LNG VS SCRUBBER TECHNOLOGY IN FUTURE GREEN SHIPS

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ABSTRACT

Many vessel owners will shortly be faced with making imminent decisions as to whether to convert to LNG fuel or to continue using HFO fuel with scrubber technology in order to meet new regulations of lower SOx emissions. The IMO (International Maritime Organization) has legislated that by the year 2020 the part of sulphur in fuel is to be reduced from the present 3.5% to 0.5% in the ECA - Emissions control area. One possible solution is the use of scrubbers which removes up to 98% of SOx gas emissions. The second solution is to replace HFO with LNG fuel which practically fully eliminates SOx gas emissions. The aim of this paper is to perform a scientific binary analysis from the viewpoint of a shipowner to determine which option is best. The criteria for the analysis considers both meeting IMO legislature as well as the economic impacts in converting to new technologies as well as the costs of vessel operation in the long term. Ship owners want to choose a solution which is both environmentally compliant and financially viable enabling competitiveness in the maritime transport field.

Key words: LNG fuel, scrubber technology, binary analysis, green ship technology

INTRODUCTION

The need for ships to become green is in the process of International Maritime Organization (IMO) legislation. The shipping transportation industry plays an important role in the economic development of each nation that has a maritime boundary. Furthermore it becomes a key component to the development in the world with over 90% of global trade that is carried via maritime transport. There are over 104,000 sea-going vessels in the entire world [1]. In Figure 1 below, the emissions from one just one large cruise ship is compared to the equivalent emissions caused by a large number of cars. On the left column SO_2 (sulphur dioxide) emissions of one cruise ship is equivalent to the emissions from 376 million automobiles, whereas the NO_x (nitrous oxide) emissions of one cruise ship is equivalent to the NO_x emissions of 421,153 cars. Finally CO_2 (carbon dioxide) emissions of one large cruise ship is equivalent to the CO_2 emissions of 83768 automobiles. The reason that legislature is especially working to control SO_x emissions is because the heavy fuel oil (HFO) that most ships use has large amounts of sulphur which is particularly damaging to the environment.

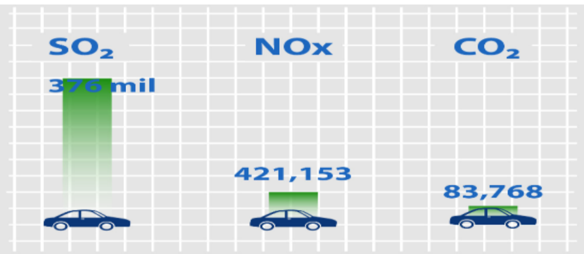

Figure 1 – The main idea and reason for IMO limitation [2]

Sulphur oxides (SO_x) are emitted in the combustion process of marine fuels that contain sulphur. Acid rain results when sulphur dioxide (SO_2) and nitrogen oxides (NO_X) are emitted into the atmosphere and transported by wind and air currents. The exhaust gases containing SO_x emissions will oxidize and in the presence of catalysts such as nitrogen dioxide (NO_2) will form sulphuric acid (H_2SO_4) which is a major cause of acid rain. Acid rain is very detrimental to water supply as well as having caustic effects on nature and particularly in cities where people and structures are affected by it. There are natural acids present in the atmosphere which include organic acids emitted by the biosphere such as volatile organic compounds (VOCs). VOCs react in the atmosphere to form tropospheric ozone, an important pollutant. Nitric acid (HNO_3) is produced by the atmospheric oxidation of NO_x originating from lightning, soils and fires. The deposition of acid rain is manifested in wet and dry formation. Wet deposition (H^+ ; NH_4^+; NO_3^-; SO_4^{-2};) is what is commonly considered as acid rain; whereas dry deposits include acid particles and gases (NO_x, SO_2) which may deposit to the surface or may react during atmospheric transport to form larger particles that can be harmful to human health. The acid rain pathway from the emission of cruiser exhaust gases is shown in Figure 2. The effects of acid rain which includes both wet and dry deposits is very detrimental to human health due to its entrance into drinking water as well as its negative effects on nature and on buildings.

A recent study by German scientists concluded that running on Heavy Fuel Oil (HFO) and on an Exhaust Gas Cleaning System (EGCS) is less harmful than running on Low Sulphur

Marine Gas Oil (LSMGO) in port near populated areas [3]. Therefore, the scrubber system is a very viable solution that should be considered by vessel owners in order to be in compliance with upcoming legislation.

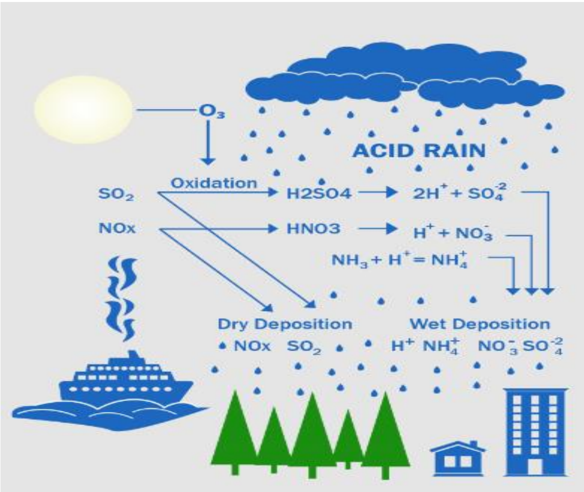

Figure 2 - Gas emission influence on nature [2]

The second type of fuel which has very little sulphur is liquid natural gas (LNG) and it would not require the instalment of an expensive scrubber system. Therefore, LNG is a very viable fuel that meets IMO SO_x requirements. The purpose of this paper is to compare the instalment and use of scrubber technology on ships that would continue to use the common HFO with ships that will be powered by LNG fuel. The positive and negative sides of both solutions is analysed and weighed using a binary analysis method.

BACKGROUND

IMO and European Union (EU) policies require ship operators to reduce the sulphur emissions from their ships. Vessels operating in a Sulphur Emission Control Area (SECA) need to use distillate fuels in these regions or apply a technology that can reduce emissions to an acceptable level. Several options are available to comply with the new limits, including:

- Marine Gas Oil (MGO);
- HFO + Scrubber (different types);
- LNG (Liquefied Natural Gas).

