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(2019)

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Transportation Research Part D: Transport and Environment, 70, pp. 123-134.

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<https://doi.org/10.1016/j.trd.2019.04.001>

Global Impacts of Recent IMO Regulations on Marine Fuel Oil Refining Processes and Ship Emissions

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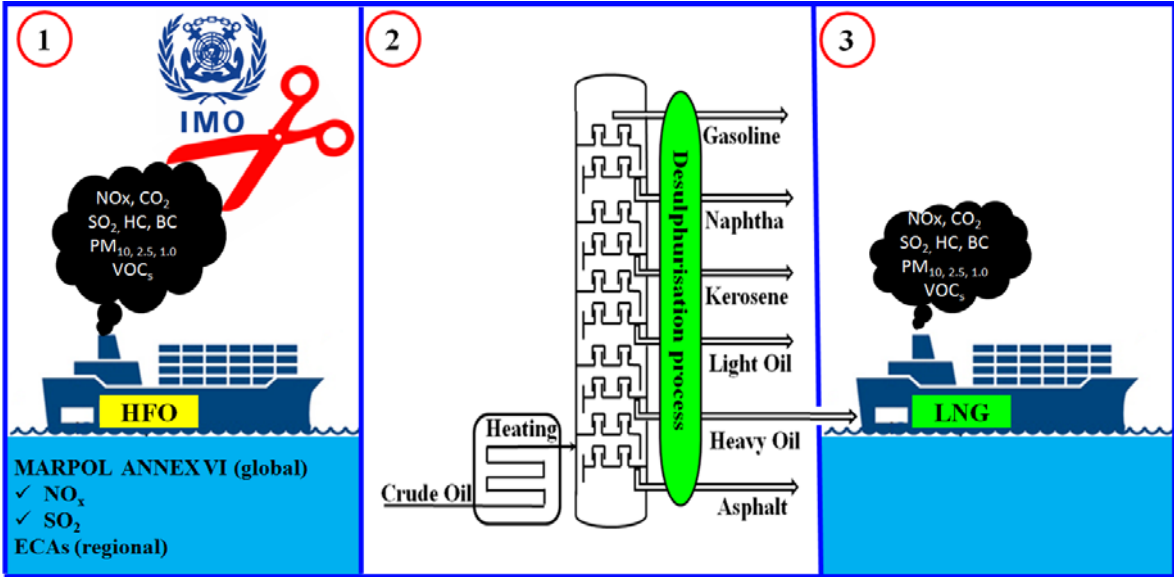
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Highlights

- Newly implemented IMO regulations require a significant reduction of ship emissions;
- Ship emission studies related to switching to low-sulphur fuels are thoroughly reviewed;
- Refinery processes to produce low-sulphur fuels require extra energy consumption;
- Scope for new regulations to be added to reduce particle number and methane slip;
- Future marine fuel mix needs to be involved to meet fuel regulations and emission reduction;

35 **Graphical Abstract**



37 **Abstract**

38 This study presents an overview of the context and global impacts of recent International Maritime
39 Organization (IMO) regulations on the marine fuel oil refining industry, future marine fuel mix and ship
40 emissions. IMO limited marine fuel sulphur content in both Sulphur Emission Control Areas (SECAs) and
41 Nitrogen Oxide Emission Control Areas (NECAs) to 0.1% (wt. %) by 2015, and to 0.5% globally by 2020. It
42 is anticipated that the newly implemented IMO regulations will help to mitigate negative impact of ship
43 emissions on public health and environment. IMO regulations require significant changes to refineries to
44 increase the production of low sulphur fuels through a shift to distillates, use of novel deep desulphurization
45 techniques, or fuel blending. Changes to the refinery processes can bring forth increases in greenhouse gas
46 emissions and high capital investments. Alternative fuels will need to meet the required reduction of air
47 pollutants and greenhouse gas emissions in coastal areas. Alternative marine fuels consisting of liquefied
48 nature gas (LNG) and biofuel may be suitable fuels to meet both targets. These two fuels are predicted to
49 account for 50% of shipping energy demand by 2050, while the remainder will still be supplied by
50 conventional heavy fuel oil (HFO)/marine gas oil (MGO). Switching to low sulphur fuels as a results of the
51 new IMO regulations has led to measureable reductions in ship emissions generally. This fuel switching also
52 resulted in changes in engine emission characteristics, especially on particulate matter chemical composition.

