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The future of the fuel in the marine industry

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ABSTRACT

The marine propulsion plants of modern commercial marine vessels are based on huge two-stroke low-speed engines, which consume very low-quality residual fuel. As a result of heavy fuel combustion, emissions of harmful (toxic) pollutants into the atmosphere, particularly sulfur oxides, occur. Consequently, such acts are subject to the laws and regulations norms governing their use in national waters, the European Union and the whole world. On the other hand, ship owners who do not comply with prescribed standards are subject to high fines and therefore the maritime economy is looking for new, cleaner sources of energy in shipbuilding. Authors based on the analysis of literature and legislation present possible solutions to the problem mentioned.

Keywords**:** fuel, LNG, hydrogen, biofuels, maritime economy, sulfur oxides, alternative energy sources, MARPOL Convention

1. INTRODUCTION

The source of power of marine combustion engines is fuel derived from crude oil, differing in both source of origin and physicochemical properties. These marine fuels are divided into three basic groups: marine gas oils (*MGO*), marine diesel oils (*MDO*) and heavy fuel oils (*HFO*) [1].

The highly viscous, residual product of crude oil refining – HFO - are the largest group of fuels used to propulsion marine engines. HFO are composite fuels, whose main constituents are residues derived from equal technological processes of crude oil processing such as conservative distillation and cracking. In order to reduce the viscosity of the component obtained, some amounts (about 5%) of distillate fuels - mainly gas oils - are added. These oils require careful cleaning, usually by two-stage centrifugation, with high temperature of separation [2].

In maritime transport, the most important organization that determines all matters relating to life at sea is the International Maritime Organization (*IMO*). One of the most important IMO documents is the Convention on the Prevention of Pollution from Ships (*MARPOL*), Annex VI, which regulates the pollution of the atmosphere by ships, especially those derived from engine exhaust [3].

2. RESTRICTIONS FOR FUELS - ANNEX VI MARPOL

Annex VI of the MARPOL Convention consists of 19 regulations and several so-called supplements. One of the most important parts is Regulation 2, which defines ecological concepts such as emissions (i.e. substances emitted to the atmosphere), ozone depleting substances, or Sulfur Emission Control Area (*sECA* – Figure 1). Is the area where sulfur oxides (SO_X) emission measurement is required to prevent, reduce and control air [3].

The most important part of the Annex is Regulations 12-18 (Chapter three), which deal with the requirements for the control of emissions of sulfur oxides (SOx), nitrogen oxides (NOx), volatile organic compounds (VOCs) and burning on the ship with incinerator [3].

The Annex VI to the MARPOL Convention is inserted in the Annex described above. It contains primarily the limits on sulfur and nitrogen oxide emissions from ships. One of the biggest limitations in the 6th Annex is the introduction of sulfur content limits for marine fuel (Table 1). This limitation was quite radical, as the 1% sulfur content of the fuel has so far been set at 0.10%. The fuel corresponding to such a parameter in practice is much more expensive, up to 50% less than 1% sulfur fuel [3].

Table 1. Limits of sulfur content in fuel [4].

Date of limit introduction	Limits of sulfur content in fuel [% m/m]	
	SECA	Global
05.2005	1.5%	4.5%
07.2010	1.0%	
01.2012		3.5%
01.2015	0.1%	
01.2020*		0.5%

*The standard of 0, 5% sulfur in the fuel will be assessed by a special group of experts appointed by IMO in 2018, which will check the possibility of its introduction, due to future trends and availability of such fuel on the fuel market. In case of negative rating 0, 5% will only apply from 01.01.2025.

