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Liquefied Natural Gas (LNG): Alternative Marine Fuel Restriction and Regulation Considerations, Environmental and Economic Assessment

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Abstract
Energy, environment, and economy are three pieces of a chain which are cohesively bound together and always in a correlation with each other. Therefore, offering a suitable substitution for current fuels that satisfies energy requirements and reduces fuel costs with less pollutant gases needs a detailed assessment of available alternative fuels as well as a complete analysis of Strength, Weaknesses, Opportunities, and Threat (SWOT). A comprehensive overview of the environmental and economic aspects of liquefied natural gas (LNG), as an alternative to marine fuel, is presented with a focus on the codes, standards, regulations, restrictions, and guidelines which are vital for maintaining a balance between market and industry. The various characteristics of LNG has been compared with other fuels and depicted that LNG has lower emission and offers major environmental benefits at regional and global levels.

Keywords: Liquefied Natural Gas (LNG), Marine Fuel, Heavy Fuel Oil (HFO), Marine Gas Oil (MGO), Marine Diesel Oil (MDO), International Maritime Organization (IMO).

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1. Introduction

NG has been consumed as a low-carbon fuel for many years [1]. It is the fastest growing energy source in the world as well as the most flexible of all fossil fuels [2]; furthermore, since it has been nominated as the future fuel [3], its liquid form (LNG) plays a substantial role as an alternative for traditional marine fuels, i.e., Heavy Fuel Oil (HFO) and Marine Diesel Oil (MDO). Nevertheless, using LNG as a fuel has certainly some disadvantages, including the low density which enforces the use of 3- or 4-time larger fuel tanks than HFO or MDO fuel tanks. However, its benefits are much more than its disadvantages. Recently, Natural Gas (NG) [4 and 5] has emerged as a potential connection between renewable energy sources and the existing distribution infrastructures. Furthermore, British Petroleum has declared that [6] the Global identified gas reservoir rose slightly by 0.4 trillion cubic meters (TCM) or 0.2% of 193.5 TCM. With this current production rate, gas fuel will last 50 years more than oil (52.5 years)[1]. This large amount of resources has directly affected fuel consumption markets and, thus, re necessitates a thorough survey about their aspects (regulation, price, and environmental effects) compared with other prevalent fuels to facilitate their SWOT analysis. On the other hand, since the human life is negatively affected by the Earth's permanent climate pollutants, reducing the thresholds of both Green House Gas (GHG) and local pollutants [Nitrogen Oxides (NO_X) Sulfur Oxides (SO_X), particle matter and …] seems an appropriate solution. Hereupon, ship-owners have three realistic alternative choices. One possible way is to use MDO by installing scrubbers on the ship boards or using Low Sulfur Heavy Fuel Oil (LSHFO). Other solution is to use nuclear energy; the last possible way is using LNG. LNG is a perfect choice because of its cleanliness and lower emission levels [7 and 8].

The following illustrates why LNG, as ship fuel, is going to become popular all around the world:

1. The Sulphur Oxide (SO_X) emission will reduce from 90% to 95%.[2] In fact, the sulfur content value of LNG is approximately zero.
2. LNG possesses a higher hydrogen-to-carbon-ratio in comparison with traditional ship fuel; therefore, it emits less carbon dioxide (CO_2) per unit energy produced and reduces CO_2 emission from 25% to 20%.[3]
3. LNG is expected to be more economical and has cost benefits compared with Marine Gas Oil (MGO) and HFO [9 and 10].
4. LNG has lower nitrogen content than oil; therefore, the NOx emissions that contribute to depletion of ground-level Ozone from burning LNG are negligible.

Moreover, one of the brilliant advantages of employing LNG as the marine fuel is the considerable saving attained from less maintenance of the engines, since gas combustion is significantly cleaner than its HFO or MDO corresponding fuels. Generally, LNG is becoming a strong corrival with oil products for heavy-duty trucks [11 and 12], railroad [13 and 14] and marine transportation [15 and 16].

LNG consumption, as a marine fuel, is increasing extensively in recent years [17][4]. According to the statistics in September 2014: from about 119 ships ordered for manufacturing in 2014, 50 finished and 69 under construction, LNG was considered an alternative marine fuel, especifically in ECAs.

LNG and the related issues have caught scientists and researchers' attention lately [18 and 19]. An alternative fuel for switching from HFO to IMO Arctic area was studied by Roy et al [20]. The commercial stimulants required to promote using LNG, as an alternative marine fuel, were assessed by Schinas and Butler [21]. Life-cycle emission of natural gas compared with conventional petroleum-based fuels in the marine sector has been addressed by Thomson [22].

Energy and cost effect for three different locations-- capture site, liquefying plant, and shipping terminal for ship transportation-- has been investigated by Zahid et al [23]. Ships usually utilize HFO because it is less expensive than MGO.

1. By region, the Middle East holds the largest proved reserves (79.1 TCM, 40.9% of the total global) [6].
2. This reduction level will also be mandated within the so-called Emission Control Areas (ECAs) by 2015. A similar reduction is expected to be enforced for worldwide shipping by 2020.
3. Any slip of methane during bunkering or usage needs to be avoided to maintain this advantage.
4. Emission control area regulation is one of major drivers in adopting LNG as a marine fuel.

However, since up to 70% of ship emissions occur within 400 km of coastal areas [24] that tags coastal land as a polluted area. In addition, by the development of LNG fuel systems technology as well as bunkering infrastructure, LNG could be a very suitable nominate fuel for coastal pollutant reduction and marine transportation. The result of Yoo's research has showed that LNG fueled CO_2 carriers are much better in term of price than CO_2 carriers, which consume MGO [25]. Nardon studied transportation of CO_2 by those ships that consume HFO in North Sea [26]. Skagestad et al. has presented an overview of the current status of CO_2 ship transport [27]. The impact of considering various regulations, including MARPOL Annex VI, on bunker prices was discussed by Schinas et al. [28]. On the other hand, protecting environment and preventing the release of pollutants and particles emissions as well as studying emissions from ship fuels have been challenging issues for researchers in the past few years. Fridell et al. researched on the primary particles in ship emissions [29]. Winnes and Fridell could measure particles emitted from a 4500 kW four stroke main engine on-board of a product tanker [30]. Environmental evaluation of LNG, Liquefied Bio Gas (LBG), methanol and bio-methanol, has been accomplished by Brynolf et al. [31]. The Criteria for future marine fuels [32] and life-cycle assessment of LNG and three other fossil fuels as marine fuels were studied by Bengtsson et al [33]. Recent regulations defined by China for certain areas, enforces the use of the fuels containing less than 0.5% Sulphur by January 1st, 2019. These areas are different from those included in SECA [34]. Utilizing LNG, as an alternative marine fuel, has also been studied by Semolinos [35].