Since MGO is considerably more expensive than HFO, scrubbers have received attention over the last few years and the number of scrubbers installed onboard of ships has increased. LNG on the other hand meets the requirements and is the more 'green' solution, but also requires an entirely different approach, explained in this paper.

COMPARISON OF LNG AND SCRUBBERS

HFO with scrubber

HFO will still be an option after 2020. However, to be in compliance with reduced SO_x emissions, it will require the installation of an exhaust gas cleaning technology commonly known as SO_x scrubbers. No changes will have to be made to the engines or fuel treatment plant, but the instalation of a scrubber could be complex, especially for retrofits. There is a significant investment cost for the exhaust gas cleaning system, and there will also be operational expenses related to increased power consumption and the possible need for chemical consumables and sludge handling.

LNG as fuel

LNG is expected to gain a more favourable position as an alternative marine fuel that is in compliance with the global sulphur cap. LNG as a ship fuel is now a technically proven solution. While conventional oil-based fuels will remain the main fuel option for most existing vessels in the near future, the commercial opportunities of LNG are interesting mainly for new-buildings, but in some cases also for conversion projects.

Scrubber configuration description

Exhaust gas scrubbers, in combination with the use of HFO, have been accepted as an alternative means to lower sulphur emissions. Four different types of scrubbers are available today:
1. **Seawater scrubbers** (open loop) utilize untreated seawater, using the natural alkalinity of the seawater to neutralize the sulphur from exhaust gases.
2. **Freshwater scrubbers** (closed loop) are not dependent on the type of water the vessel is operating in because the exhaust gases are neutralized with caustic soda, which is added to freshwater in a closed system.
3. **Hybrid scrubbers** give the possibility to either use closed loop or open loop technology.
4. **Dry scrubbers** do not use any liquids in process but exhaust gases are cleaned with hydrated lime-treated granulates.

- **Open-loop systems**

The IMO stipulates the global fuel sulphur limit of 0.50% that will enter into force in 2020. That requirement is in addition to the 0.10% sulphur limit in the North American, US Caribbean, North Sea and Baltic Emission Control Areas. Open-loop systems can meet both 0.50% and 0.10% sulphur requirements and can be used in all areas with sufficient seawater alkalinity, except where there are restrictions on wash water discharge.

The technical illustration of a scrubber open loop system (SW pump – seawater pump; ME – main engine) is shown in Figure 3. In an open-loop system, large volumes of seawater (light blue line in Figure 3) are pumped to the scrubber tower. The scrubber tower is designed to ensure sufficient retention time of the exhaust gas (yellow lines in Figure 3). Spray nozzles disperse the sea-water in a pattern designed to maximize the neutralization of acidic gases. The wash water is drained from the bottom of the scrubber tower and exits the ship through discharge pipes (dark blue lines Figure 3). Some open-loop systems also include equipment for the treatment of wash water.

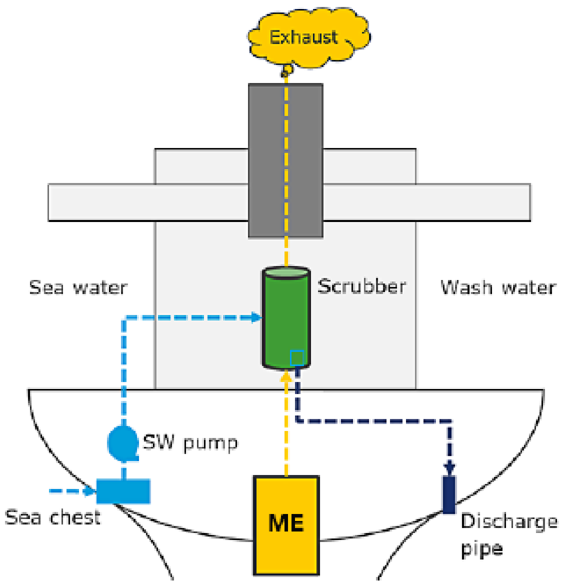

Figure 3 - Open loop scrubber system [4]

- **Closed-loop/hybrid systems**

A closed-loop system provides flexibility for operation in areas with restrictions on wash water discharge or low-alkalinity seawater. A technical illustration of a scrubber closed loop/hybrid system is shown in Figure 4.

In a closed-loop system process water is circulated from a process water tank through the tower and back to the tank (light blue lines – Figure 4). The process water is cooled in a heat exchanger to reduce evaporation of the process water. The ship's technical water is added to the process water to compensate for evaporation and drained wash water, while alkali is added to maintain the alkalinity (red line – Figure 4). Some process water is drained and treated using centrifuges or chemicals.

Treated process water is transferred to a holding tank and discharged when permitted and sludge is transferred to a sludge tank. Some systems can operate both as open and closed-loop and are called hybrid scrubbers, offering increased flexibility for operation in all areas regardless of seawater alkalinity or rules constraining the use of open loop scrubbers [4].

The closed loop scrubber is considerably more complex than the open loop scrubber system and is used in areas where it is forbidden to use open loop scrubber system. The closed loop scrubber requires less than half of the wash water flow than an open loop scrubber to achieve the same scrubbing efficiency. The reason for this is that higher levels of alkalinity level are ensured by the direct control of the alkalinity level using the caustic soda injection process. 2015 IMO Guidelines require a limit of pH 6.5 and certain level of polycyclic aromatic hydrocarbons for discharged water. Areas where restriction is adopted it is not possible the usage of open-loop scrubbers.