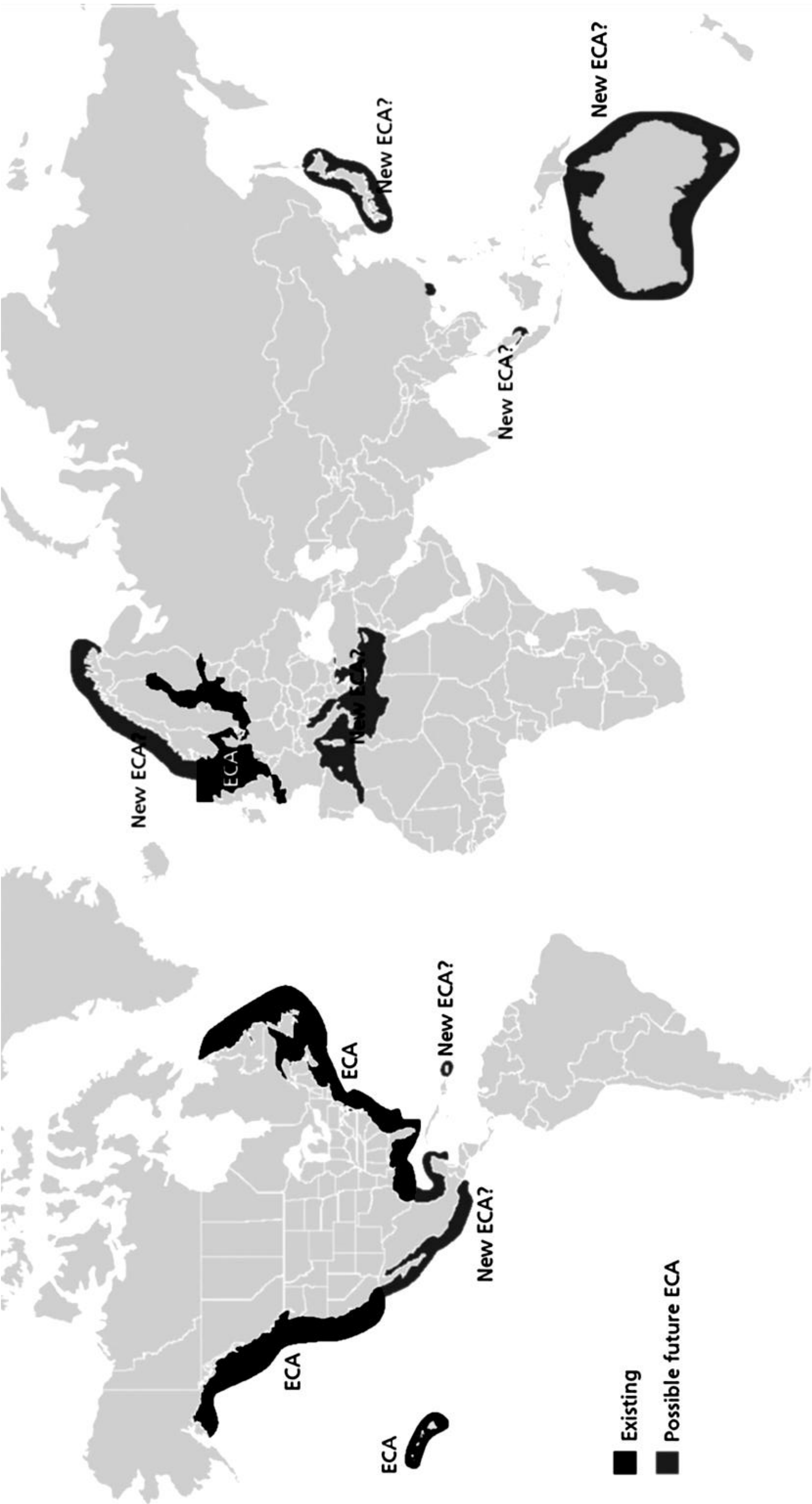

Figure 1. Existing and possible ECA zones based on [4]

3. THE FUEL ALTERNATIVES

Introducing by IMO restrictive sulfur emission limits, as described in second point, is a cause for concern among ship owners and ship operators who will most suffer by the immediate consequences of the new legislation. Today we can show the first ways of adapt to the new regulations (Figure 2). Temporary solutions are low sulfur fuels, unfortunately their cost is much higher than traditional fuels and they are characterized by worse lubricating properties. It is also possible to use exhaust gas treatment system, the so-called sulfur-reducing scrubbers, but the most "clean" energy sources are alternative fuels, such as Biofuels, Liquefied natural gas (*LNG*), and hydrogen. It seems that hydrogen will be likely to be most future [5].