In this paper various aspects of using LNG, as an alternative marine fuel, compared with traditional fuels are addressed. In the first step, regulations, standards, and resolutions (IMO A.963 (23), IMO MPEC/Circ.471, MPEC 65/INF.10, MSC.285 (86), MARPOL73/78, ISO/TC 67, ISO/DTS 18683, ISO 8217, 2012/33/EU) were studied. In the next step, the environmental issues of LNG (SO_X, NO_X, CO_2 and P.M emissions) for medium ships using Lean-burn gas engines[1] – spark ignited engines were taken into account. Thereafter, the spillage problem of fuel oils that makes one of the major environmental problems vs benefits of LNG was thoroughly investigated. Subsequently, for perusing LNG economic appraisal, the historical price development of crude oil, LNG price compared with crude oil, LNG price fluctuations at different import terminals, and LNG price comparison with other prevalent marine fuels in a specified time interval have been taken into consideration. Afterwards, Fuel price prediction scenario and payback time for small and large vessels were reported in detail.

2. Methodology

The information used in this study was obtained from a number of articles, researches, restrictions, regulations, and also ship manufacturer companies such as DNV and Rolls-Royce. Then, the different aspects of LNG (Restrictions and regulation, environmental and economic) are discussed. Finally, the SWOT analysis sum ups pros and cons of the purposed solution.

2.1. Assessment of Regulations, Standards, and Resolutions

One of the serious concerns of the 21st century is climate change [36 and 37], and one of the most major challenges is eradicating GHG emissions from transportation and industrial processes [38]. In 1997, IMO issued a resolution about CO_2 emissions from ships[2] [39 and 40]. IMO estimates that international shipping contributes approximately 3 percent of total

1. Totally combustion engine concepts that utilize LNG as a transport fuel to provide propulsion power can be divided into 2 following group:1. DF engines; 2. Lean-burn gas engines – spark ignited engines.
Beside these group, gas-diesel engines exist, but these can only utilize natural gas and not LNG.
2. Resolution 8 of the 1997 International Conference of Parties to MARPOL 73/78 [39]. The MARPOL Convention addressed five types of pollutants through its five original Annexes: Oil, Noxious Liquid Substances, Packaged Harmful Substances, Sewage, and Garbage. MARPOL Annex VI began an effort to reduce both Sulphur and nitrogen emissions by rate of 80%. On 10 October 2008 the MEPC of the IMO unanimously adopted the revised MARPOL 73/78 (International Convention for the Prevention of Pollution from Ships) Annex VI on air pollution from ships [40].

GHG emissions worldwide [41]. In this field, IMO has many guidelines [42] such as Resolution A.963 (23)[1] [43], which is focused on GHG and evaluates that ships contribute about 1.8 percent of the world's total CO_2 emissions. Furthermore, MPEC/Circ.471[2] [44] declared that CO_2 was the main GHG emitted by ships, and MPEC 65/INF.10 discussed about their air pollution and energy efficiency [45]. In addition, IMO published guidelines that contained safety concepts for using gas as ship fuel, including resolution MSC.285 (86) [42]. Besides, there were many concerns about Sulphur content of fuels for shipping around the world.[4] IMO adopted a resolution to update Annex VI of MARPOL, i.e., a convention on air emission control for ships in 2008, and it was revised on July 1, 2010; there Sulfur content in marine fuels was reduced from 4.5% to 3.5% at the worst condition. 2020-2025 perspective is to decrease it as low as 0.5% worldwide as shown in Fig. 2[5] [46].

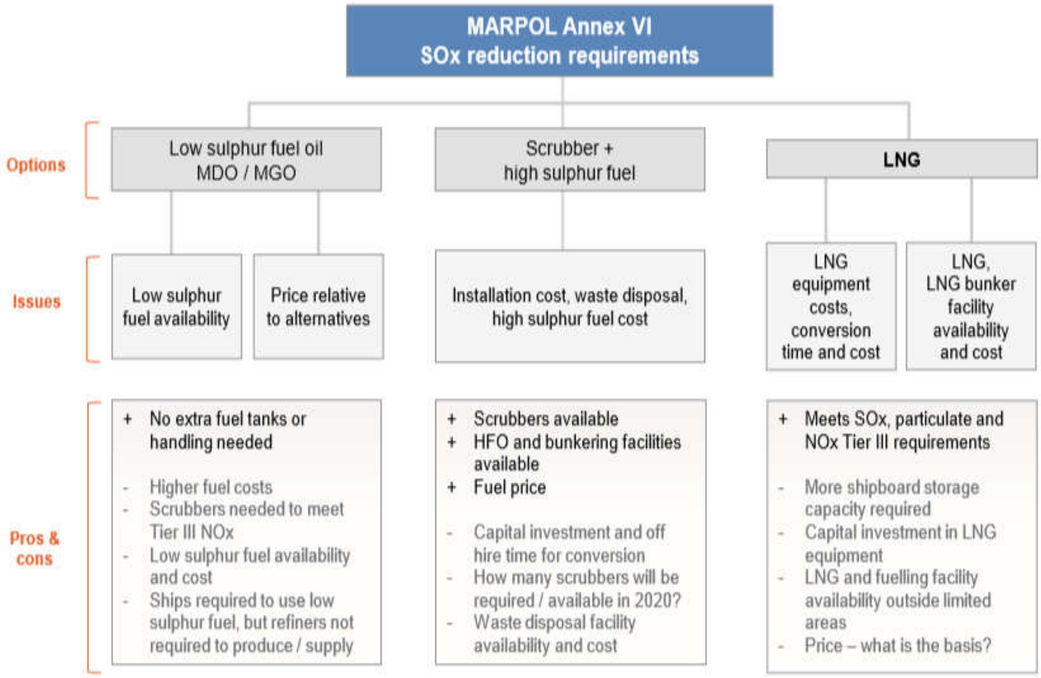

Fig. 1: MARPOL Annex VI – SO_X reduction alternatives [47]

NO_x emissions, as other environmental pollutant, shall be 80%, reduced by 2020 in new-built ships [35].

Furthermore, European Commission[3] published an amendment which enforced ships to lower the contribution of CO_2 emissions in maritime transport up to 40% in 2050 compared to 2005 and also 50% of road freight would be shifted to rail and sea transportation [48]. All these regulations are major key factors leading to the use of LNG as marine fuel and catchy enough to be used [49].

Fig. 2: IMO restrictions for SO_X emissions [35]

1. IMO Policies and Practices Related to the Reduction of Greenhouse Gas Emission from Ships.
2. Interim Guidelines for Voluntary Ship CO2 Emission Indexing for Use in Trials.
3. Roadmap to a Single European Transport Area

4. From 1 January 2015, new regulations on the Sulphur content of fuel for shipping in the Baltic Sea, the North Sea and the English Channel will come in force. Accordingly, the Sulphur content has to be decreased from 1.0 % to 0.1 %, setting the competitiveness of short sea shipping under pressure compared with land-based transport and especially trucks [46].
5. It also introduces the possibility for countries to enact more restrictive rules in the so-called Sulfur Emission Controlled Areas (SECA).