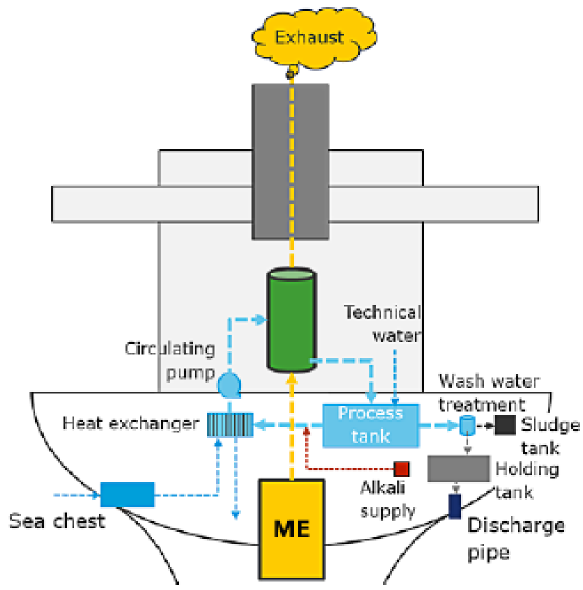

Figure 4 - Closed loop/hybrid system [4]

Scrubber type market trends

With the global 0.50% sulphur limit approaching fast, owners are taking action to ensure they are prepared for 2020. Many more ships are expected to order scrubbers in the following time but the question is when these systems will be installed, because many scrubber equipment manufacturers and shipyards as well of providers of necessary sensors and emission analyzers are working close to full capacity. The industry including banks, financial institutions, charterers and owners seem to be willing to invest in a scrubber in return for the potential benefits from the expected savings in the fuel bill.

The open-loop systems is significantly the most popular design due to their relative simplicity, particularly for retrofitting on existing vessels as shown below in Figure 5 represented by the light blue color in the chart. Closed loop and hybrid systems are in use in restricted areas (green and navy blue). Global share of implemented scrubber system technologies analysed by Det Norske Veritas (DNV GL) (Figure 5).

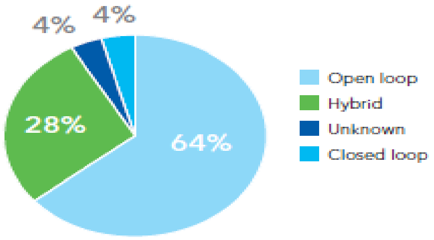

Figure 5 - Share of scrubber system technologies [4]

Scrubber maintenance

The whole process of purifying exhaust gases occurs inside of the scrubber. Seawater and chemicals are sprayed using nozzles over the exhaust gases. Along with seawater there are also often marine organisms that can clog the nozzles (See Figures 6 and 7). The clogging of spray nozzles is a common problem with wet scrubbers. For this reason, they need to be checked regularly. In addition, no waste should ever be poured anywhere into the wet scrubber, filters should be kept clean, and the equipment washed down daily to remove any residual build-up.

A maintenance procedure that needs to be performed on a weekly basis is the draining, cleaning and refilling of the sump with clean water. At this time the pumps should be checked too. Water is the critical component of wet scrubbers. It functions as the actual scrubbing agent as it traps gases and particulate matter. A constant supply is required to replace the overflow of contaminated sump water. As a result, water levels need to be carefully monitored. Purification must be regular and thorough for reliable scrubber operation. The fact that people need to enter the scrubber to access nozzles, requires the use of adequate safety equipment because of the hazardous chemicals located inside of it. A typically contaminated nozzle covered with marine organisms is shown in Figure 6. All of this needs to be cleaned manually which is a drawback to scrubbers.

Figure 6 - Contaminated nozzle (Wärtsila Moss scrubber unit)

As shown in Figure 7, every nozzle needs to be cleaned which means that the scrubber needs to be turned off which means that the ships engine needs to be turned off and the ships voyage is temporarily stopped while the nozzles are cleaned. This is usually done when the ship arrives at port in order to not stop the ship during the middle of its journey.

Figure 7 - Contaminated nozzles (Wärtsila Moss scrubber unit)

Scrubber retrofitting to existing traditional HFO diesel engine machinery

The justification for choosing scrubber technology is based on the following criteria:

1. Return on investment which includes the CAPEX (Capital Expenses) and OPEX (Operating Expenses) cost.
2. The weight of the scrubber that will be added on to the vessel. Horizontal scrubbers weigh half or even less as compared to vertical scrubbers as shown in Figure 8. The vessel saves in not having to carry this extra weight all through its lifetime.

Figure 8 - Example of installed horizontal scrubber [13]

3. The space occupied by horizontally positioned scrubbers is less than half of the space taken by a vertical scrubber. Therefore, the vessel can carry more cargo in terms of weight, the vessel can carry

additional cargo equal to the weight saved. For example: extra container on container ship, which brings noticeable profit.

4. Retaining of existing fuel type supplier which eliminates additional cost.
5. No need for crew replacement or extra special education because main engine and technology remains.

One of the greatest advantages of the scrubber system vs LNG technologies is the simpler process of retrofit technology installation. The possibility to retrofit a scrubber on a ship and to match the lifetime of the ship and scrubber is apparently the most common and profitable option as illustrated by the green colour (62%) in Figure 9. On the other hand there are certain number of new-building vessels whose owners opted for scrubber installation as shown with the light blue colour (38%) in Figure 9. The global share of scrubber system technologies retrofitted on existing vessels and installed in the new-building vessels analysed by DNV shown in the Figure 9.

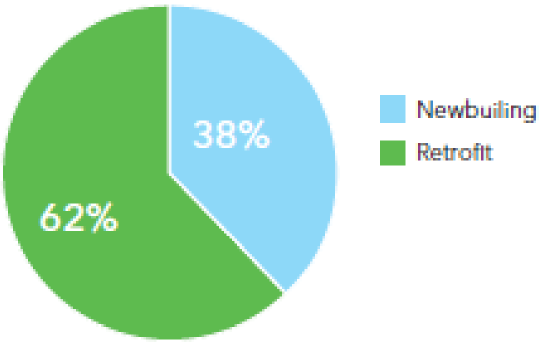

Figure 9 – Percentage of scrubbers installed in new-building vessels vs. retrofitting in existing vessels [4]

Viability calculations for container vessel (example)

Container ships come in sizes of 1000 TEU's (twenty-foot equivalent container units) to the bigger ones of about 20 000 TEU's. The 1000 TEU ship consumes about 30 MT (metric tonnes) of fuel per day, while 20 000 TEU ships consume about 250 MT per day.