Unfortunately, the use of any of mentioned methods is costly and, in some cases, there are additional restrictions [5] such as lack of developed infrastructure, technology, or too high a risk factor.

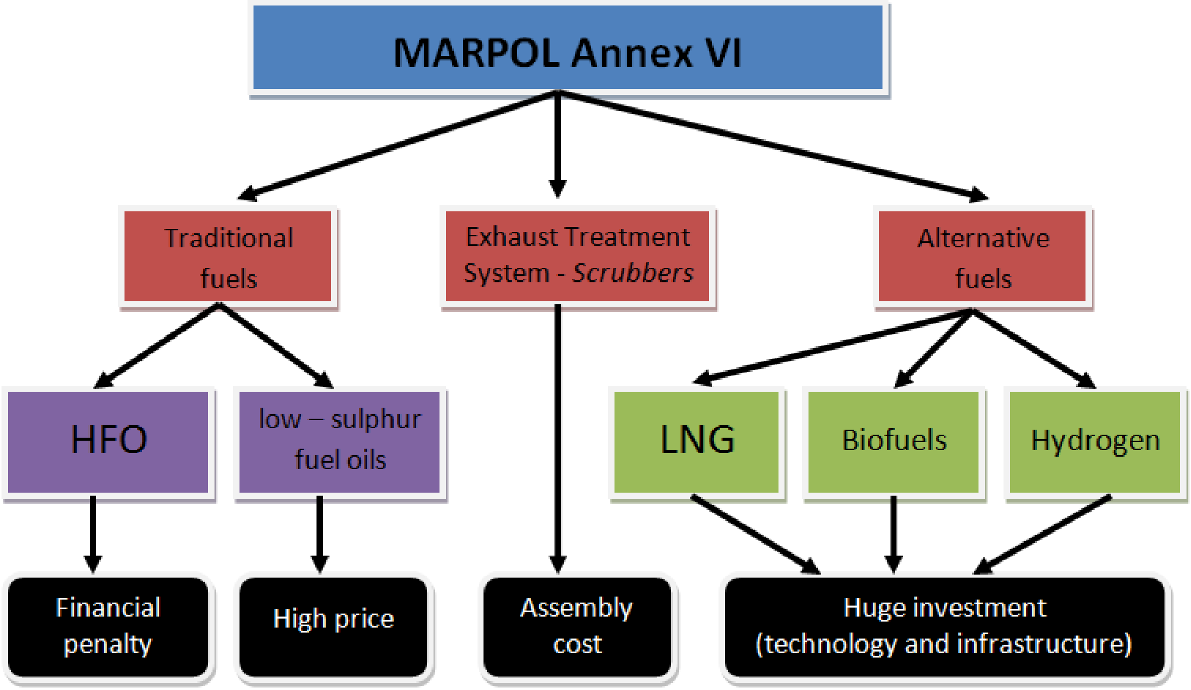

Figure 2. The directions of development of adaptation of ships to Annex VI of the MARPOL Convention (own elaboration)

3. 1. Scrubbers

Sulfur oxides form when the sulfur that is contained in the fuel reacts with oxygen, and more than 90% of the sulfur oxides produced by marine engines are sulfur dioxide [6]. SOx reduction technologies is a proven technology on land, so it can be safety used at sea.[6]. Gas scrubber is a technique in which sulfur oxides react with water and form sulphates. There are two types of cleaning units on the exhaust gas: open scrubber (seawater) and closed scrubber (freshwater). It is also possible to use combinations of both, e.g. closed in ports and sensitive areas such as the Baltic Sea and open at open ocean water [6].

The open system uses natural alkaline sea water to capture sulfur oxides. The amount of captured sulfur oxides depends on the alkalinity of the water. In the Baltic Sea, where alkalinity is low compared to the open sea, more seawater is needed to capture the same amount of sulfur oxides. An example of a seawater scrubber is shown in Figure 3 [6].

