction potential of about 50% compared to diesel (IEA 2011, 2017). The energy content of FAME is lower than the content of conventional marine fuels, while the GHG reduction achieved by LBG is significantly better compared to LNG.

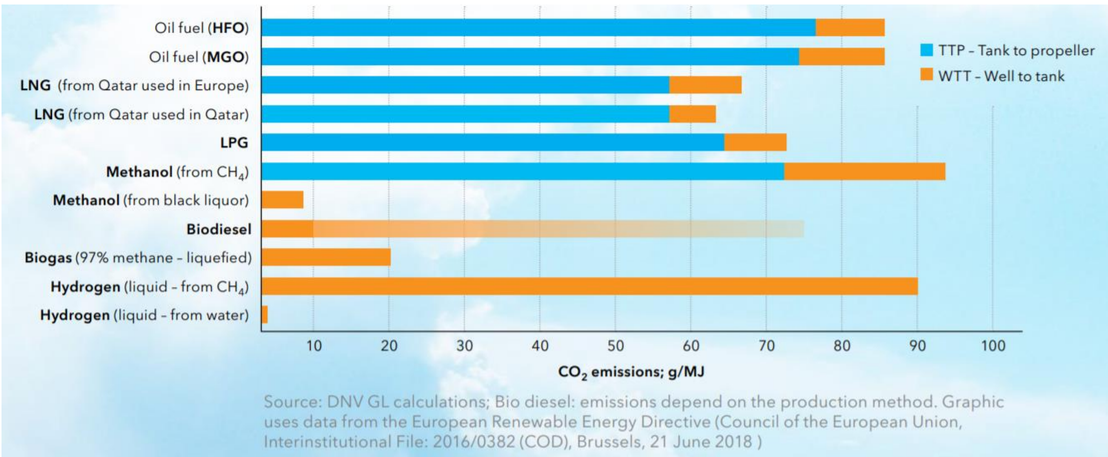

Figure 2.2.1 CO_2 emissions of fuel alternatives in shipping.

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The NO_X emissions from HVO are approximately 10% lower compared to conventional fuels, while NO_X emissions from FAME are about 10% higher than conventional fuels. The values of LBG are in the same range as those for LNG, which reduces NO_X emissions by about 90%. As a result, only LBG can satisfy the IMO Tier III NO_X requirements without using additional NO_X abatement technology. In case of SO_X, all three biofuels (HVO, FAME, LBG) produce very low SO_X emissions. The particular matter (PM) emissions of biofuels are also lower than those of conventional marine fuels.

Technology

Biofuels can be blended with conventional fuels or used as drop-in fuels as full substitutes of conventional fossil fuels. A drop-in fuel can directly be used in existing installations without major technical modifications. For this reason, biofuels are well suited to substitute petroleum-based fuels in the fleet in service.

HVO is a high-quality fuel from which the oxygen has been removed using hydrogen, which results in long-term stability. The characteristics of HVO make it suitable as drop-in fuel substituting fossil fuels. In general, HVO is compatible with existing infrastructure and engine systems, subject to approval by the manufacturer. In some cases, modifications may be required. Overall, there is limited operational experience with HVO as a ship fuel. HVO is currently used on board, with three ferries operating it in Norway, and no negative effects have been reported to date.

FAME is not a drop-in fuel. Blending with conventional fuel in concentrations of up to 7% is permissible only as specified by ISO 8217:2017 for DF (Distillate FAME) grades DFA, DFZ and DFB. The technical feasibility of various FAME biodiesel blends in shipping has been tested in several demonstration projects. FAME differs from MGO/ MDO in terms of fuel stability, cold flow properties, compatibility with materials (e.g. in packs), durability and lubrication properties. In general, FAME performs poorly in cold temperatures, is less stable when blended, and has a short shelf life. Some tests have experienced increased corrosion and susceptibility to microbial growth. Knowledge regarding other potential effects of FAME is limited, as

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most of the tests performed to date studied the use of FAME for shorter time periods only.

LBG can in essence be used as a fuel by LNG-powered ships and is unlikely to require any engine, tank and pipeline upgrading. Reliability is not expected to change when replacing LNG with LBG. It is also possible to blend LBG with LNG.

CAPEX

In case of FAME, additional costs related to modifications of ship engines and infrastructure are estimated by engine manufacturers to be less than 5% of engine costs. Regarding switching to HVO, there are no additional costs reported. Concerning LBG, the additional costs associated with its use would be the same as of LBG. If a vessel is already running on LNG, there are no additional costs reported when mixing LBG and LNG.

OPEX

In general, the operational costs for biofuel systems are expected to be comparable with those for HFO/MGO fueled vessels. However, additional costs for biofuels may result from monitoring, operational practice, and staff training. This needs to be investigated further.

Furthermore, there are reports that using FAME increases maintenance costs, such as costs of cleaning tanks, clogged filters, and similar items.

Biofuels are currently more expensive than fossil fuels, so the associated fuel costs are expected to be higher than those of conventional marine fuel.