53
54 **Key words:** Shipping Emissions, IMO Regulations, Air Pollution, Oil Refinery, Heavy Fuel Oil, Alternative
55 Marine Fuels.

56 **Acronym Table**

57	bbl/d	Barrels of oil per day
58	BC	Black Carbon
59	CFR	Code of Federal Regulations
60	CH ₄	Methane
61	CO	Carbon Monoxide
62	CO ₂	Carbon Dioxide
63	CONCAWE	Oil Companies International Study Group for Conservation of Clean Air and Water in
64		Europe
65	EC	Elemental Carbon
66	ECAs	Emission Control Areas
67	EGR	Exhaust Gas Recirculation
68	ELTs	End-of-life tyres
69	EPA	United States Environmental Protection Agency
70	EU	European Union
71	FAME	Fatty Acid Methyl Esters
72	FCC	Fluid Catalytic Cracker
73	GHGs	Greenhouse Gases
74	HC	Hydrocarbons
75	HCO	Heavy Cycle Oil
76	HDS	Hydrosulphurisation
77	HFO	Heavy Fuel Oil
78	HTL	Hydrothermal Liquefaction
79	IARC	International Agency for Research on Cancer
80	IMO	International Maritime Organization
81	LCO	Light Cycle Oil
82	LNG	Liquefied Natural Gas
83	LSHFO	Low-sulphur Heavy Fuel Oil
84	MARPOL	Marine Pollution Convention
85	MDO	Marine Diesel Oil
86	MGO	Marine Gas Oil
87	N ₂ O	Nitrous Oxide
88	NECAs	Nitrogen Oxide Emission Control Areas
89	NO _x	Nitrogen Oxides
90	OC	Organic Carbon
91	ODS	Oxidative Desulphurisation
92	PM	Particulate Matter
93	PN	Particle Number

94	RMB30	Hybrids Fuel
95	SCR	Selective Catalytic Reduction
96	SECAs	Sulphur Emission Control Areas
97	SO _x	Sulphur Oxides
98	UN	United Nations
99	VOCs	Volatile Organic Compounds
100	WHO	World Health Organization

1. The context of regulating global ship emissions

1.1. IMO regulations and current ship emission abatement systems

IMO – the International Maritime Organization is a specialised branch of the United Nations (UN) which issues global regulations on the safety, security and environmental performance of global shipping. In particular, Annex VI of the International Convention for the Prevention of Pollution from Ships – the Marine Pollution Convention (MARPOL) was adopted by the 1973 Convention, and then modified by the 1978 Protocol with regard to limit the harmful impacts of ship emissions on air quality (IMO, 1997). These regulations were effective as of May 19th 2005, and aimed to reduce nitrous oxides (NO_x), sulphur oxides (SO_x) and particulate matter (PM) from marine engines. Responding to the desire of some coastal nations for further reduction of SO_x emissions from ships in their regions, Sulphur Emission Control Areas (SECAs) have been instituted by applying provisions contained in the Regulation 14 of MARPOL Annex VI. SECAs consist of the Baltic Sea area, the North Sea area, the North American region (containing the coastal sector of the United States and Canada), and the United States Caribbean Sea areas (around Puerto Rico and the United States Virgin Islands). These regulations limit the marine fuel sulphur content to 0.1% by mass in SECAs by 2015, and to 0.5% globally by 2020 as shown in Fig. 1 (IMO, 2016a). These IMO regulations will have a strong impact on marine oil refining, the future marine fuel market and ship emissions, which will be discussed in the present paper.