In a closed system the water is instead re-circulated with continuous addition of alkali, normally caustic soda. The following reaction occurs in a closed system with addition of caustic soda [6].

$$NaOH + SO_2\,(g) + \tfrac{1}{2}\,O_2\,(g) \rightarrow (Na^{+}) + (HSO_4^{-}) + H_20$$

To some extent the scrubber removes the particles and NOx. In the maritime scrubber tests, the particle reduction was 0 to 85%. Seawater is filtered before returning to the sea of sludge that should be treated on shore [6].

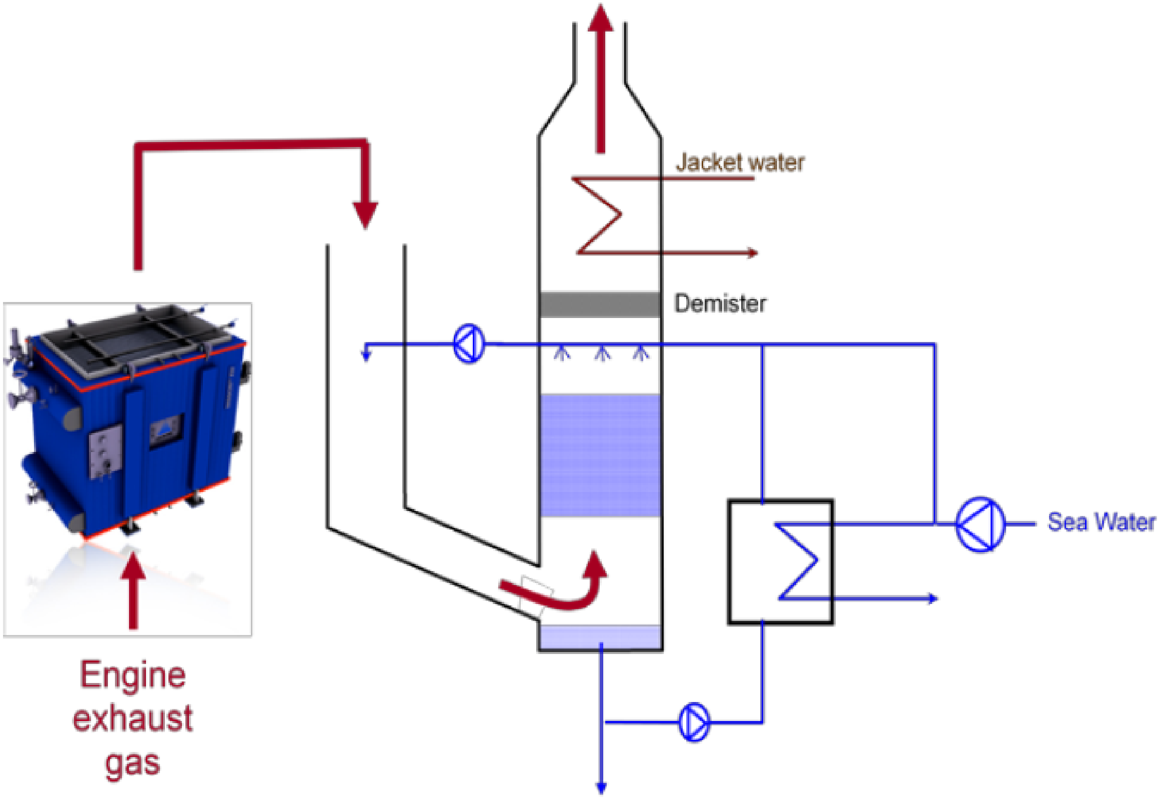

Figure 3. Exhaust gas seawater scrubber [6].

3. 2. LNG

In the case of alternative fuels, currently the most talked about is the use of LNG. These discussions are heated by the forecasts of classification societies, and the most enthusiastic Danish - Det Norske Veritas, claims that by 2025 up to 5,000 LNG units would be built [7]. The economic factor is quite an important aspect in favor of the extensive use of LNG as a shipping fuel. Firstly, the lower price and higher LNG calorific value compared to residual and distilled fuels (Table 2), which is associated with lower demand [11].