To overcome the aforementioned concerns, IMO has issued restrictions on GHG emissions that were compulsory in 2015 in the ECA and will become mandatory worldwide since 2020. For conformity with rules and restrictions, one of the best possible procedures is to consume LNG because of its substantial share of the world bunker markets, environmental benefits, and economic privileges in many aspects.

Beside IMO Restrictions, EU[1] [50] has updated former directive, called directive 2012/33/EU, which was in fact the development of the first implemented in the Sulphur Directive (1999/32/EC) [48 and 51]. This directive was related to the sulfur content of marine fuels in Europe which aligned with IMO Annex VI[2]. ISO/TC 67/WG 10 PT1 (ISO/TS 18683:2015) also offered complimentary guidelines for systems and installations that supplied LNG for ships [52 and 53]. In the United States, Maritime Environmental and Technical Assistance Program (META) is actively working to force consideration of the environmental issues (Focusing on emerging environmental issues that impact air and water quality) in the maritime industry. Developed in 2010, META was a research and demonstration program housed within the Maritime Administration's Office of Environment (MAOE) [41].

2.2. Environmental Assessment

2.2.1. Assessment of Emissions of Various Fuels

Ship emissions are currently a hot environmental issue which includes the emission of various gases and particles with significant contribution on GHG emissions. 2.7% of the global CO_2 emission in 2007 was produced by international shipping that unfortunately made the most severe damage to the environment and human health [9].

The marine fuel oils generated in a refining process are residual fuel oil, commonly referred to HFO and distillates, which are further divided into MDO and MGO. One of the main differences between the marine fuel oils is viscosity [54]. Table 1 shows the characteristics of marine fuel oils according to ISO 8217:2017 [55] standard and depicts that HFO, MDO, and MGO are very close to each other regarding density and flashpoint, and none are comparable with LNG in case of energy and sulfur content s shown in.

Table 1: The characteristics of marine fuel oils [55]

Characteristics	Limit (max/min)	HFO	MDO	MGO
Viscosity[3] at 40^0 C (mm^2/s)	Max	10.00-700.0[4]	11.00	6.000
Viscosity at 40^0 C (mm^2/s)	Min	-	2.000	3.000
Density at 15^0 C (kg/m^3)	Max	920.0-1010.0	900.0	890.0
Flash point (^{0}C)	Min	60.0	60.0	60.0
Ash[5] (%m/m)	Max	0.040-0.150	0.010	0.010
Vanadium (mg/kg)	Max	50-450	n.d.	n.d.
Sodium (mg/kg)	Max	50-100	n.d.	n.d.
Aluminum plus silicon (mg/kg)	Max	25-60	n.d.	n.d.

Table 2: Energy and sulfur content of marine fuel oils [56 and 57]

Fuel Type	Energy MJ/kg	Sulfur content
IFO 380[6]	40.6	3.5%
LSHFO 380[7]	40.6	1% or 1.5%
MDO	42.7	0.2 %
MGO	42.7	0.1% - 0.05%
LNG	49.2-49.5	0%

1. The Commission's 2011 Transport White Paper includes a high-level target to reduce EU CO2 emissions from maritime bunker fuels by 40% by 2050 (50% if feasible) [50].
2. The European commission published a draft new directive recently that aimed replacing old fuels with the alternative clean fuel and strengthening its infrastructure. In this draft directive, LNG introduced as a preferred fuel for marine and heavy-duty transport [35].
3. The viscosity is one property used as an indicator of fuel quality. Fuels with low viscosity are more fluent compared with fuels with high viscosity. Generally, HFOs with higher density have a higher viscosity than marine distillates.
4. Includes the residual fuels: RMA10, RMB30, RMD80, RME180, RMG180, RMG380, RMG500, RMG700, RMK380, RMK500 and RMK700. The number after each set of letters represents the maximal viscosity of the fuel oil. In general, RMA10 represents the lowest value and RMK700 the highest. Values for the other residual fuel oil types are located in between.
5. Ash content different material such as sand, silicon, sodium, and other particles that reduced performance of engine and polluted areas.
6. It is a mix of 88% of residual oil and 12% of distillate oil.
7. Residual fuel with low sulfur content.

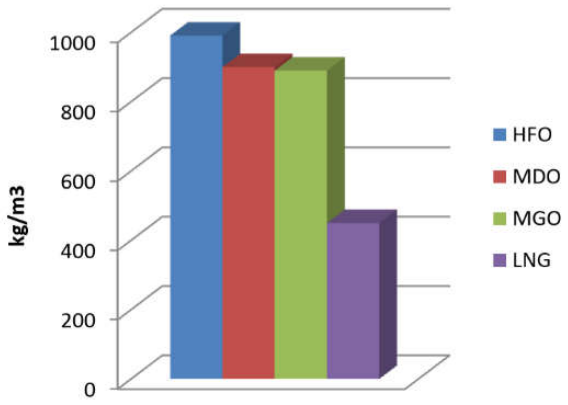

Fig. 3: Density of LNG and other fuels [58]

Figure 3 shows that not only does LNG have a lower energy density compared with conventional fuel oils, but also it, in a normalized condition, possesses about half the energy density of HFO. Fig. ***3*** also depicts the differences between the energy density of normalized fuel and LNG.

For neutralizing LNG density problem, building larger tanks with larger volumes than those required for HFO, MDO, and MGO is an obligation. The key point to the use of LNG as a fuel for combustion in ships is satisfying safety requirements [9].