3) Methanol

Methanol or methyl alcohol is one of the most promising fuels due to its high potential. It is compatible with the IMO regulations and can be a cost-efficient solution in case its production will be launched in large quantities. Technically, it is

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feasible to produce and distribute this alternative fuel by building or upgrading the worldwide methanol network.

In the below picture we can see the chemical structure of Methanol.

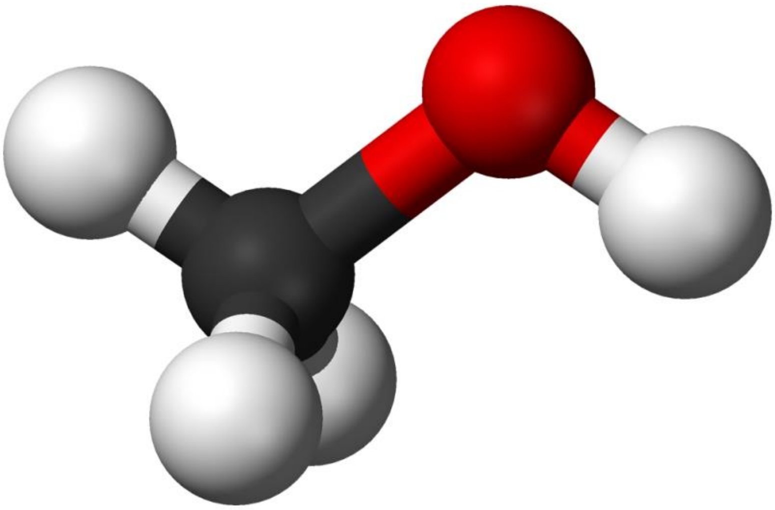

Figure 2.3.1 Methanol Chemical Structure CH_3OH.

Characteristics

Basically, it is an alcohol containing the lowest carbon and the highest hydrogen among all other liquid fuels. It is extremely flammable, colorless and has a liquid form between (–93°C to +65°C) at atmospheric pressure. Methanol is used in countless daily activities as it can be major building tool for plastic paint and coating. It is also a transport fuel and a hydrogen carrier for fuel cells. As far as storage is concerned the fuel tanks are larger than oil tanks due to lower heating value of Methanol (19.5 MJ/kg). In addition, we consider Methanol as a low-flashpoint fuel of 11°C to 12°C. Last but not least, the NO_X and SO_X reductions are 45% and 8% respectively comparing to conventional fuels.

Production

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Methanol can be produced by a wide variety of sources. The feedstock can be either fossil or renewable. In the fossil feedstock category methanol can be produced by oil, coal and natural gas (Methane CH_4). On the other hand, methanol can also be produced by renewable sources but according to Methanol Institute it's below 1% of the global production (Biomass, Renewables). The renewable sector can be divided into gasification of biomass & waste and into CO_2 plus renewable energy by the criteria of production procedure. Examples from gasification of waste and biomass are municipal solid waste, farmed wood, forest residues, black liquor. The CO_2 with renewable energy example we can notice it in geothermal, still mill or CO_2 from waste plant liquid wind. Methanol produced by coal is with doubt a cheaper option and widely available but GHG emissions are twice higher than natural gas.

When produced from natural gas, a combination of steam reforming and partial oxidation is typically applied, with an energy efficiency up to about 70 per cent (defined as energy stored in the methanol versus energy provided by natural gas). It can also be converted to dimethyl ether (DME), which can be used as a fuel for diesel engines.

In the next pages we will study methanol in a more detailed procedure through the 8 basic criteria of Price, Infrastructure, Regulation, Scalability, Environmental impact, Technology, CAPEX, and OPEX. We will also mention some projects that have already operated around the world regarding methanol as marine fuel.

<u>Price – CAPEX - OPEX</u>

Since 2010, methanol prices have been fluctuated between HFO and MGO prices. Nevertheless, any drop in oil prices especially the current situation with COVID-19 by which the oil prices have been plummeted renders methanol more expensive than distillate marine fuels. In some cases, the production is managed by natural gas or coal, but the latter can bring the price down and the GHG emissions up quite drastically. As far as the methanol produced by renewable energy, can make it green ship fuel but the costs are higher than the cost of methanol synthesis from methane.

<u>Fuel costs</u>

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The most important and crucial factor of the operational costs of a vessel is its' fuel cost approaching nearly the 50% of the total OPEX. If we compare methanol costs with the already known fuels, methanol wins as a more cost-efficient solution. However, the current circumstances in which the oil prices are lower affected methanol prices negatively and render them less competitive in contrast to marine diesel prices (except China).

Methanol can also compete quite comfortably with LNG, because if take into consideration the distribution costs, methanol is equal or even lower than LNG.

Large Ferry example:

Diesel Fuel Consumption: < 10.000 m3/year

Payback Period: 3-5 years

Methanol Prices: 100-200 lower per ton of MGO equivalent

<u>CAPEX</u>

Retrofit Cost from diesel fuel to dual-fuel methanol/diesel fuel: € 250-350/kW for large engines (10-25 MW).