Table 2. Properties of different fuels [11][14][17].

	LNG	HFO	Diesel	Hydrogen
Density (kg m^{-3})	450	978	840	0,08
Auto ignition temperature (K at 1 bar)	810	678	553	858
Flame velocity (m/s)	0,4	-	0,3	2,7
Calorific value (MJ/kg)	119	40,6	42,7	49,55
Fuel carbon content (wt %)	75	86,3	85	0
Fuel hydrogen content (wt %)	25	10,7	15	100
Fuel oxygen content (wt %)	0	0	0	0
Fuel sulphur content (wt %)	0	2	<350 ppm	0

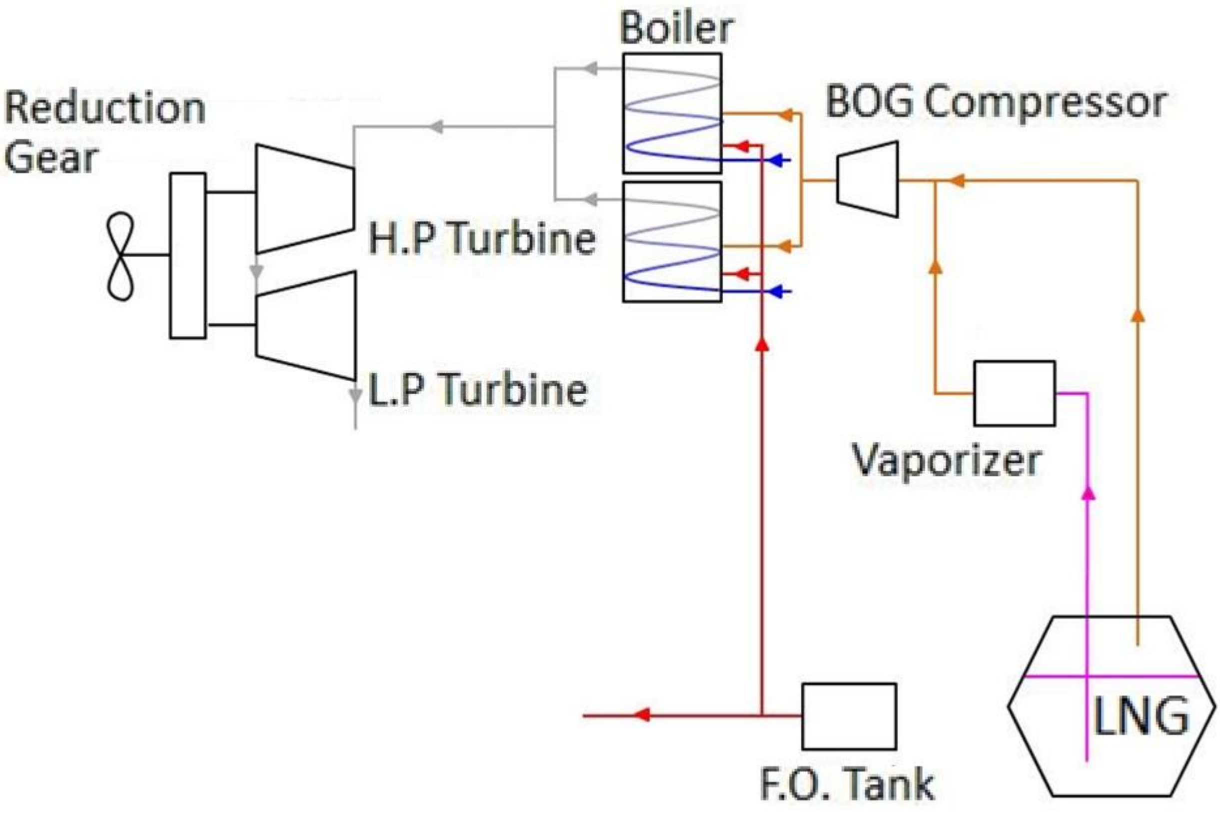

Figure 4. Double turbine installation diagram [10]