Considering the biggest container vessel (20 000 TEU) consuming 250 MT of fuel per day, based on the average differential price of HFO and LSMGO of $200/MT, the additional cost of using LSMGO over HFO is

250 MT x $200/MT = $50 000 per day (1)

Major factor for this calculation will be time spent at sea in days. For example, if the vessel is sailing for 300 days, the vessel will be paying

$50 000/day x 300 days = $15M (Million). (2)

additionally per year for low sulphur fuel – unless a scrubber is fitted.

The cost of scrubber installation is calculated based on the following criteria. The average cost of scrubber retrofit is around $250 per kW. The engine size for this type of vessel is about 30 000 kW:

$250/kW x 30 000 kW = $7,5M. (3)

The purchase and installation of a scrubber for this size of vessel will cost in total about $8M - estimated by Viswa Lab [5]. This means a ROI (Return on Investment) of 6 – 7 months

$8M : $15M = 0,534 x 12 months = 6,4 months. (4)

The daily extra costs for consuming LSMGO is $50 000, or per container basis which yields $2.5 per day per container

$50 000 : 20 000 containers = $2,5 per container (5)

and if we assume a typical voyage of 18 days, the added cost is

18 x $2,5 = $45 per container per voyage. (6)

If the vessel is charging $1 200 per container for a voyage, this $45 per container represents a 3.75% higher cost

$45 : $1200 = 0,0375 x 100 = 3,75%. (7)

An owner/operator who does not want the complication of a huge scrubber, installation, maintenance etc. can easily pass on the 3.75% increase to the customer – calling it "fuel surcharge". However then the vessel owner will be less competitive than owners who opt for scrubbers with HFO as opposed to vessels operating on LSMGO without scrubbers.

Considering the smallest container vessel (1 000 TEU) consuming 30 MT per day, based on an average differential price of HFO and LSMGO of $200/MT, the additional cost of using LSMGO over HFO is

$200/MT x 30 MT = $6 000 per day (8)

For example, if the vessel is sailing for 300 days, the vessel will be paying

$6 000 X 300 days = $1.8 M (9)

additionally per year for low sulphur fuel – unless a scrubber is fitted.

The average cost of a scrubber retrofitted to a vessel with a classical engine room is around $250 per kW of the engine power. For the vessel of 7 200 kW the calculation is as follows:

$$\$250 \times 7\,200 \text{ kW} = \$1{,}8\text{M}. \qquad (10)$$

The purchase and installation of a scrubber for the 7200 kW vessel will cost in total about $2,25M. This means a ROI of 15 months when compared to using the low sulphur fuel

$$\$2{,}25\text{M} : \$1{,}8\text{M} = 1{,}25 \times 12 \text{ months} = 15 \text{ months}. \quad (11)$$

The daily extra cost for consuming LSMGO is $6 000, or per container basis this is $6 per day per container

$$\$6\,000 : 1\,000 = \$6 \qquad (12)$$

If we assume a typical voyage of 18 days, the added cost is $108 per container per voyage

$$18 \text{ days} \times \$6/\text{container} = \$108/\text{container} \qquad (13)$$

If the vessel is charging $1 200 per container for a voyage, this $108 per container translates to a 9% higher additional cost

$$\$108 : \$1200 = 0{,}09 \times 100 = 9\%. \qquad (14)$$

when compared to ships that use HFO with scrubber. An owner operator may find it difficult to pass on the 9% increase to the customer – calling it “fuel surcharge”.

From this calculation we can clearly see the reason why the smaller vessels needs to install the scrubbers, while the bigger ones, with the way shorter time of ROI can avoid this investment for now [5].

LNG conversion is way more expensive

According to the research from Fearnley LNG, it would cost $28M to convert an existing 8,500 TEU container ship to LNG compared with $13M for an equivalent-sized new one. For VLCC (Very large crude carrier) ship the cost of fitting an open loop scrubber in a new-build ship is around $2.5-$3.0M, whereas the cost of retrofitting a scrubber on an existing VLCC is $4-$4.5M [10].

New vessels are also expected to run more efficiently, further reducing the relative cost of fitting a scrubber or LNG system in a new-build. Importantly, it is suggested that the installment of a scrubber is significantly cheaper than the installation of an LNG unit in the more cost-effective new-build scenario.

For such an operator it seems that early adoption of a scrubber solution, especially as a retrofit, is not only a cheaper option, it might be the only viable one [10].

One of the greatest problems with fuel conversion and LNG technology installation is machinery space occupation which was not foreseen for present ship machinery space configurations. The specific problem is the LNG tank volume, which is 2,5 times bigger than that of an HFO tank, explained in detail calculation.

There is even real life example, as shown in Figure 10 of a ship lengthened in order to increase space for cabins and LNG tanks. Royal Caribbean International's Enchantment of the Seas received a new 73 foot mid-body section in May 2005.
The reason for undertaking such a huge project is explained by several benefits obtained with this operation such as an improved environmental footprint (reduction of exhaust gases emission), cheaper fuel and lubricants, additional cargo (public) space, reduction of main engine maintenance hours, cleaner engine room, no need for scrubbers or catalytic reactors and lower noise level in the engine room.

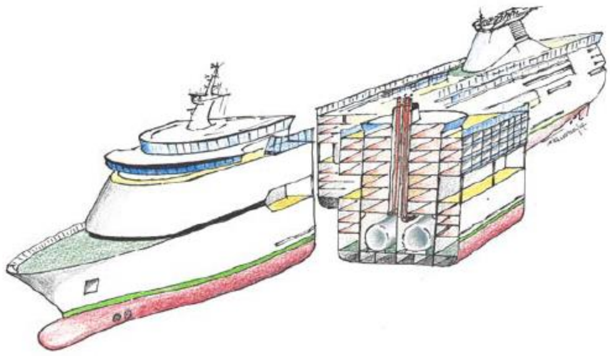

Figure 10 - Ship elongation concept [8]

LNG configuration description

The number of ships using LNG as a fuel is continually increasing and more and more infrastructure projects are planned or proposed along the main shipping lanes. But maybe not as expected. In earlier phase of vessels with LNG as a fuel, (2010-2014) it was estimated that by the year of 2020 it will be reached the number of 1 000 non – LNG carrier vessels running on LNG. Five years later when we are almost in 2020 we are talking about the number of 400 including LNG-ready vessels.