Comparing to LNG: € 1.000/kW 1/3

Actual cost depends on the layout of each vessel.

It is common to any new launched technology to be more expensive in the first retrofits. Project plans must be rendered from scratch and there is no experience.

After several tests and retrofits the technology will be mature enough to claim that a NB Methanol-fueled vessel would be like a traditional HFO ship.

<u>Stena Germanica Project</u>

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Conversion Time: 2 Weeks.

Conversion Specific Costs: € 13 million

Total Project Cost: € 22 million (including a methanol storage tank onshore and the adaptation of a bunker barge).

Obviously, the costs are expected to be substantially lower for the next retrofit projects.

The job was performed through the EU TEN-T program as an R&D project providing the first data of the Methanol solution as a shipping fuel.

For large engine size range, some additional installation will be needed on board. Therefore, the conversion would not be cost-efficient and as a result the size of the ship is an important factor.

<u>SPIRETH Project</u>

From 2011-2014.

Laboratory testing of 2 fuel concepts.

1) Methanol used in a full-scale marine diesel engine.

2) Di-methyl ether (DME), converting methanol onboard and used in the auxiliary (diesel engine).

Funding: Swedish Energy Agency, Nordic Energy Research, Nordic Investment Bank and Danish Maritime Fund.

NB of a 10 MW tank ship

Estimated costs:

- Engine costs: € 825.000
- Work on engine: € 300.000
- Fuel supply system: € 600.000
- Fuel tanks: € 500.000

- Piping: € 500.000.

Total of € 270/kW.

<u>Infrastructure</u>

One of the top requirements for a fuel to be distributed successfully worldwide is its' infrastructure. In other words, the bunkering can be performed either in terminal ports or by bunkering vessels.

Methanol maintains its' presence in the spotlight because of its' chemical use. It is considered as one of the leading chemicals in Europe and as a result it can be supported in worldwide demand and distribution.

Easy and flexible example to delivery methanol:

- Distribution from the hubs is performed by heavy barges, rail or tank trucks.
- Bunkering of methanol fueled vessels is performed by truck.
- The trucks deliver the methanol to a bunkering facility with pumps built in containers on the quay next to the ferry.

Methanol as a low-flashpoint fuel can be handled quite safely as there is enough technology experience already.

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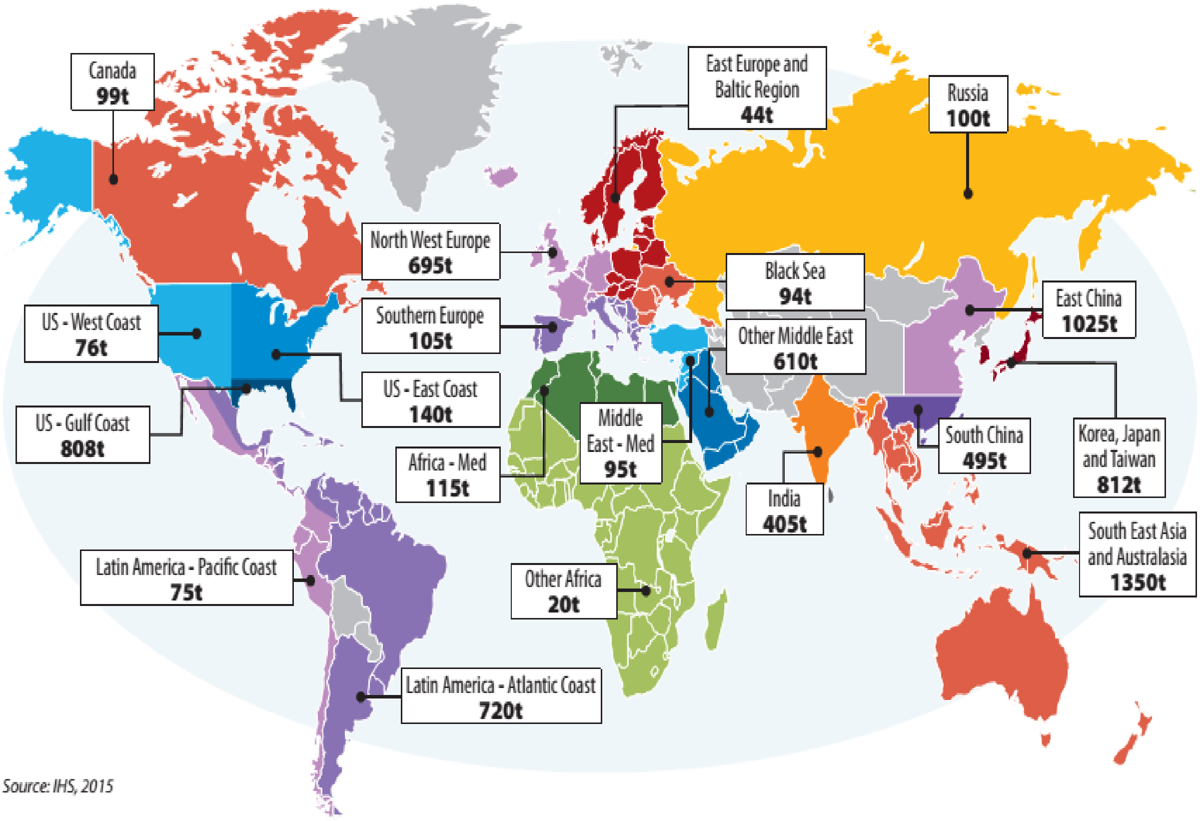