It is worth mentioning that the use of LNG in ship propulsion is not a completely new solution, as already in the 1960s methane vessels used to carry gas to power main propulsion [9]. Also for many years, the basic solution on LNG vessels were a system of two low- and high-pressure steam turbines powered by two boilers. LNG losses (*BOG – Boil-off gas*) in the form of steam from cargo tanks were compressed (by BOG Compressor) and then fed to boilers which create steam for propulsion of turbines (Figure 4) [10]. However, the use of LNG on a broader scale, in all types of ships, was initiated only at the beginning of the 21st century [9].

The largest engine manufacturers, such as MAN Diesel, Wärtsilä, Rolls-Royce and Mitsubishi Heavy Industries, are heavily involved in the popularization of LNG as fuel for vessels. They recommend two solutions for internal combustion engines: LNG or dual fuel engines. The first are single-fuel engines with spark ignition, which will be beneficial only in areas with well-developed network of bunker stations. Dual fuel engines consume gas as the main fuel and diesel as an additional fuel that initiates the ignition. The engine mode can be freely changed (gas - oil - gas), without stopping it, but is characterized by a complicated construction compared to traditional single - fuel engines [5].

The largest shipping companies are skeptical about the matter, according to Maersk (container ships owner), gas as a fuel for container ships will be a major alternative no quickly than 20 or 30 years. Due to technical barriers, as well as infrastructure. The most important technical hurdle for ocean units is the need for huge space for gas fuel tanks [8].

3. 3. Hydrogen

Hydrogen (H_2) is gas, which is regarded as an appealing source of energy for the further future. During it's combustion is non-polluting as its exhaust emissions produce nothing but water vapors [14]. The physical and chemical properties of H_2 are greater when compared with other fuels (Table 2) [12]. Hydrogen has special characteristics compared to hydrocarbon fuels, such as: wide flammability range, high flame speed, high infusibility, low minimum ignition energy, zero carbon content, and smaller quenching gap which provide more complete combustion [14]. Handling of hydrogen is dangerous because of its flammability and explosiveness in contact with oxygen, so it requires special precaution. Therefore, the purity and composition of hydrogen must be closely monitored and controlled.

There are several methods for producing hydrogen:

- Natural Gas Reforming - two methods such as steam methane reforming and partial oxidation. Both produce a synthesis gas, which is then reacted with additional steam to produce a higher hydrogen content gas stream;
- Gasification - process in which coal or biomass is converted into gaseous components by applying heat under pressure and in the presence of air and steam.
- Electrolysis - uses an electric current to split water into hydrogen and oxygen. This process needs a lot of supplied energy.

The use of hydrogen as a fuel can take place in three directions [20]:

- Fuel cells generating electricity then used for example in an electric motor. Conversion of hydrogen to electricity with fuel cells is usually more efficient than with internal combustion engines [22,23],
- The fuel that drives the internal combustion engine,

- Additive to the combustion process of commonly used fuels.

The concept of adding pure hydrogen to diesel engines is still at the research stage. However, it is already known that, due to the high self-ignition temperature, hydrogen cannot be applied directly to ignition engines without spark plug or glow plug. In addition, a hydrogen storage tank is required. These problems disappear when hydrogen is replaced with water or Brown gas (HHO), which does not need an external source of ignition and is produced and consumed by the engine at the same time [17-19,21].

The most important disadvantage of hydrogen is the low storage density as a fuel. For automotive applications this gas is often stored in pressurised vessels at either 350 or 700 Bar, but it is not good solution for ships. Alternatively, hydrogen can be stored cryogenic at a temperature of –253 °C at ambient pressure, or somewhat higher temperatures and elevated pressures, referred to as cry compressed hydrogen (LH_2) [24]. The latter is currently the most energy dense physical storage method and more effective methods are still under investigation.