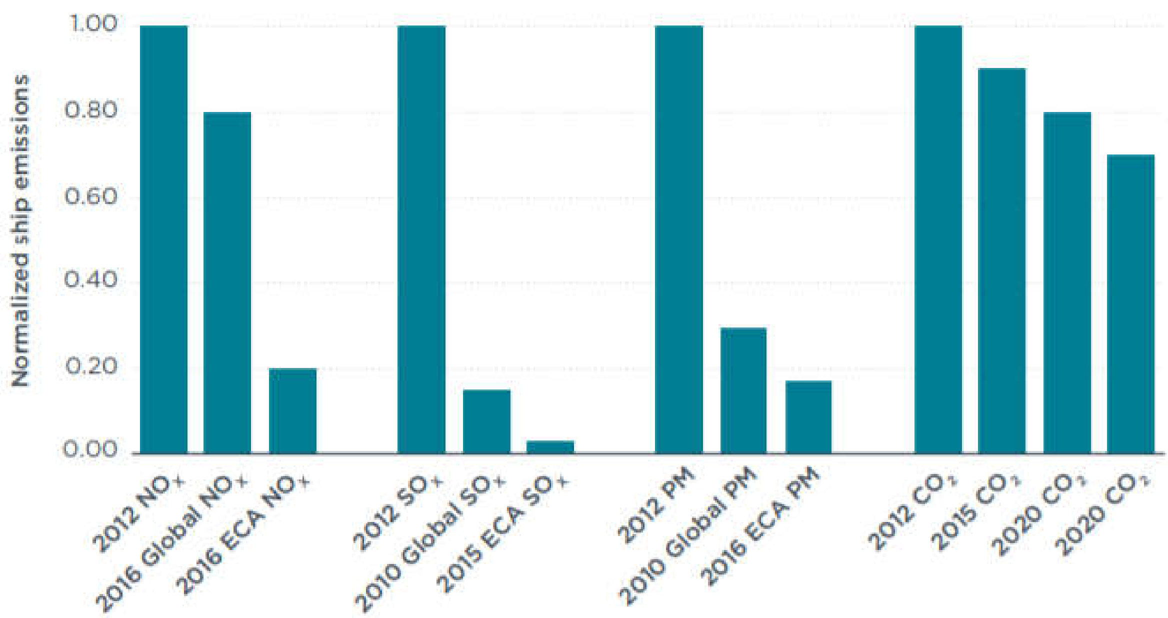

Fig. 4: Required NO_x, SO_x, PM, and CO_2 emission reductions to meet new shipping vessel engine and fuel requirements in 2015–25 time frame [59]

Another important issue about ship's fuel is CO_2 emission. The Energy Efficiency Design Index (EEDI) standards for ships confines ship CO_2 emissions. The standards require that new ships reduce their CO_2 per dry-weight tonnage capacity by 10, 20, and 30 percent until 2015, 2020, and 2025 respectively [59] (Fig. ***4***). It can be concluded that those ships that only use cleaner fuel, e.g., LNG, and, thus, produce lower emissions will be able to travel, especially in ECA.

Gas emission of any fuel depends on many factors. In the sea or ocean, it is directly related to the type of ships and engines used as a propulsion system and the chosen path. For medium ships that use Lean-burn gas engines and spark ignited engines, the average of various emissions of different fuels are shown from Fig. ***5*** to Fig. ***8***.

It can be deduced from the above figures that the percentage of emission reductions of LNG compared with HFO are as follows:

SO_x = 100%

NO_x = 90-93%

CO_2 = 15-20%

PM = 100%

Although LNG has many environmental benefits, it contains methane which has negative effects on the reduction of GHG when some incomplete combustion happens. The considering of the effects of potential methane slips leads to the reduction of net greenhouse gases up to about 15 % when LNG is used as ship fuel. Another important thing which relates to the emissions of LNG is to consider the total amount of emissions which includes extraction, processing, transport, storage, and final usage as an engine fuel.

2.2.2. Assessment of Spillage

One of the major environmental problems of fuel oils is spillage. Multiple factors such as the type of oil, the rate & amount of spillage, biological, the physical and also economic characteristics of the spill location, have great impacts on the environment, especially that around the marine field. Due to their specific gravity, they could easily spread over sea waters by waves and make the sea polluted. Another challenge is laid in modeling spillage phenomena since the movement prediction of spilled fuel oils are so hard. Fuel oils are generally less toxic than crude oils, but they have severe influences on marine life and the environment. Based on the cost per tons calculation, it was shown that heavy fuel oil spills are the most expensive pollution phenomenon to clean up [60]. On the contrary, LNG vapor is lighter than air, and if the resultant flammable mixture of vapor and air, after spillage of LNG on the ground or water, does not meet an ignition source, it will evaporate and, consequently, dissipate into the atmosphere, and there will be no significant harms to the environment. Even if large volumes of LNG are released on water, it may vaporize very quickly causing a rapid phase transition [60].

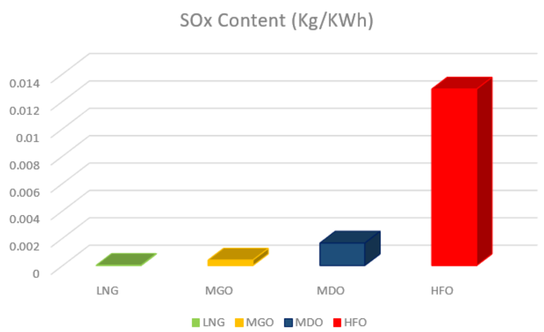

Fig. 5: SO_X Emissions of LNG, MGO, MDO and HFO of medium ships [59]

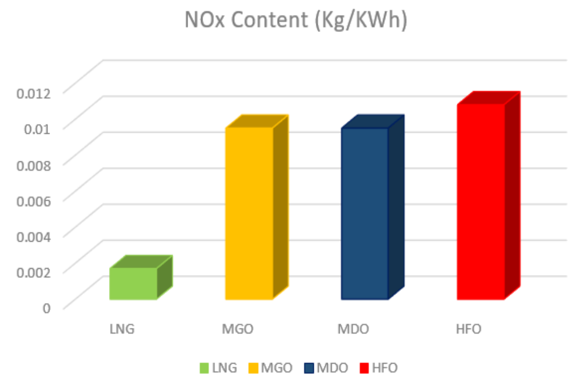

Fig. 6: NO_X Emissions of LNG, MGO, MDO and HFO of medium ships [59]

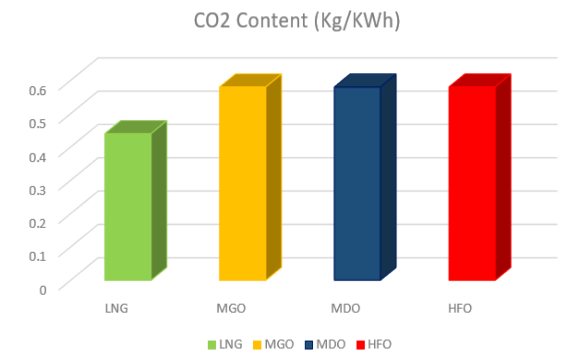

Fig. 7: CO2 Emissions of LNG, MGO, MDO and HFO of medium ships [59]

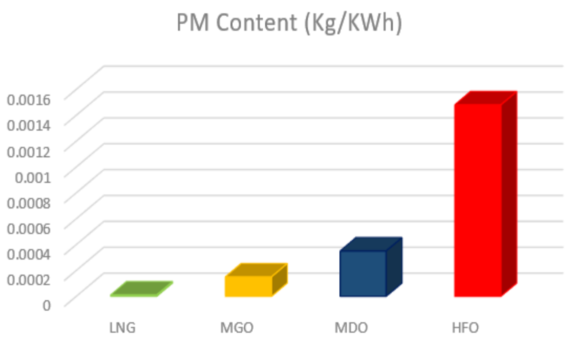

Fig. 8: PM Emissions of LNG, MGO, MDO and HFO of medium ships [59]

2.3. Cost and Economic Assessment

2.3.1. International Historical Price Development

In the marine industry, fuel choice has a long historical background. In 1940s and by shifting from coil to oil at large scale in this industry, marine engines were developed to operate with a cheap residual fraction from refined crude oil or heavy fuel oil [62]. But this advantage has gradually been altered. Since the demand for energy is directly related to its price, it seems necessary to analyze fuel price changes in recent years. According to BP statistical review of the world energy, the crude oil price in recent years[1] is as high as the very beginning of oil industry as shown in Fig 9.