The main reason besides the price competitiveness of the scrubber system installation on an existing HFO diesel engine is the insufficient development of LNG terminals in the world, respectively the limitation of LNG propelled vessels due to impossibility of LNG fuelling.

Nonetheless, LNG as a fuel is a proven and viable solution. While conventional oil-based fuels will remain the main fuel option for most existing vessels in the near future, the commercial opportunities of LNG are interesting for many new-build and conversion projects.

There are various LNG powering configurations available. The two key engines on the market today are gas-only and dual-fuel types. Gas only engines "Lean-Burn Spark Ignited engines" (LBSI-engine) are designed as a medium or high speed engine with the power range from 0,5 - 8 MW. They are used on all gas powered ferries in Norway. However, other ship types as ROPAX, RORO, Product Tankers, Patrol ships and OSV have also selected this engine type. The main disadvantage of the LBSI concept is backup fuel or the possibility to run on diesel oil if LNG is not available, explaining why shipping industry prefer Dual Fuel gas engines [14].
Dual fuel engine can seamlessly switch from gas to liquid fuel at any time and load. Even at full load no loss of engine output or speed is measurable and the engine will not trip. Generally, a dual-fuel engine is started on liquid fuel and is switched to gas after a few minutes.

The main differences in engine design are the components of the combustion chamber, such as the cylinder liner, piston and cylinder head of the fuel supply systems for gas and pilot fuel, and special electronic control modules (including knocking detection).

A dual-fuel upgrade in marine application could therefore be carried out in the following steps:

- Conversion of existing main engine to dual-fuel operation
- Adaptation of engine room systems
- Safety installations
- Installation of bunkering equipment
- Installation of Fuel Gas Preparation Unit
- Adaptation of HFO and MGO tanks
- Installation of LNG-tanks in cargo holds

Characteristics and advantages of dual-fuel upgrades

- Dual-fuel upgrades offer the opportunity to use gaseous fuels in existing diesel engines
- High reduction of fuel cost by use of natural gas
- CO_2 emissions decrease
- Fuel flexibility and switch over at almost all engine loads

As the 2020 deadline for lower emissions looms ever closer, ship owners increasingly prefer to install LNG propulsion in new ships rather than retrofit existing ones. The numbers show that just 8 of the current global LNG-fuelled fleet of 145 vessels are retrofits – all the rest are new-builds. Further, all of the eight vessels are larger ships – four ferries, three oil product/chemical tankers, and a container ship. In short, vessels with high fuel consumption.

And that looks to be the trend for the future. The evidence shows that ship owners increasingly prefer to invest in new LNG-fuelled vessels rather than retrofit LNG-fuelled propulsion systems to existing vessels.

The biggest challenges with LNG retrofitting are mainly with the amount of space on board which is extremely limited. The engine room is too small, so manoeuvring parts in and out is difficult. The economics change significantly in favour of new-builds.

LNG ready ship is a good option in situations where LNG is unlikely to be available for another few years in the vessel's intended area of operation, or if the current commercial terms are not sufficiently favorable for the required extra investment. By making a new-build LNG ready, prepared for cost-efficient retrofitting to LNG fuel with class approved designs, ship owners can reserve their final decision and delay the major investment until a point in time when the terms are favorable and the risk level is acceptable. A small amount of effort and investment upfront can pay off in terms of increased flexibility and tradability, an extended commercial lifetime and increased second-hand value.

Retrofitted LNG 15, 000 TEU (example)

This project is scheduled to take place in 2020 when the five-year old vessel will spend 90 days in dock. The DNV GL approved 6,700 cubic meter gas storage system will occupy an area equivalent to 350 containers, including the pipework between storage and the main engine. This tank size will mean the vessel has to bunker twice per round trip between Asia and Northern Europe [11].

LNG bunkering calculation

(Comparison HFO – LNG)

- $Needed\ volume\ of\ LNG: V_{LNG} = \frac{Q*Hd_0}{\rho_{LNG}}$
- $Real\ volume\ of\ the\ LNG\ tank: V_s = V_{LNG} * 1{,}15$
- $Calorific\ value\ of\ HFO: Hd_{HFO} = 40\ 600\ [kJ/kg]$

- $Calorific\ value\ of\ \ LNG: Hd_{LNG} = 48\ 500\ \left[\frac{kJ}{kg}\right]$
- $Real\ ratio\ of\ calorific\ values: Hd_s = \frac{Hd_{HFO}}{Hd_{LNG}} * 1{,}1$
- $Density\ of\ LNG: \rho_{LNG} = 0{,}425\ [t/m^3]$

Example:

- $HFO\ bulk: Q_{HFO} = 1000\ [t] \approx$ $HFO\ volume: V_{HFO} = 1000\ [m^3]$
- $Hd_s = \frac{Hd_{HFO}}{Hd_{LNG}} * 1{,}1 = \frac{40\ 600}{45\ 800} * 1{,}1 = 0{,}92$
- $V_{LNG} = \frac{Q_{HFO} * Hd_0}{\rho_{LNG}} = \frac{1000*0{,}92}{0{,}42} = 2190{,}5\ [m^3]$
- $V_s = V_{LNG} * 1{,}15 = 2190{,}5 * 1{,}15 = 2519\ [m^3]$

This calculation show us that the equality for tank volume of $1000[m^3]$ or $1000\ [t]$ for HFO fuel is $2519[m^3]$ size tank for LNG fuel, which is approx. 2,5 times more space on the ship. That is a serious problem for the shipping industry because it is hard to accept the cargo (profit) reduction on an equally sized ship.
The way this problem will be resolved is by adjusting gas and oil prices on the world market and creating strict environmental regulations for the emission of exhaust gases into the atmosphere, which includes the IMO 2020 regulation.

EMISSION COMPARISON

Compared to HFO, LNG emits significantly less exhaust emissions. Gas or dual-fuel engines running on LNG according to the Otto cycle have a 25% lower level of CO_2 emissions as shown in the first blue column in Figure 11, while scrubber installation does not reduce it at all (first orange column).