Figure 2.3.2 Methanol Worldwide Production and Availability.

Infrastructure Costs

1) Installation of a small bunkering unit: € 400.000 (Stefenson)
2) Conversion of an existing barge into a bunker vessel for methanol: € 1.5 million
3) For a 20.000 m^3 methanol tank and the installations for loading and unloading to a bunker vessel: € 5 million

Regulations

To manage and diminish the risk of fire and danger in general many guidelines have been issued. IGC Code provides the regulations for methanol's safe transport. In addition, there are also guidelines for the use of methanol as a fuel. In specific, for

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natural gas-fueled engine installations in ships there are the IGF Code but also guidelines from the technical supervisors of the ship, the Classification Societies (DNV-GL, LRS).

Stricter rules can be noticed in the bunkering and the delivery which must be risk-assessed. Risk assessment might be quite costly for small shipowners.

As a next step, methanol requires larger scale tests to accomplish the remarkable performance that would lead to the modification of marine engines to methanol-optimized.

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4) **Hydrogen**

General characteristics for Hydrogen as marine fuel

Hydrogen or H_2 is a very well-known gas in the chemical industry. It is also colorless, inodorous and non-toxic.

Boiling Point: 20 Kelvin (-253 Celsius).

Hydrogen can be liquefied at 33 Kelvin (-240 Celsius) in the critical pressure of 13 bars.

Energy Density per mass: LHV of 120 MJ/Kg (3 times bigger than HFO).

Volumetric Density: LH2 71 kg/m^3 (5 times the energy stored in the form of HFO).

The storage in the form of compressed gas is 10-15 times equal to HFO energy.

H_2 is a globally used chemical commodity and it can be produced from various sources.

1) Electrolysis of renewable energy
2) Reformation of Natural Gas

Nowadays, the most common production form of H_2 is from natural gas.

Applications in transport

In the natural gas reformation if the CO_2 is captured and secured then we can manage to obtain zero emissions with the necessary sustainable supply chain for shipping.

CO_2 and H_2 can be used to produce methane in a similar use to LNG or synthetic liquid fuel substitutes of diesel or gasoline.

On the other hand, in the H_2 production from electrolysis there is an opportunity to store and transport surplus renewable energy to sustain and balance the energy output of solar and wind power plants. If we also combine the H_2 with the fuel cells technology, the emission amounts related to other fuels could be plummeted.

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H_2 Price

The H_2 price depends on several different factors but also in evaluation with the form of production. In the electrolysis of renewable energy, the electricity price in each area is the key ingredient to output the final price. Similarly, in the reformation way of production the H_2 price depends on the general gas price.

Electrolysis Cost Range: 3,5-8,3 $/kg (1.170-2.770 $/t Crude Oil Equivalent)

Average: 5,3 $/kg (1.770 $/t Crude Oil Equivalent)

Natural Gas or Biogas reformation: 2,4-6,5 $/kg (800-2.170 $/t Crude Oil Equivalent)

Average: 4,1 $/kg (1.370 $/t Crude Oil Equivalent)

The total costs are consisted of production, compression, storage and transport.

Many experts state that in the future, the electrolysis price will be diminished. As a result, there will be a reflection upon CAPEX which will be also reduced and then the production cost of H_2 will be also decreased. Moreover, the industrial and production facilities also play a vital role in the general formation of the price. For example, in a country with low electricity prices like Norway the production cost remains low and the H_2 production is flourishing.

Infrastructure

Most of the H_2 production is performed through Natural Gas worldwide. Additionally, the general industrial infrastructure is land-based and still there is no demand for H_2 as a fuel. Therefore, there is no bunkering network for vessels either yet. The liquefied hydrogen can develop a similar distribution network as LNG. For instance, a 40-feet container which is available in the market with typical tank (capacity 3.600 kg of H_2/Tank) filled up to 94%. Hydrogen has a very low boiling point and super insulated vessels appeared as the solution for the storage liquid in cryogenic form. The boil-off rate is 0,3-0,5 % but it is highly depended on the specific technology and conditions. In addition, the tank surface area and the volume is also connected with the boil-off rate.

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Electrolysis production can be established in a local port point-terminal where the electrical power would be enough to facilitate the production procedures with the aim of eradicating the long-distance distribution network.