2.3.2. LNG and Fuel Price

By supplying a significant amount of gas by the United States in mid-2010, gas price dropped. It also became more competitive and started to decelerate from oil prices.[2] Since the price of crude oil and natural gas are interdependent, the reduction of crude oil price leads to the fall of natural gas price; for example, in March 2016, the average delivered price into Japan was below $7.00 per MMBtu.[3] This drop-in price also happened in Europe. By June 2016, the natural gas price for the UK's NBP was $4.12 per MMBtu, and the continental price was very similar. The price of natural gas at Henry Hub was $2.15 per MMBtu. The lower price for customers ranges from $4.72 to $5.47 for natural gas processed at Sabine Pass, and $5.97 for gas processed at Corpus Christi [63]. demonstrates the price of LNG from 1986 to 2016 and compares it with the price of crude oil in those years; Fig. 11 shows LNG price fluctuations in various import terminals [6]. In addition, Fig. 11 presents the price of gas and LNG at different terminals. It can be inferred that the current price of LNG is a little higher than its initial price during the last two decades[4] [64].

US dollars per million Btu	LNG Japan CIF[1]	LNG Japan Korea Marker (JKM)[2]	Natural gas Average German Import Price[3]	Natural gas UK (Heren NBP Index)[4]	Natural gas Netherlands TTF (DA Heren Index)[4]	Natural gas US Henry Hub[5]	Natural gas Canada (Alberta)[5]	Crude oil OECD countries CIF[6]
1987	3.35	–	2.55	–	–	–	–	3.09
1988	3.34	–	2.22	–	–	–	–	2.56
1989	3.28	–	2.00	–	–	1.70	–	3.01
1990	3.64	–	2.78	–	–	1.64	1.05	3.82
1991	3.99	–	3.23	–	–	1.49	0.89	3.33
1992	3.62	–	2.70	–	–	1.77	0.98	3.19
1993	3.52	–	2.51	–	–	2.12	1.69	2.82
1994	3.18	–	2.35	–	–	1.92	1.45	2.70
1995	3.46	–	2.43	–	–	1.69	0.89	2.96
1996	3.66	–	2.50	1.87	–	2.76	1.12	3.54
1997	3.91	–	2.66	1.96	–	2.53	1.36	3.29
1998	3.05	–	2.33	1.86	–	2.08	1.42	2.16
1999	3.14	–	1.86	1.58	–	2.27	2.00	2.98
2000	4.72	–	2.91	2.71	–	4.23	3.75	4.83
2001	4.64	–	3.67	3.17	–	4.07	3.61	4.08
2002	4.27	–	3.21	2.37	–	3.33	2.57	4.17
2003	4.77	–	4.06	3.33	–	5.63	4.83	4.89
2004	5.18	–	4.30	4.46	–	5.85	5.03	6.27
2005	6.05	–	5.83	7.38	6.07	8.79	7.25	8.74
2006	7.14	–	7.87	7.87	7.46	6.76	5.83	10.66
2007	7.73	–	7.99	6.01	5.93	6.95	6.17	11.95
2008	12.55	–	11.60	10.79	10.66	8.85	7.99	16.76
2009	9.06	5.28	8.53	4.85	4.96	3.89	3.38	10.41
2010	10.91	7.72	8.03	6.56	6.77	4.39	3.69	13.47
2011	14.73	14.02	10.49	9.04	9.26	4.01	3.47	18.55
2012	16.75	15.12	10.93	9.46	9.45	2.76	2.27	18.82
2013	16.17	16.56	10.73	10.64	9.75	3.71	2.93	18.25
2014	16.33	13.86	9.11	8.25	8.14	4.35	3.87	16.80
2015	10.31	7.45	6.72	6.53	6.44	2.60	2.01	8.77
2016	6.94	5.72	4.93	4.69	4.54	2.46	1.55	7.04
2017	8.10	7.13	5.62	5.80	5.72	2.96	1.60	8.97

[1]Source: EDMC Energy Trend.
[2]Source: S&P Global Platts ©2018, S&P Global Inc.
[3]Source: 1987-1990 German Federal Statistical Office, 1991-2017 German Federal Office of Economics and Export Control (BAFA).
[4]Source: ICIS Heren Energy Ltd.
[5]Source: Energy Intelligence Group, Natural Gas Week.
[6]Source: ©OECD/IEA 2018, Oil, Gas, Coal and Electricity Quarterly Statistics www.iea.org/statistics.

Table 3: Prices of LNG during 1986 until 2017 and in compare with crude oil [6]

1. The price of oil in 2011.
2. Although all long-term contracts for natural gas transported as LNG in Asia have their price contractually tied to crude oil.
3. As the same way and by estimating of the Japanese Customs Cleared linked price for natural gas, given a Japanese Customs Cleared price of $37, will also be under $7.00 per MMBtu [63].
4. One of the most important goals of using LNG is the willingness for some countries to reduce their dependence on oil imports

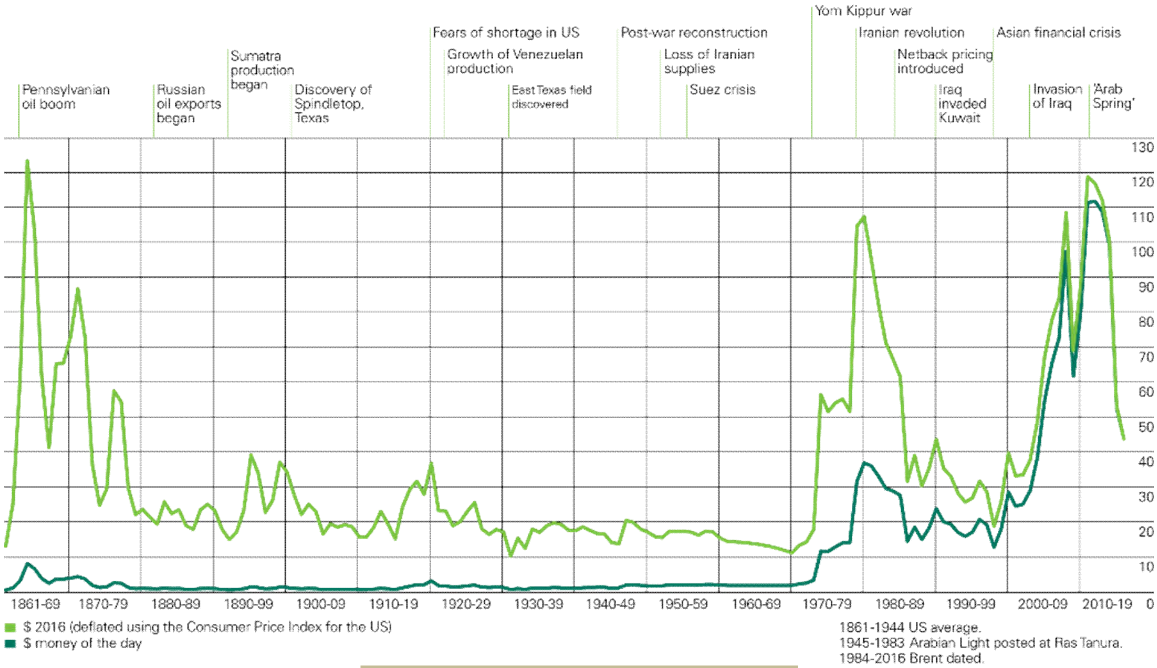

Fig. 9: Oil price- BP historical data [6]