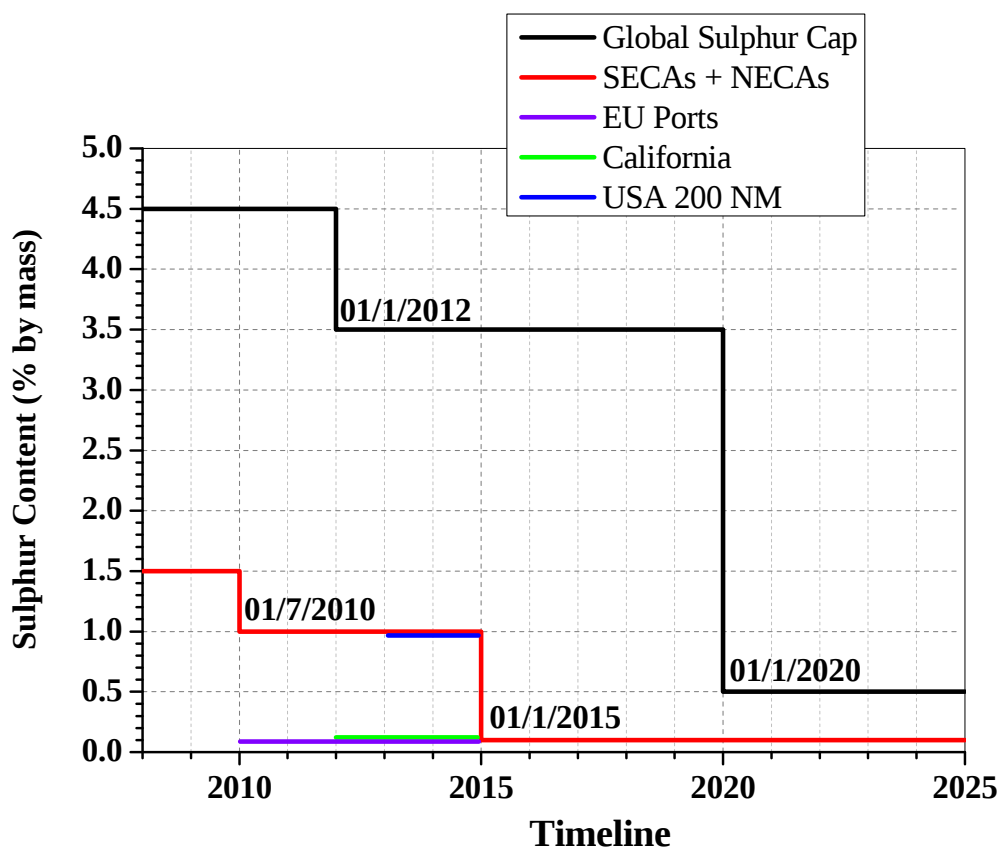


Fig. 1. IMO regulations on marine fuel sulphur content (this Figure is adopted from Cullinane and Bergqvist (2014) and then updated from IMO (2016a))

In order to control emissions of SO_x and PM, fuel sulphur content must be reduced as it significantly increases the emissions. SO_x emitted from marine diesel engines will form sulphate aerosols or sulphur-containing particles, which are the major component of PM. In addition, SO_x emissions are also able to condense to form small-size particles in nucleation mode which may stick to coarse particles resulting in the growth of particle composites. These secondary sulphate particles are an important contribution to land based air pollution and also have a role in marine aerosol budget. The IMO therefore does not particularly limit PM emissions directly, but regulates the sulphur-related portion of PM formation. It does this through the fuel sulphur content requirements of Regulation 14 to Annex VI. The maximum value for sulphur content of marine fuels used for vessels operating in SECAs was reduced from 1% to 0.1% on 1 January 2015 as seen in Fig. 1. As an alternative to using low-sulphur fuel oil, approved systems for the abatement of emissions, such as SO_x (wet and dry) scrubbers are likely to be dominantly used ([Chu-Van et al., 2018b](#)). In case these systems for the abatement of emissions are used, the approval of the ship's administration (the flag state) is needed. Scrubber systems play a role as filters of the engine exhaust gasses to remove SO_x by using washing-water that will be discharged directly into ocean (open loop), treated with chemicals and reused for a time before discharging (closed loop), or treated through a hybrid mode of the above ([Lindstad et al., 2017](#)). A cost efficiency analysis of three abatement options – retrofitting of scrubbers in ships using HFO, using LSHFO, and using diesel – found that using HFO combined with scrubber installation gives the lowest cost. However, this option encourages ships operating at high speeds which will increase fuel consumption and greenhouse gas emissions (CO_2). In addition, CO_2 will be released through the neutralization process of the acidic washing water after using at scrubbers ([Williams, 2010](#)). Therefore, reducing SO_x by using scrubber systems may result in increase of CO_2 .