In the future, it is expected that the energy production will exceed the grid demand and that the H_2 will be produced by the energy renewable surplus instead of natural gas. In addition, the transport to ports will be performed from storage sites by roads or pipelines judging from the volume and the distance.

Regulations

Hydrogen is considered as a low flashpoint fuel and as a result, the International Code for Safety of ships (IGF Code) will be applicable. Nevertheless, there is still no cover for H_2 yet even though fuel cells technology is under development and will be included in the future. The H_2 storage and use is supervised by SOLAS Regulation 1.55. Also, DNV-GL Classification Society developed several bulletins, especially for fuel cells technology installation in Part 6, chapter 2, section 3. The aspects covered are referring to design principles and several arrangements, safety systems and material requirements. Regarding H_2 use, there is a general safety overview by the ISO/TR 15961. Additionally, IGC and IGF Codes apply for storage onboard but due to the very low storage temperature, many additional technical details will be considered. Regarding the bunkering system, there are no regulations for H_2 yet and each case is evaluated in a case-by-case perspective.

Scalability

An important reference is that annually 50 million tons of H_2 are produced globally and this can be translated in 150 million tons in ship fuel equivalent. Almost all this amount of energy is produced from natural gas and the electrolysis form is a future consideration for the industry.

Environmental Impact

Undoubtedly, H_2 can be determined as a low-emission alternative fuel but only in the production source of nuclear or renewable energy with the necessary supply chain.

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There are also many actions observed to investigate the H_2 production by natural gas and the safe storage and capture of CO_2 results.

Hydrogen as a marine fuel in combination with the fuel cells technology as an energy converter release no CO_2, NO_X, SO_X, and Particulate Matter emissions. In general, H_2 internal combustion engines in the marine applications can decrease the Green House Gas Emissions but they cannot avoid the NO_X.

Technology

Basically, there are two options regarding the selected technology to use as a shipowner. At first, there is the conventional fossil-fueled based technology which is the most widely known. On the other hand, there is an alternative option with a power generated system with H_2. The key point in the H_2 generated system is the fuel cells technology which is used as an energy converter and can eliminate the emissions. There are also other technologies such as gas turbines or internal combustion engines that can be a stand-alone project or a hybrid one because of adopting the fuel cells.

The H_2 piston engines are still not available in the market and we can only find them in land industry where it is already ongoing. In many industrial operations in the marine sector, there is the waste heat recovery with high temperature technologies using Solid Oxide Fuel Cells (SOFC) or molten carbonate fuel cells. All in all, one of the most promising technological options seems to be the fuel cells in combination with the batteries.

CAPEX

Comparing to LNG the conventional energy converters (pistons) are costed similarly to LNG-Fueled.

Storage Tanks for LH_2 are more expensive because of:

1) Lower Storage Temperatures
2) High insulation quality
3) Fewer maritime applications

In addition, the below equipment costs in similar levels to LNG:

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1) Piping
2) Ventilation
3) Heat exchangers
4) Pumps

<u>OPEX</u>

It has been noticed that conventional systems have analogous running costs to oil-fueled systems. Nevertheless, the price of H_2 demonstrates huge variation in the market and that is because of the individual contracts which have been developed. As a fuel price though the H_2 is depended on the energy price of H_2 plus the logistics cost which is much higher than other fuels. The latter can be significantly changed when the production of H_2 will be changed to renewable sources and not from natural gas.

The energy converters (fuel cells technology) are indicating shorter lifetime than piston turbines but that is highly based on the fuel quality and definitely on the operation management by the crew and the technical department of the shipping company.

As the cost of pollution (GHG) becomes higher and the limits and regulations by the authorities stricter, we will be transferred to more innovative and modern ideas such as batteries in combination with H_2. The Norway example is very suitable in this case because the vessels which were battery-powered were more competitive than conventional ones regarding the operational costs. However, this technology requires extremely innovative infrastructure and fast-charging technology at every stop.

Hydrogen Production Paths:

a) Natural Gas (Most Common)
b) Electrolysis using renewable energy

(Converting to H_2 certainly loses some energy)

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The battery tech has a shorter based technology range because of the small amounts of energy that can produce but the H_2 is a longer based option as a higher energy volume option.

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ALTERNATIVE TECHNOLOGIES

1) Batteries

General

There is another alternative technology in the market which could be a promising idea for shipping industry in order to comply with the regulations and to be cost efficient as well. Batteries, is a known technology in several industries and can also uprise as a suitable alternative instead of conventional combustion engines upon vessels. It is based on electrical energy and it contributes to the metamorphosis of energy in the way it can be distributed and used on vessels. The electrical power systems created by batteries, will be considered as effortless and easy to manage in its' operation. That leads to the optimization of the system in terms of Safety, Performance & Efficiency. Many experts state that, the ship electrified power systems along with the affordable upgrades in the battery technology render this alternative solution as a new opportunity to be exploited.