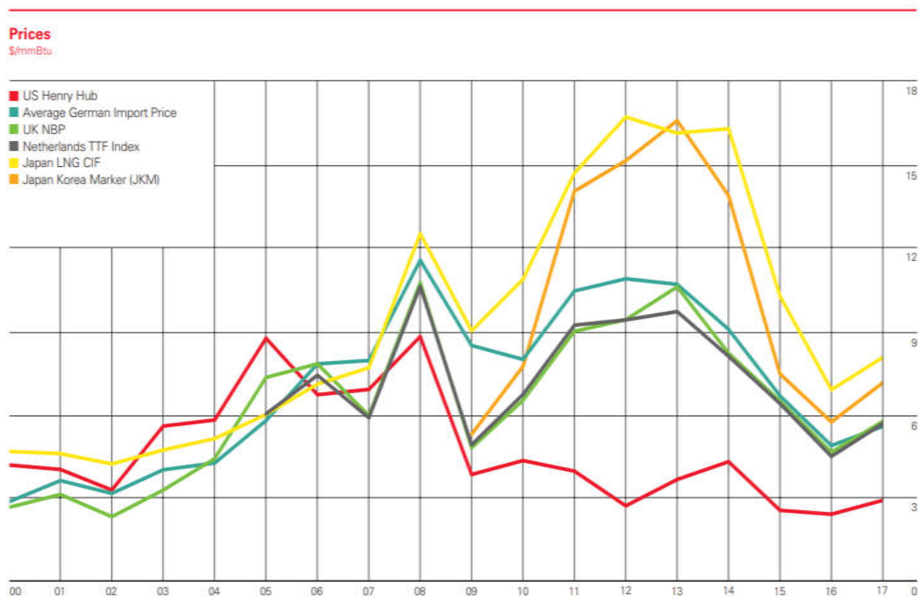

Fig. 10: Price fluctuations of LNG in different import terminal (1989-2017)[1] [6 and 65]

1. The decline in oil prices and growing weakness in Pacific demand led all global LNG price markers to fall in 2015, from an average $15.60/MMBtu in 2014 to $9.77/MMBtu in 2015 [65].

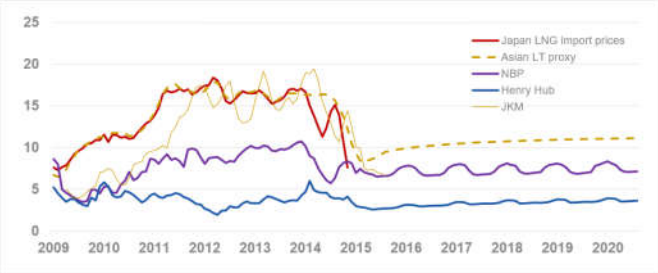

Fig. 11: Gas and LNG price by different import terminal ($/MMBtu) [66]

Table 4 describes the projections of regional imbalances of natural gas according to BP's 2016 outlook to 2035[1] [67]. It is noteworthy that Russia is included within the Europe & Eurasia region, and Australia[2] is included within the Asia Pacific region as defined by BP.

In 2015, global LNG imports increased by 2.5% (6 MT), reaching its highest level ever [68]. The LNG producing countries and the target terminals with an import volume ratio of LNG are depicted in Fig. 12.

Regional imbalance (production minus consumption) - mtpa	1990	1995	2000	2005	2010	2014	2015	2020	2025	2030	2035
North America	4.06	(18.16)	(21.80)	(23.33)	(20.33)	(0.02)	1.50	72.11	73.76	139.82	138.77
S & C America	0.23	0.39	4.52	12.27	10.77	3.63	1.33	(5.52)	(11.99)	(22.04)	(29.93)
Europe & Eurasia	(9.14)	(27.84)	(37.52)	(51.40)	(73.52)	(5.34)	(22.28)	(18.43)	4.44	(0.07)	(10.91)
Middle East	5.34	5.19	15.27	30.78	68.72	100.26	93.42	91.06	89.52	85.43	88.25
Africa	21.50	27.89	53.01	67.71	78.32	60.91	55.48	53.13	45.52	60.03	92.59
Asia Pacific	(1.43)	(1.72)	(13.92)	(25.65)	(56.69)	(108.79)	(106.85)	(127.34)	(213.33)	(260.66)	(287.49)
Total Natural Gas Imbalance	20.56	(14.25)	(0.43)	10.39	7.27	50.64	22.59	65.01	(12.08)	2.51	(8.73)

Table 4: Projected Regional Natural Gas Imbalances [6]

The above figures show that Qatar and Indonesia are the largest LNG exporters in the world while Japan is the greatest consumer among other countries.

LNG prices in USA and Europe (based on energy content) are comparable with HFO and MGO. The prices of these fuels at six years interval are drawn in Fig. 13.

2.3.3. Fuel Price Determining Scenario

Obviously, the fuel price entirely depends on oil and gas price; however, it is expected that LSHO and MGO prices increase faster than LNG and HFO, while demands for LNG are increasing strongly. The starting price for fuels at 2010 were assumed as below:

HFO= 650 USD/T (15.3 USD/mmBTU), MGO= 900 USD/T (21.2 USD/mmBTU), LNG= 13 USD/mmBTU which includes small-scale distribution costs of 4 $/mmBTU.