NOx emissions are 85% lower while operating on LNG than on HFO shown with the second blue column in the chart below. The scrubber technology does not remove nitrogen oxides or only very small amount of it, about 2%.

Since LNG does not contain sulphur, SOx emissions are eliminated completely as shown by the third blue column from the left with a value of zero. The purpose of scrubber installation is to remove SOx emissions and they do it almost perfect by eliminating 99% of SOx in comparison with having no scrubber.

Finally in the fourth set of column from the left of the graph, the scrubber has 35% of particulates matter in comparison with HFO with no scrubber which is represented by the orange colour. The blue column which represents ships powered with LNG fuel shows virtually all particulates eliminated, with only 0,1% in comparison to classic vessels powered by HFO. Even though there are no official regulations for particulates, the almost complete elimination of particulates matter by switching to LNG fuel cannot be understated.

Particulate matter is the general term used to describe liquid droplets and solid particles which occur in the air as a product of exhaust gasses. The composition and size of these airborne particles and droplets vary. Some particles are large enough to be seen as dust or dirt, while others are so small they can only be seen using a scanning electron microscope.

If we are just talking about IMO 2020 sulphur restrictions, scrubbers are fulfilling it, but it is necessary to consider that the green initiative will most likely continue to spread into NOx and particulate regulations. Therefore, LNG appears to be the green solution for the present and the more distant future.

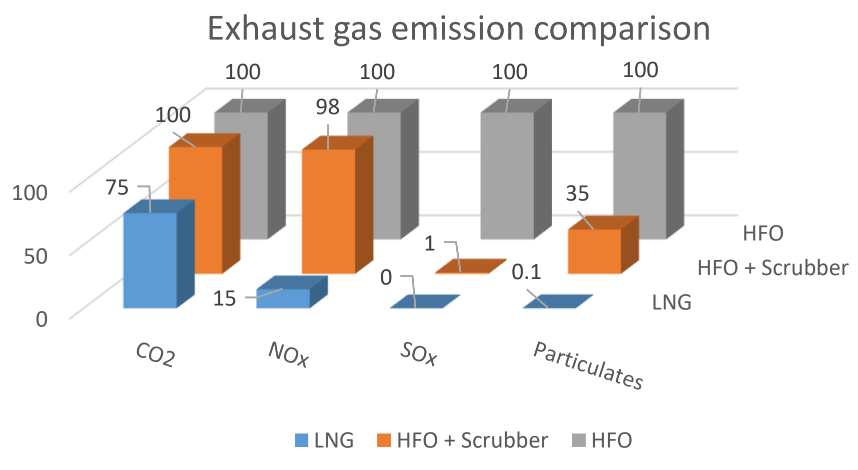

Figure 11 - Emission comparison [6]

Financial analysis

In order to examine the commercial attractiveness of LNG fuel for ships, a high-level financial analysis is made, comparing LNG fuel switch to MGO (Marine gas oil) and to HFO with and without a scrubber. In the analysis it includes both capital and operational expenditures.

Figure 12 presents an estimate of the total additional capital cost of the LNG system, meaning the delta cost of installing dual-fuel engines and the LNG system compared to a regular, diesel fueled vessel. The black line represents baseline costs of a ship consuming HFO fuel without any additional technology. It is well known that HFO is not environmentally friendly and is dangerous for humans and nature. However, these facts were not enough important for ship owners and there was no right initiative for alternatives until legal regulations were announced. Ship owners were used to that policy and they hardly accept any extra costs, especially a high start investment.

From Figure 12 it is easy to see that, in this case, relatively high start investment is truly worth it. Blue line represents the cost without any investment just switching from HFO to expensive MGO fuel, which meets IMO regulation. MGO describes marine fuels that consist exclusively of distillates. Distillates are all those components of crude oil that evaporate in fractional distillation and are then condensed from the gas phase into liquid fractions. MGO usually consists of a blend of various distillates, maximum permissible sulphur content of MGO lies below that of HFO and it is acceptable for the upcoming IMO regulative. The blue line shows that ships that operate with MGO cumulate costs as the years go by all the way to 2032. Therefore, MGO is definitely not economically optimal when compared with the baseline HFO. It will be very expensive for ship operators.

The green line in Figure 12 represents the LNG technology solution. It includes a relatively high start investment due to the machinery space investment. However, after eight years, its ROI pays off because it equals that of HFO which is where it intersects the black line. By year 2032, there is actually a saving of $2 million in comparison to just using HFO. Therefore, LNG technology is the most economical solution.

The yellow curve represents the cumulative cost of an HFO fueled ship with scrubber technology. The initial investment is a little over $3 million which is less than the $6 million investment for LNG technology investment. However, the cumulative costs increase as the years go by. The increase is less than that of MGO. However, in comparison with both HFO and LNG the costs are higher. The results of Figure 12 clearly show that LNG fuel is much more economical during the long term, while MGO is the most expensive. Scrubber technology while having a financial argument for the short term is not viable in the long term.