However, there is still a very narrow expand of this technology in shipping as there are only a few passenger or ferry vessels that have installed fully electric power systems instead of conventional combustion engines onboard. Basically, the use is

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established in short distance routes which can be reflected in many stops and station-terminals for charging. Moreover, there is a question arises regarding the general sustainability of the electric systems such as batteries. For example, the size of the battery or the cost can be quite common obstacles for this kind of investments. Undoubtedly, research and development programs are necessary for the accomplishment of improvements in that direction.

Price

Principally, the battery electric systems demand is derived through the Automotive industry. The continuous and expeditious price drop can be explained by the phenomenal improvements in the performance by the electronics industry which eventually contributed to the cost plummeting. Typically, the Lithium-ion battery price has drop 50% since 2016 and the outspread continues in terms of performance, technology and applications.

Battery systems acquire large installations in marine applications both in cost and time. The costs can be divided in two categories.

1) Lithium-ion battery cells
2) Incorporation of system:
    a) Module Construction
    b) Battery Control (Software, Hardware)
    c) Power electronics
    d) Thermal Management
    e) Testing

The Lithium-ion Battery is expected to remain as the leading technology and only competitive price from other technologies will be able to overthrow lithium.

As far as battery storage systems are concerned, the top goal would be to increase the energy density in new applications and as a result to react in descending the price slope.

Price Developments – Raw Materials Status

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- Graphite: Widely Used, 80% China production, the stricter regulations would lead to an increase in price and then in new mines.
- Cobalt: Extremely fast-growing industry, 50% production by Congo Africa
- Lithium: Large amounts available and the 1/3 is feasibly accessible. Saline waters and lengthy evaporation procedures required, production in Chile, China and Australia.
- Nickel: Extravagant component of lithium-ion battery, well developed market.

<u>Infrastructure</u>

Undoubtedly, battery electric systems can be provided through a different type of supply or network than conventional energy sources. In battery solution, we can observe that there are no consumption costs for the shipowners, but there must be a sufficient charging network with multiple charging stations provided. The system power demand is depended on the shipping application and the size of battery system.

Example:

	Equivalent	Requires	Time
1.000 Kwh Charge	100 ltrs oil fueled	2.000 kW of power	30 minutes
1.000 Kwh Charge	100 ltrs oil fueled	6.000 kW of power	10 minutes

Vessels can be supplied by electricity from systems on shore, but the question is if these systems can be a burden to the local area electrical system.

The critical point here is to identify the technical information in a precise level.

Battery is a device which can store DC electricity and interfaces to the power grid with standardized power electronics hardware. Basically, this means that the infrastructure of battery can be easily reused and the nature of these technologies provide interchangeability.

<u>Regulations</u>

The regulatory framework is principally focused on the Safety and Installation of battery systems. It is known that DNV-GL Classification Society have already cultivated the ground for new regulations. Several rules were established along with

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many R&D programs with the participation of DNV-GL. Many experts express the opinion that many price-competitive technologies will uprise in the future.

Since 2016 the requirements have become stricter which led to more approval costs and testing equipment. As a result, the performances in safety levels were highly increased. In addition, the onshore connections for charging are chiefly supervised by regulations and requirements established for the electric grid.

<u>Scalability</u>

The demand for battery manufacture and cell development is driven by the automotive industry. Nevertheless, the possible boost in the demand coming from the shipping industry would only be indulged with an improved infrastructure. The critical point is how we can upgrade the required infrastructure to cover the needs of the maritime industry. The answer lies in the maritime sector itself where there are many companies activated and which could contribute to build the commensurate infrastructure.

<u>Environmental Impact</u>

Battery electric systems for maritime applications produce zero emissions during operation, however the production process requires intensive manufacture procedures. There have been several investigation surveys regarding this alternative solution for the maritime sector. Especially for the CO_2 equivalent emissions the surveys compared the conventional combustion engines to the battery systems and the latter reflected a superiority in environmental benefits.

Norwegian NO_X Fund

There are two basic projects already performed; the Hybrid (PSV) platform supply vessel and the Electric ferry which are both studying the environmental payback period.

Using Norwegian Electricity mix

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	Environmental PP	
	(GWP) Global Warming Potential	Nox
Hybrid PSV	1,5 months	0,3 months
Fully Electric Ferry	1,4 months	0,3 months

The GWP is increased by 2,5 months for EU and 1 year globally.

Lithium-ion Battery seems like a feasible material to recycle and is also provided by some companies. In addition, aluminum and copper are on the spotlight for recovering because of the big revenue flow. Lastly, a very price-competitive option proved to be the mined lithium.

Regardless of, the feasibility of the recycling solution for battery systems, there is a limited action now due to the essentially low inflow of recycled or deactivated batteries. The refurbishment seems to be a common end of life direction with a better environmental footprint.