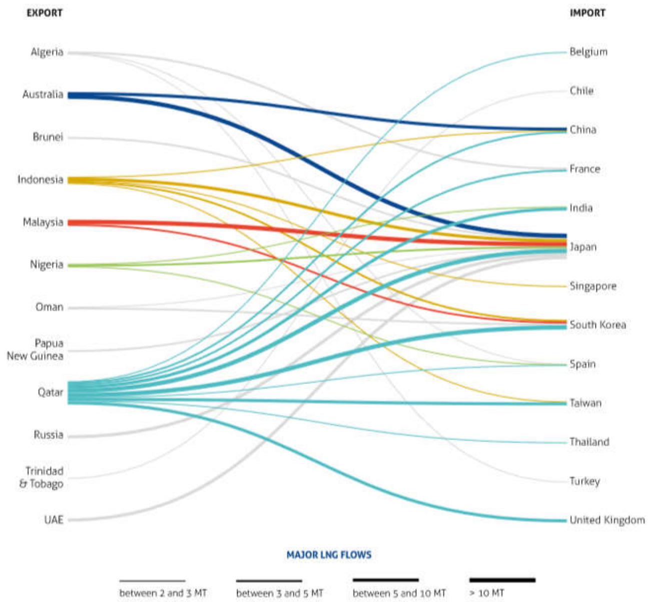

Fig. 12: Major LNG Flows between export and import terminals [68]

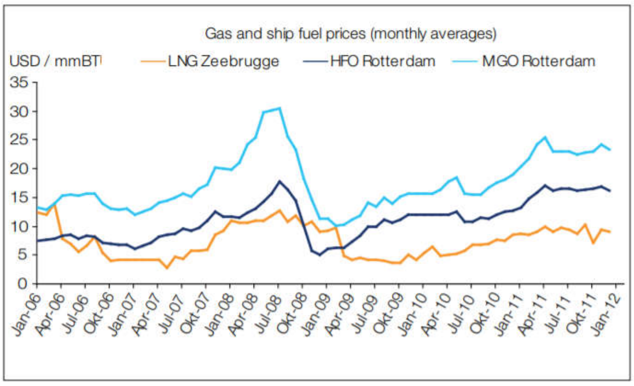

Fig. 13: Prices of LNG, HFO and MGO as ship fuel in period time of six years [69]

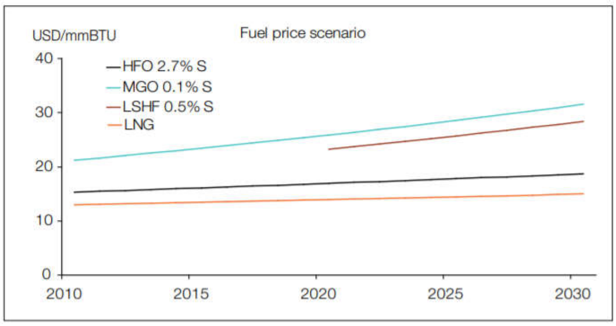

Fig. 14: Price of different fuels (between 2010 to 2030) [10]

1. The International Energy Agency has estimated that worldwide investments in LNG liquefaction, shipping, and regasification may total $252 billion between 2001 and 2030 [67].

2. Australia will become the largest exporter of natural gas in the form of LNG by 2018.

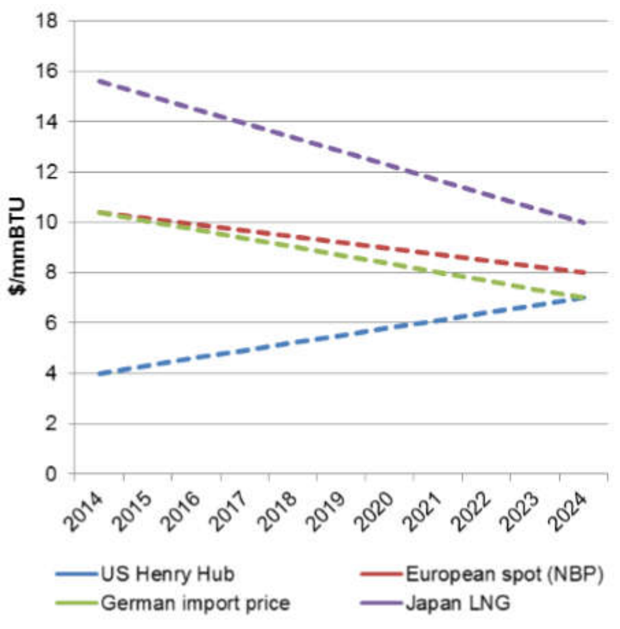

Fig. 15: The future gas price scenario in different regions [43]

In Fig. 14 the price of various types of fuels are predicted[1]. Generally, by reducing the amount of Sulphur contents, the fuel price increases. MGO is also far more expensive than HFO. Moreover, it appears that LNG can be the most cost-effective option among the aforementioned fuels in the future [40]. In 2014, it was predicted that in 2015 the bulk and container segments' favorite fuel would be LNG [70 and 71]. In Fig. 15 the scenario of future gas price in different regions is illustrated.

Fig. 16. shows the variation of Marine fuel prices during the past few years and predicts their price in near future. Furthermore, it depicts the economic advantages of LNG fuel. It could also be inferred that applying more rigid environmental restrictions extends LNG's popularity and ultimately decreases the LNG price.

2.3.4. Payback Time

Payback time for smaller vessels (2,500 TEU and 4,600 TEU) is shorter than that for 8,500 TEU vessels or higher [10], and the reason is relatively smaller investment requirement for the LNG system of large vessels. Considering the global prices in 2015, Fig. 17 shows the payback time for LNG system of smaller vessel is about two years.

LNG tank cost is another decision concern [10]. Considering a type C tank for 2,500 TEU and a type B prismatic tank for larger vessels, specific costs for LNG tank system are presented in Fig. 18. The payback time even for larger ships is reasonable.

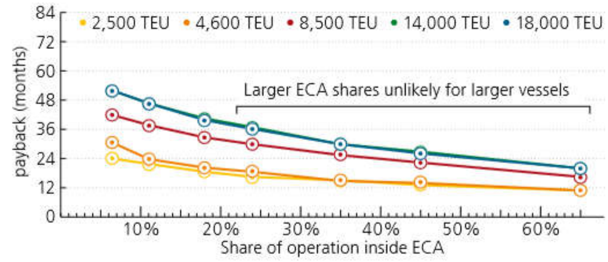

Fig. 17: Payback for LNG system (starting in 2015) [10]

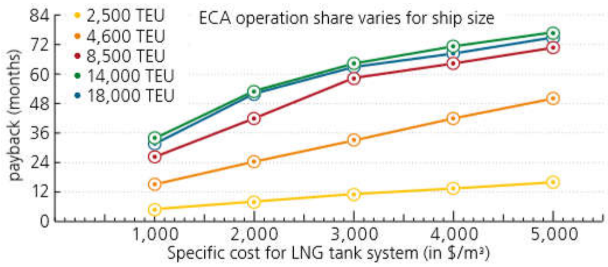

Fig. 18: Payback for LNG system (starting in 2015) [10]

3. SWOT Analysis

After all, based on the results of this study, SWOT analysis can justify all overt and covert hints of exploiting LNG, as an alternative marine fuel concluded during this study. Table 5 lists the SWOT analysis of LNG fuel.