Regulation 13 of MARPOL Annex VI controls NO_x emissions from both used and new marine diesel engines that are over 130 kW output power. Different levers or tiers depend upon the ship construction date and engine speed as presented in Fig. 2. It should be noted that Tier III requirements apply only to new vessels operating in Nitrogen Oxide Emission Control Areas (NECAs) established to limit NO_x emissions, namely the North American and the United States Caribbean Sea regions. It is well-known that NO_x emissions are a function of various engine parameters such as combustion temperature, residence time of combustion process, oxygen availability and ignition delay ([Patel et al., 2014](#)). NO_x emissions are mainly formed by reaction of atmospheric nitrogen with oxygen through the Zeldovich mechanism which is strongly influenced by the combustion temperature ([Mwangi et al., 2015](#)). Exhaust gas recirculation (EGR) arrangements and selective catalytic reduction (SCR) systems seem to be a feasible abatement technology to achieve NO_x reduction. By recirculating a part of exhaust gas to the scavenging air intake, EGR decreases oxygen availability in the engine combustion chamber resulting in a reduction of peak combustion temperature. However, this system can cause an increase in engine emissions such as black carbon (BC) due to the lack of oxygen during engine combustion process ([Nielsen et al., 2018](#)). Using metal catalyst combined with ammonia as a reduction element, SCR system reduces NO_x in engine exhaust by converting NO_x into N_2 and water. To maintain required NO_x reduction, exhaust temperature needs to be kept as high as possible.

Therefore, engine low load or low exhaust temperature conditions normally resulted in less efficiency of SCR system (Brynolf et al., 2014). It reveals that the practical challenges for the use of exhaust cleaning systems are still existed.

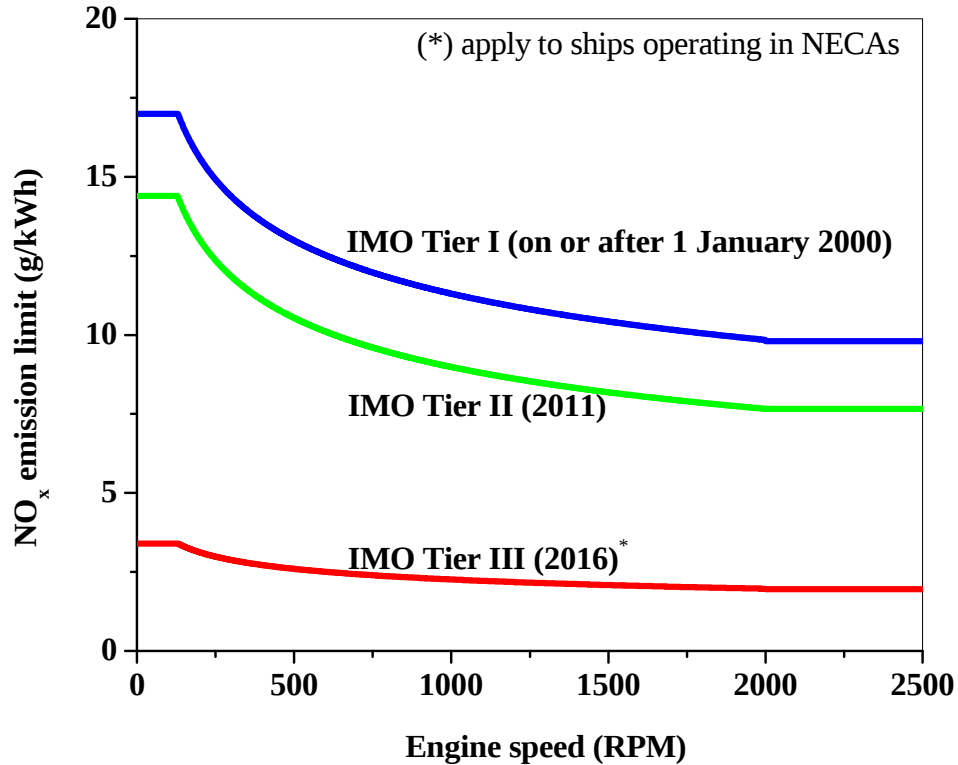


Fig. 2. IMO regulations on NO_x emissions (IMO, 1999)