Technology

During the last 9 years radical improvements have been rendered in the battery industry because of the amended procedures in the quality control inside the chemical industry. Nowadays, the Ion Phosphate (LFP) and the Nickel Cobalt Manganese (NCM) seem to be the leaders in the market. Therefore, several developments concerning the industry were established and were equated with the continuous improving knowledge around the complex electrochemical processes of batteries. The benefits observed are advanced design and general utilization. Many new developments derive from components like silicon or titanium which provide the affordable energy density and absolutely high performance.

The source of the advanced safety solutions around lithium batteries was revealed as the stricter regulations imposed by the authorities.

Promising Technologies

Solid Electrolyte is stated to be a promising technology solution with many advanced abilities around safety. Moreover, it is proved to be one of the most durable

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technologies against the stringent maritime regulations with its safety performance and for sure it will be a valuable asset in the maritime industry.

In battery electric systems used in maritime applications the main force of dependency is the lithium -ion battery and that is the main difference with other industries like consumer electronics or stationary grid support. The applications must be investigated in case-by-case scenario because there is a variation in energy requirements or lifecycle among the projects. All in all, the technology development is derived by the same requirements. In the short term, the only advancements and improvements that can be rendered are only in existing battery types.

What is expressed by many experts is that we are 10 years away from many new technologies which will deliver fundamental changes in the market. However, there are many doubts regarding the potential penetration of these innovations in the market especially because the shipping industry is characterized for its conservative direction and nature.

<u>CAPEX</u>

Significant incorporation Costs:

1) Storage System and Purchase Price
2) Switchboard Modifications
3) Purchase Changes (PMS/IAS/DP)
4) FMEA
5) Yard Installation
6) Commissioning
7) Testing

Additionally, the lifetime of the battery is an essentially critical factor in the general assessment and it depends firstly on the size of the battery and secondly on the duty cycle of their use. Basically, the maker of the system also plays a vital role in the final lifetime result because there is a variation in the battery chemistry in each case. The systems are commercially provided with a 10-year warranty in most cases.

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OPEX

The operational costs are driven by the efficiency of the system and by the electricity prices which can be volatile from region to region.

Example:

	Price Range in $
Norway	0,12 $/kWh
EU	0,09 - 0,30 $/kWh

Assuming that		
Comparing to Marine Diesel	Average	Cost
11.800 kWh/t	600 $/t	11.800/600 = 0,05 $/kWh

Battery electric systems vs Conventional Combustion Engines.

We can detect the higher efficiency of batteries against the conventional systems as a beneficially top advantage because of the lower consumption and cost that lead to lower operational costs.

The electrical propulsion systems' efficiency provided reaches the range of 76-85% of the onshore power and diesel generator the range of 40-45%.

2) **Fuel Cells**

General

Fuel Cells is another alternative technology to be recommended for the shipping industry to comply with all regulations instead of conventional engines. Comparing with the common conventional technology the fuel cells provide 60% electrical efficiencies and much lower noise and vibration onboard.

The Fuel Cell System is consisted of the fuel cells which are being furnished with fuel chemical energy and then it is converted to electrical and thermal energy through the

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procedure of electrochemical oxidation. Electrical efficiencies in the range of 60% are accomplished by that direct energy conversion, however it is fully depended on the fuel quality and type to be used.

Fuel Cells Technologies in General

1) Alkaline Fuel Cells (AFC)
2) Molten Carbonate Fuel Cell (MCFC)
3) Proton Exchange Membrane Fuel Cells (PEMFC)
4) High Temperature (PEMFCs) (HT-PEMFC)
5) Direct Methanol Fuel Cells (DMFC)
6) Solid Oxide Fuel Cells (SOFC)
7) Phosphoric Acid Fuel Cells (PAFC)

Based on the current literature, the most promising for the marine applications seem to be the SOFC, PEMFC and the HT-PEMFC.

The fuels used in this technology are basically hydrogen rich and also natural gas, methanol or low-flashpoint fuels to react in the conversion procedure. Therefore, the beneficial result which is requested it the absolute decrease in the air emissions.

Price

Fuel Cells as an alternative solution for vessels propulsion are still considered as an expensive option. The only direction to render its price competitive is to proceed with mass production something that cannot be expected before 2022. One of the major factors in determining the price is the material costs to be used in the system. All in all, the operational costs in general can be competitive only when Fuel Cells Technology will have the same durability with the conventional combustion engines.

Infrastructure

As stated in the price paragraph above there is still no development in this market, at least in a wide scale to cover the shipping industry. There is no commercializing resulting no reliable network to support the upcoming demand. Several projects have been developed but, in a Research and Development style (e4ships project) or for a

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military use. Nevertheless, the possible infrastructure network to be established is expected to develop many similarities to diesel engines.

Regulations

Once again, the regulatory framework is still weak for this alternative option as the production has not flourished yet. In addition, the design and construction applications are under development. Moreover, the general responsible for the code establishment is the IMO through the International Code of Safety for Ships for Gases or Low-Flashpoint fuels (IGF Code). The Classification Societies also play a vital role in the rules development as they maintain the technical supervisory of the vessels and have already contributed in the building of the regulatory framework for combustion engines.