Table 5: SWOT analysis result

Strengths	- Most flexible of all fossil fuels; - Fastest growing energy source in the world; - SO_X emission reduction from 90% to 95%; - Zero sulfur content; - Reduction of CO_2 emission from 20% to 25%; - Lower NO_X emission of LNG than oil; - Approximately zero PM emission of LNG compared with HFO; - Expansion of existing current and future ECAs; - Lower maintenance and operating costs.
Opportunities	- 52.5 years more life span than oil resources; - Environmentally friendly and correspondence with the restrictions and emissions treaties and regulations that came into force;

1. It is assumed that these distribution costs do not increase over time

	- Most cost-effective fuel among the current fuels in the future; - Much less maintenance cost of engines; - Formidable rival with oil products for both marine and heavy- duty transportation.
Weaknesses	- Lower energy density compared with conventional fuel oil; - Much lower density than MDO; - Inability for optimizing space on board due to cylindrical fuel tank shape; - 15-20% extra investments compared to standard ship for LNG tank, control room, piping, fuel system, engine, …); - Larger LNG fuel tank (between 3 and 4 times larger than old fuel tanks used for MDO or HFO); - Negative effect on reduction of GHG if an incomplete combustion of methane in LNG happens; - Restricted cargo capacity
Threats	- Operational and regulatory risks; - Lack of LNG infrastructure; - Skilled and trained crew; - Despite all predictions the price of LNG increase

4. Conclusion

This paper provides a complete survey which includes codes, standards, regulations, the environmental and economic aspects of LNG as an alternative marine fuel.

The assessment of three most influencing factors (economic, restriction, and regulation and environmental aspects) reveal that LNG is an appropriate competitive marine fuel. Among these factors, the overall economic aspect is the most challenging issue in selecting marine fuel. Hence, not only the competitive price of LNG is impressive for ship owners but also payback time issue is an encouraging factor for owners to convert ships to operate with LNG. In addition, economic analysis deduced that LNG is a top ranked fuel among marine fuels.

To reduce the environmental burdens of the ships' exhaust gases, air emission restriction, and uninterrupted narrowing down regulations that dictate ships to diminish SO_X, NO_X, CO_2 and PM emission, LNG is found to be the most suitable choice as a marine fuel which offers significant pollutant emission advantages. LNG noticeably satisfies all current and proposed emission restrictions and regulations. (Table 6)

	Environmental features compared to the traditional HFO alternative				Factors influencing viability compared to the traditional HFO alternative		
Alternative	SO_X	NO_X	PM	CO_2	Cargo capacity	Capital Investment	Operating costs
LNG	++	++	++	+	Restricted	Very high	Low
MGO	+	-	-	-	Not restricted	Low	Very high
MDO	+	-	-	-	Not restricted	Low	-
HFO/ Scrubber	+	--	+	-	Slightly restricted	High	Medium

++ Very good, + Good, - Bad, -- Very bad.

Table 6: Comparing LNG and other marine fuels

Abbreviations and Acronyms

CO_2 = Carbon Dioxide
DF = Dual Fuel
ECA = Emission Control Area
EEDI = Energy Efficiency Design Index
EU = European Union
GHG = Green House Gas
GWP = Global warming potential
IFO = Intermediate Fuel Oil
IGF = International Gas Union
IMO = International Maritime Organization
ISO = International Organization for Standardization
HFO = Heavy Fuel Oil
LBG = Liquefied Bio Gas
LNG = Liquefied Natural Gas
LSHFO = Low Sulfur Heavy Fuel Oil
MAOE = Maritime Administration's Office of Environment
MARPOL = International Convention for the Prevention of Pollution from Ships
MDO = Marine Diesel Oil
MEPC = Marine Environment Protection Committee
META = Maritime Environmental and Technical Assistance Program
MGO = Marine Gas Oil
MMBTU = 1 million Btu
MTPA = Million Tons per Annum
NG = Natural Gas
NO_x = Nitrogen Oxides
NPB = National Balancing Point
OECD = Organization for Economic Co-operation and Development
PM = Particulate Matter

SCR = Selective Catalyst Reduction
SECA = Sulfur Emission Control Area
SO_X = Sulfur Oxides
SWOT = Strength, Weaknesses, Opportunities and Threat
TCM = Trillion Cubic Meters
TEU = Twenty-foot equivalent unit
ZEP = Zero Emission Fossil Fuel Power Plants

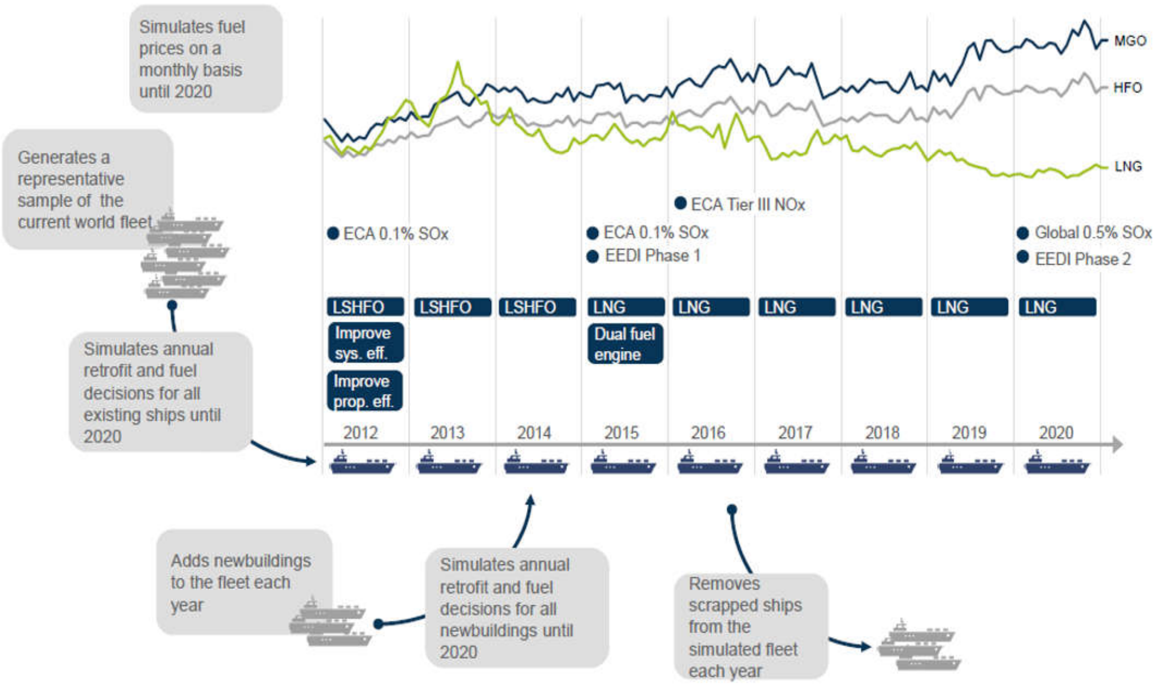

Figure 16: Quick view of marine fuel price vs environmental restriction [43]

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