In April 2017 to launched first hydrogen vessel named "Energy Observer”. The boat will test and prove the efficiency of a full production chain that relies on the coupling of different renewable energies. Energy Observer will be the "first hydrogen vessel around the world". On winter 2017, the boat will leave on a world tour lasting 6 years in order to optimize its technologies and lead an expedition that will serve durable solutions for energy transition.

Figure 5. Energy Observer [www.en.wikipedia.org/wiki/ Energy_Observer]

Through science-based safety engineering and a sound understanding of hydrogen physical and combustion phenomena, hydrogen technology can be used safely in maritime applications [13].

3. 4. Biofuels

Biodiesel is a renewable and environmentally friendly fuel that is made from vegetable oils, animal fats and algae. This alternative fuel is characterized with reduced emissions of harmful gases in marine applications. Residue fuels are of lower quality compared to marine diesel and biodiesel distillates.

Table 3, compares three types of fuel:

- Standards for residual marine fuel (*RMA*),
- Marine distillate fuel (*DMA*),
- Biodiesel specifications of EN1421.

Table 3. Fuel properties of the specification ISO 8217 RMA for residual marine fuel and DMA for distillate marine fuel and the specification EN 14214 for biodiesel

Fuel parameter	Unit	ISO8217 RMA	ISO8217 DMA	EN 14214 Biodiesel
Cetane number, min	-	20	40	51
Sulfur, max	ppmw	45,000	15,000	10,000
Density (at 15 °C)	kg/m³	920 max	890 max	860 to 900
Flash point, min	℃	60.0	60.0	120.0
Carbon residue, max	wt.%	2.5	0.3	0.05
Kinematic viscosity (at 40 °C)	mm²/s	10.0 max	2.0 to 6.0	3.5 to 5.0
Heating value	MJ/kg	40	42	38
Water content, max	ppm	3,000	-	500
Acid number, max	mg KOH/g	2.5	0.5	0.5

The above characteristics indicate that the residual fuel has the worst properties against the background shown in the table. This study considers the variations in the properties of marine fuel, including it's flash point, sulfur content, kinematic viscosity, carbon residue and lower heating value, along with the biodiesel blending ratio. Biofuel has properties that meet the sulfur oxide content of the flue gas [25]. Unfortunately it is more expensive than other fuels. Biodiesel may also dissolve nonmetallic material such as gaskets, seals and rubber hoses. Biofuels for long-term storage can over time change their properties or create acids or peroxides [26].

In order to reduce the amount of sulfur oxides emitted into the atmosphere, it is possible to mix residual fuel with Biofuels. Biodiesel can be mixed in any proportions with residual fuels. However, there are indications to compose the mixture in proportional proportions, which mixture meets the requirements of the MARPOL convention. The appropriate amount of Biofuels added to marine fuel oil will significantly reduce the sulfur content [25].

For example, if 23.0 vol % biodiesel is added to the residual marine fuel oil RMA as shown in Figure 5, the sulfur content of 4.5 wt% in marine residual fuel can be reduced to 3.5 wt %, which would meet the 2012 sulfur content requirement of the 2008 MARPOL Annex VI Amendment. In this way, the ship-owner can save a lot of money to buy expensive exhaust purification systems. In addition, blending biodiesel into petroleum-derived diesel can also improve the latter's lubricity characteristics. Fuel sulfur not only increases SOx emissions, but also lubricates the moving parts of engines [25].