Scalability

At this stage there is still small production of numbers by several manufactures, but we should take into consideration the large amounts of suitable fuels to be needed in order to adopt the technology rapidly and widely.

Environmental Impact

The Fuel Cells technology have emerged as a quite promising option because of the full compliance that it provides with the environmental regulations which seem to become more and more stringent. So far, the data that have analyzed demonstrate that by adopting the fuel cell technology the shipowners will be able to eliminate the NO_X, SO_X emissions and Particulate Matter upon their vessels. In addition, after several investigations it was proved that there a high efficiency in this alternative with a 30% reduction of CO_2 emissions. In particular, the fuel cells technology in combination with hydrogen as the main fuel can eradicate completely CO_2, NO_X, SO_X and PM to zero.

Technology

Currently, the only operations that are taking place are small projects with the power energy of 100 kW because the technology is still at early stages regarding its

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production. The R&D programs are very positive though as they are expected to be commercialized in the next years. However, the gloomy point in this technology is the lifetime of the system, something that will bother the shipowners with further costs but also will force the manufacturers to take initiatives for further technological improvements.

<u>Projects performed</u>

1) MS Mariella – Viking Line for the route Helsinki – Stockholm (Methanol Fuel Cell)
2) MS Innogy – White Fleet (Methanol Fuel Cell)

Some of the most promising fuel cell technologies are the combination of fuel cells with batteries and the Proton Exchange Membrane (PEM). The latter proved to be an optimistic option regarding the enhancement of lifetime, because of the flexible materials required for its operation. Moreover, from the already known technologies, there is the Solid Oxide Fuel Cell which is a hybrid application using the peak-shaving technology.

<u>CAPEX</u>

Fuel Cells solution for shipping industry should be considered as a technology under development. Therefore, any costs investigated and examined are volatile because of the radical change in case of a mass production. Nowadays, the installation costs of a fuel cell system vary in the range of 3.000-4.500 $ / kw. The Research and Development programs are examining into many development improvements to secure a decrease in the cost for rendering the technology price-competitive to conventional combustion systems. Proton Exchange Membrane System indicated to be too expensive in the car industry, but its price drop enables us now to consider it as competitive one for the shipping industry. As a result, PEM arises as an attractive option with a derived demand from the automotive industry.

Automotive Cost	Production
PEM 280 $/kw	20.000 units/year

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However, a complete fuel cell system for the maritime applications can be more expensive as it will be needed a lot more requirements for safety precautions.

OPEX

Fuel Cells are still considered as an expensive option but in order to become a competitive solution it is highly dependable on the below:

1) Same Durability and Lifetime as Conventional Combustion engines.
2) Cost and time of FC Exchange is equal to a general engine overhaul.
3) Prices of suitable fuels to be competitive with MGO, less maintenance than conventional systems and Gas Turbines.

CONCLUSION

This thesis was developed to annotate the International Maritime Organization's decision to implement the regulation of limiting the global sulfur cap to 0,5%. Apparently, there was a general environmental back round behind this decision, as several surveys and investigations concluded that the atmosphere emissions had to be decreased. The shipping industry faced a new challenge to adopt and maintain a more environmentally friendly operation strategy. Eventually, the shipowners confronted the stringent regulations to diminish the SO_X emissions.

Heavy Fuel Oil which is the major shipping fuel globally in terms of worldwide availability, infrastructure and its' competitive price is now considered as a non-compliable fuel. Shipping companies have the option to use Low Sulfur Fuels like Marine Gas Oil (MGO), Very Low Sulfur Fuel Oil (VLSFO) or Liquefied Natural Gas (LNG). For those who will continue to burn HFO the installation of Exhaust Gas Cleaning Systems (Scrubbers) is inevitable.

As analyzed in the main body, Scrubbers is a high cost investment and dependable on each vessel's technical characteristics. On the other hand, turning to a different fuel requires engine modifications, approvals by Classification Societies but most importantly prerequisites the necessary availability and infrastructure to support the vessel's operation.

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Investigating small examples of vessels and adopting each case accordingly, we concluded that Scrubbers will have a slow market penetration for next years but as far as the price gap between the HFO and the Low Sulfur Fuels closes, the Scrubber investment will be useless. In addition, judging by the radical technological improvements and the new fuel blends that arise in the market, compliable fuels will be available in a competitive price.

For the time being, a Scrubber investment was cost-efficient only in large size and young age vessels which would obtain fewer capital costs and a larger lifetime to depreciate the initial investment.

Through our small case study, Liquefied Natural Gas (LNG) arises as the most promising alternative solution in terms of potential and cost-efficiency. However, there are also some other alternatives like Methanol, Hydrogen, Liquefied Petroleum Gas (LPG) or Biofuels which should be taken under consideration. These fuels as presented in the thesis main body, are still in a R&D scale investigated only in research projects with tight availability. Nevertheless, it is expected that in the next years along with the alternative technologies like Batteries and Fuel Cells, they will be starring in the shipping industry.

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