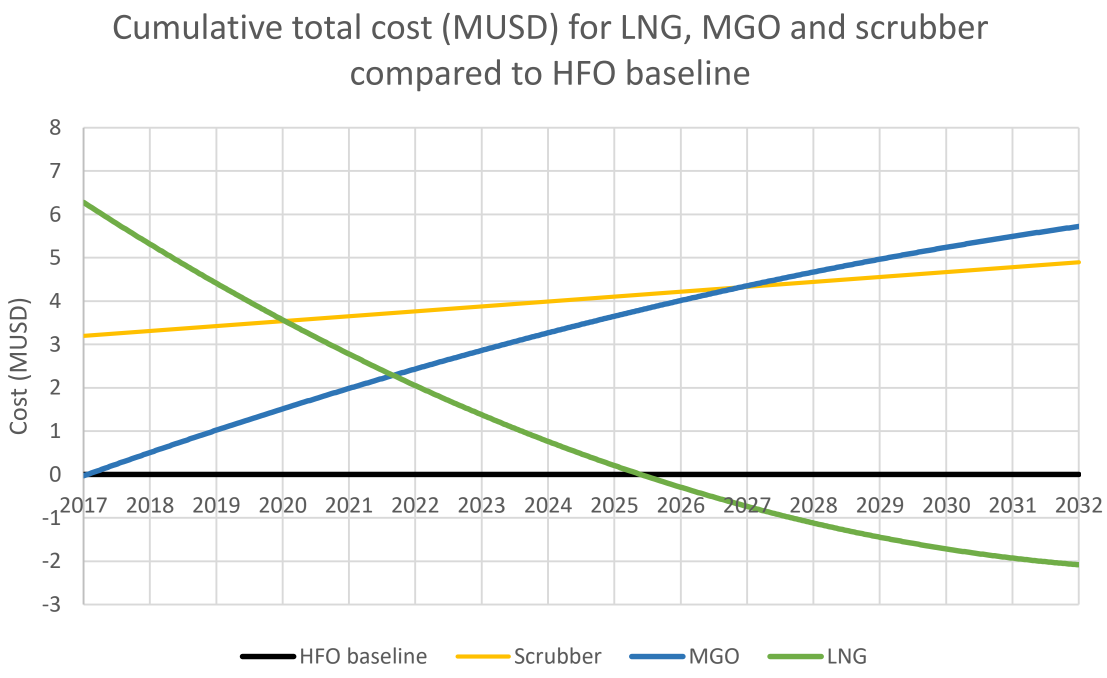

Figure 12 - Cumulative discounted cost differences for different compliance options compared to HFO baseline [5]

BINARY ANALYSIS

In order to make a scientific decision as to which technology is optimal between scrubber and LNG is to use binary analysis which takes into consideration multiple criteria. The reason for this is the clear picture of results that we get from it.

All processes in computers and robots can be broken down into lines of binary code. There are two states of electricity on and off. These on and off states of electricity are represented by 1 and 0. This method analyses the raw binaries that compose a complete application.

After research and study of available literature from several resources we found 13 major criteria as shown in Table 1. The idea was to collect multiple relevant factors of approximately equal importance and then to sum them up and the column with the greatest value is the scientific solution for choosing HFO with scrubber technology or LNG fuel technology on sea going vessels.

1. Criterion number one is the SO_x emission level. Since LNG fuel has no Sulphur to begin with and the scrubber treatment still results in some Sulphur emissions, the LNG gets a one and the scrubber a zero.
2. The other relevant exhaust gases include CO_2, NO_x and particulates emission level highlighted as pollutants which are a threat to nature and need to be considered for future regulations that will most likely be addressed due to the green trends that are likely to continue or increase. LNG is dominant in this field and therefore gets a number one, while scrubber technology is a zero.
3. Fuel price criterion is on the list because the money spent on fuel can influence whether to choose LNG or scrubber technology. LNG fuel is cheaper in comparison to HFO with scrubber. Therefore, LNG is rated a one while scrubber technology gets a zero.
4. The durability criterion refers to the lifetime of the technology in comparison with the lifetime of the ship. Since the scrubber technology lasts only about ten years before having to be replaced and LNG technology lasts for the entire lifetime of the ship which is 25 years, LNG technology is again advantageous and gets the value of 1 whereas the scrubber technology gets a 0.
5. The legislative criterion indicates present and future assumptions about restrictions in environmental protection. Since LNG is a cleaner and therefore a greener fuel, it is clearly to be in more compliance to legislature than HFO with scrubber technology. Therefore, LNG is rated a 1, while HFO with scrubber technology gets a 0 value.
6. The Maintenance criteria considers all of the costs related to maintain the new technology. Since the frequent cleaning and maintenance of the scrubber nozzles is very time and crew intensive, and the LNG technology does not require that type of maintenance, it is clear that LNG gets a value of 1 whereas HFO with scrubber technology gets a value of 0.
7. Government incentive criterion refers to mitigating circumstances which are coming. Since green politics appears to be here to stay, it can be assumed that LNG technology will receive government incentives and subsidies whereas anything related with HFO and traditional fuels will be ignored by most government incentives. Therefore LNG technology is rated with a 1 whereas HFO with scrubber technology gets a 0.
8. The impact of mechanism proportions on vessel stability is a realistic criteria because vessel stability is very important. Since the LNG technology does not require a scrubber technology or an additional heavy mechanism to run, it is rated a 1. The HFO with scrubber technology requires a relatively heavy scrubber in relation to other machinery elements. Therefore it is rated a 0.
9. The mechanism footprint criterion takes into consideration the space occupied by the technology in question. The LNG requires gets a 0 since it requires much more space than the HFO with scrubber technology which gets a 1. The extra space taken up by the LNG which is about 2,5 times more than HFO with scrubber means that there is less space for cargo whether it be containers, liquid cargo or even the number of passengers..
10. The installation cost criterion yields a 0 for LNG technology which is more expensive than HFO with scrubber which gets a 1.
11. The fuel availability criterion considers all the world shipping routes. Most ship ports do not have LNG refueling terminals, whereas HFO is available worldwide. Therefore HFO with scrubber gets a one, while LNG gets a 0. It will take many years for LNG fuel to become more available in the future. A perfect example is the issue of the LNG terminal that was planned in Omišalj on the island of Krk in Croatia. To date, there have been protests by the local population which is against the creation of the LNG terminal, a new technology which people question with regards to safety and unknown environmental impact to the local municipality.
12. Insurance cost criteria is also very relevant for ship owners. Insuring LNG powered vessels is higher than insuring HFO powered vessels, because the LNG technology is more delicate and requires specially controlled conditions for storage, transfer and combustion. There LNG vessels get a binary value of zero, while HFO powered ships which are less dangerous receive a value of one.
13. The education level of crews on LNG powered ships will require crew to be educated on using this more complex and still uncommon ship technology in comparison to HFO which has been the standard for over 100 years. Therefore, the HFO column receives a one whereas the LNG receives a zero.