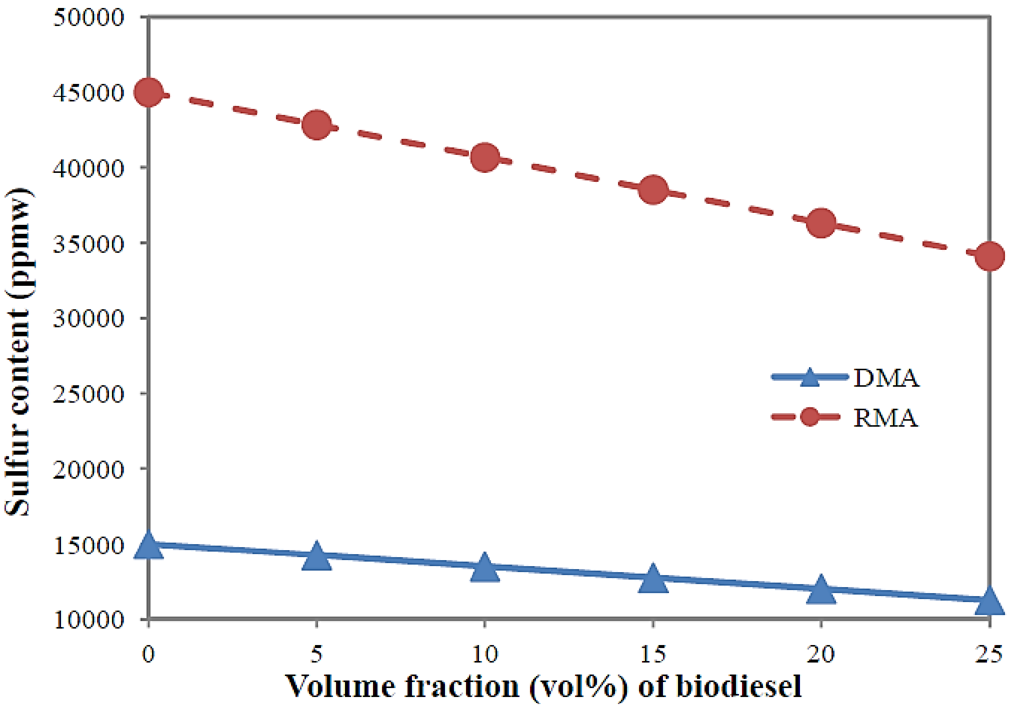

Figure 5. Variation of sulfur content with volume fraction of biodiesel blends in distillate marine fuel DMA and residual marine fuel RMA.

4. CONCLUSIONS

The restrictive requirements of the MARPOL Convention, which relate to pollution emissions from ships, force to change of heavy fuel to less damaging but much more expensive distillate fuels. For some time, petroleum-based fuels will remain the most popular source of propulsion for marine vessels. However, it is anticipated that after 2020, HFO will be completely eliminated from maritime industry. However, the continual use of the cheaper bunker fuel is possible by assembling the scrubbers into the fuel system. Scrubbers seem to be an ideal solution, but not all vessels are suitable for scrubbers and therefore retrofitting is required. The price of retrofitting a single vessel is very high (estimated to be around 3-5 million dollars per ship). One side effect of scrubbing is that the process only moves the unwanted substance from the exhaust gases into a liquid solution, solid paste or powder form. This must be disposed of safely, if it cannot be reused.

From an economic point of view, there is a great need to look for alternative energy sources that will fulfill two basic conditions, firstly burning them will not emit pollutants to environment, and secondly, they will be extremely cost effective. At present, the dominant option is the use of liquefied natural gas (LNG), but there is no proper infrastructure and the need for large space for fuel tanks make it a very difficult barrier for ocean vessels.

Another proposed source is Biofuels, which have a higher flash point than diesel, are biodegradable, and degrades quickly in water. However they can result in filter clogging and poor fuel flow at low temperatures, dissolve certain nonmetallic materials (seals, rubber hoses, and gaskets) and interact with certain metallic materials (copper and brass).

However, in the longer term, hydrogen is expected to fuel the future. Scientific studies on such fuel show that it is an environmentally-friendly energy carrier. When burning hydrogen, only nitrogen oxides and water vapor are formed, unfortunately, there are many obstacles to using hydrogen as a fuel. The first is its production, which is designed to be cheap, fast and efficient, which is a prerequisite for replacing the current energy sources. Another problem with hydrogen is its storage. Currently no material to keep this gas. The latest technology maintains hydrogen at 700 bar, but gas accounts for only 12% of the weight of the tank, which is unprofitable at high material costs.

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