Table 1 - Binary Analysis

	Major factors	Description	LNG	Scrubber
1	Exhaust gases SO_x emission level	Scrubbers remove almost whole amount of SO_x in HFO exhaust gases, but LNG does not contain any Sulphur at all.	1	0
2	Exhaust gases CO_2, NO_x, particulates emission level	LNG is considered as a green fuel, as shown in Figure 11. All relevant pollutions as CO_2, NO_x and particulates matter are worse than LNG as a fuel.	1	0
3	Fuel price	LNG price is about 200$ cheaper than HFO which is a powerful boost for LNG as a choice, even with significantly higher start investment.	1	0
4	Durability	Durability factor goes also on the LNG side, because scrubber lifetime is shorter than lifetime of the ship. It depends on the time spent at sea but is approximately 10 years. LNG technology lifetime, with proper services and maintenance is comparable to lifetime of the ship.	1	0
5	Legislature	The emission restriction legislature part is more than fulfilled, because there is a 'huge gap' between present IMO limitations and LNG pollutants so it is likely there be no need to find a 'greener' fuel for a certain time. Safety part is also satisfied considering that the whole LNG System is designed with double walled containment; the tanks, the pipes and the engine itself. Double walled pipe to lead the gas all the way into the combustion chamber. Thanks to these safety measures, legislation, one important factor goes on LNG side.	1	0
6	Maintenance	Scrubbers (open loop) requires sea water, which contains marine organisms, salt and other particles and require special maintenance procedures, unlike LNG technology. LNG has no visible exhaust emissions – nearly no particles.	1	0
7	Government incentive	Considering LNG as a green energy, LNG fuelled ship owners worldwide receive government incentives in the name of reduction or elimination of harmful air and seaborne emissions. Their aim is to provide continued financial support to green ship owners for the purpose of: • Renewing short and deep-sea fleet; • Building new environmentally sound vessels; and • Retrofitting existing vessels.	1	0
8	Impact of mechanism proportions on vessel stability	In LNG technology case, there is no additional device or mechanism which affect the stability of the ship as scrubber does. For example: on relatively small area with 3,8 [m] diameter, operational weight of scrubber is almost 20 [t], for engine with the power of 20 [MW].	1	0
9	Mechanism footprint	In the other hand mechanism foot print is bigger for LNG technology because of approx. 2,5 times bigger volume (as shown in LNG bunkering calculation in the paper above) of the fuel tank what directly impact the amount of ship cargo.	0	1
10	Installation cost	Scrubbers are considerably cheaper and easier to install on the ship. Especially when we are talking about retrofit. Start investment is usually about double or even 3 times cheaper than for LNG technology retrofit.	0	1
11	Fuel availability	Fuel viability is the factor which maybe makes LNG as a future solution. There are lots of ship routes which are not achievable with LNG as the only propulsion fuel because there are many ports that lack LNG terminals which are necessary for the refuelling of LNG powered ships. That factor often goes beyond technical decisions and involves politics.	0	1
12	Insurance cost	LNG technology requires special conditions for bunkering, evaporation and combustion. Because of the huge temperature differences and possible dangers the insurance cost is higher for LNG powered vessels.	0	1
13	Education level of the crew	There are also other benefits in not changing fuel and installation of scrubber technology. There is no need for additional education and insurance for existing crew or demand for higher educated employers respectively with higher salary.	0	1
	Total		8	5

DISCUSSION

At the end of this paper it is given the binary analysis which shows main factors. The idea is to eliminate possible dilemma that ship owners face in deciding to choose LNG solutions over scrubber technology and vice versa. If you take a close up picture, LNG is a certain winner. But in real life there is a wider perspective and lots of other factors.

In this paper 13 criteria were chosen as shown in the Table 1. Gas emission level and the fuel prices are given as most relevant factors. The worldwide fuel availability factor is a very delicate criterion, since there are many ports in the world which lack LNG terminals. LNG terminals are necessary for the LNG ship industry and they dictated the routes.

The main reason of given IMO regulations and the reason why scrubbers are eventually created is SOx exhaust gas emissions. Scrubber technology justified the purpose and, as explained in Figure 11, SOx exhaust gases are almost completely removed in both solutions. Other relevant pollutions as CO_2, NO_x and particulates matter are incomparably lower by LNG as a fuel.

In the paper above it is given analysis and calculations about scrubber as a retrofit option and it turn out to be a great solution for upcoming IMO sulphur limitation. Scrubbers are relatively easy to install and the ROI is more than reasonable.

I would like to point out that the results presented in Table 1 and in this paper represent the outcome of my research and the materials available from the university repositories as well as from the sciantific research and companies mentioned in the literature. The results obtained are not biased, but maximally objective without any preference, taking into account the available data sources.

CONCLUSIONS

The goal of this paper is to present the conceptual solution for the upcoming IMO sulphur regulations and to answer the question about preference LNG or Scrubber technology. According to the results presented as binary analysis, it can be concluded that LNG is the solution for new-buildings whereas scrubber technology is most economical for present ships.

Due to the aforementioned regulations and the installation of the desired option, one should accept the fact that the capacity of the freight transported so far has been reduced. Be it with LNG technology (tank volume 2.5x larger) or the size and weight of scubber technology that affects ship stability.

Abbreviations

IMO	International maritime organization
SO_x	Sulphur oxides
NO_x	Nitrogen oxides
NO_2	Nitrogen dioxide
HNO_3	Nitric acid
VOCs	Volatile organic compounds
H_2SO_4	Sulphuric acid
H^+	Hydrogen cation
SO_4^{-2}	Sulphuric acid, ion(2-)
NO_3^-	Nitrate ion
NH_4^+	Ammonium cation
HFO	Heavy fuel oil
MGO	Marine Gas oil
LSMGO	Low Sulphur Marine Gas oil
EGCS	Exhaust gas cleaning system
SECA	Sulphur Emission Control Area
EU	European Union
US	United States
MT	Metric tonnes
kW	Kilowatt
MW	Megawatt
M	Million
ME	Main engine
SW pump	Seawater pump
ROI	Return of investment
TEU	Twenty-foot equivalent unit
CAPEX	Capital expense
OPEX	Operating expenses
OSV	Offshore support vessels
DNV	Det Norske Veritas
RORO	Roll-on/roll-off ship
ROPAX	RORO with passenger accommodation
VLCC	Very large crude carriers

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