1.2. Regional and national regulations

In addition to the regulations issued by the IMO, fuel sulphur content limits and ship emission regulations have been introduced by other countries and jurisdictions such as the State of California, United States Environmental Protection Agency (US EPA) and the European Union (EU) in order to further reduce the negative impacts of emissions from ships on air environment. As can be seen in Fig. 1, from 1 January 2010, European directive 2005/33/EC demands all ships at berth or anchoring in European ports to use fuel oil with a sulphur content of less than 0.1% by mass (European Parliament, 2005). However, passenger ships in the EU's non-ECA waters can use marine fuels with S content of 1.5% from January 1st 2015 to January 1st 2020 (Cullinane and Bergqvist, 2014). The use of cleaner marine distillate fuels in ocean-going ships operating in the Californian coastal areas was mandated by the State of California. In particular, "Fuel sulphur and other operational requirements for ocean-going vessels within California waters and 24 nautical miles of the California baseline" has been adopted on 24 July 2008, and enforced since July 2009 (ARB, 2008). In addition, some types of vessels such as container vessels, passenger ships and refrigerated-cargo ship fleets that visit Californian ports need to comply with Californian at-berth regulations with the target of

80% emission reduction by 2020.

US Environmental Protection Agency (EPA) regulations for marine applications are available at Title 40 of the Code of Federal Regulations (CFR), Parts 94 and 1042. Three categories of engines are identified based on per-cylinder displacement ([US-EPA, 2012](#)). Marine diesel engines which belong to categories 1 and 2 normally have engine output power in the range of 500 to 8000 kW. These engines can be either used as marine main engines on many kinds of small vessels such as tugboats, supply and fishing vessels, or used as marine auxiliary diesel engines on larger vessels. Category 3 marine diesel engines, which range in output power size from 2500 to 70000 kW, are generally used to provide propulsion power for ocean-going ships consisting of container ships, oil tankers, bulk carriers and cruise ships. Application of emission control systems on category 3 marine diesel engines is limited ([US-EPA, 2012](#)). The EPA Tier 2 limits are similar to Tier II limits of Annex VI for NO_x, but also consist of limits on hydrocarbons (HC), particulate matter (PM) and carbon monoxide (CO).

1.3. Negative impact of ship emissions

The primary drivers for regulating ship exhaust emissions are their harmful effects on both public health and environment ([Anderson et al., 2015b](#); [Blasco et al., 2014](#); [Chu-Van et al., 2018a](#); [Corbett et al., 2007](#); [Mueller et al., 2015](#); [Reda et al., 2015](#); [Ristovski et al., 2012](#)). Ship emissions consist of both gaseous and particulate emissions ([Mueller et al., 2011](#)). [Viana et al. \(2014\)](#) noted that emissions from ships are one of the most significant contributors to poor air quality, especially in coastal environment around the globe. A study in 2010 reported that over 70% of shipping emissions have been detected up to 400 km inshore, significantly contributing to air quality degradation in areas closer to harbours ([Eyring et al., 2010](#)). Ship emissions caused an increase in concentrations of particulate matter as well as of gaseous pollutants, which consequently form new secondary particles in more densely-populated areas ([González et al., 2011](#); [Viana et al., 2014](#)). Particulate matter generated by engine combustion is a complicated mix of particularly tiny liquid and solid particles consisting of numerous ingredients, including acids (e.g. nitric and sulphuric acids), metals and organic compounds. A previous study indicated that BC emitted from international ships accounted for 1 to 2% of total BC around the world ([Lack et al., 2008](#)). Gaseous emissions such as SO_x form sulphate aerosols – small particles that reflect sunlight and contribute to radiative cooling of the planet ([Sofiev et al., 2018](#)). In contrast, CO₂ emissions increased warming effect ([Lack et al., 2008](#); [Lack et al., 2011](#)). Additionally, SO_x and NO_x emissions from global ships are also significant contributors to the acidification of the oceans ([Hassellöv et al., 2013](#)).

In 2012, diesel engine exhaust emissions were classified as carcinogenic substance by the World Health Organization (WHO) International Agency for Research on Cancer (IARC) ([IARC, 2012](#)) in the same group as asbestos. The links between fine particle (PM_{2.5}) emissions and increased mortality due to cardiovascular and lung problems has been noted in several studies ([Abramesko and Tartakovsky, 2017](#); [Corbett et al., 2007](#); [Pope Iii and Dockery, 2006](#); [Ristovski et al., 2012](#)). In details, almost 64,000 cardiovascular and lung cancer

deaths annually can be attributed to PM_{2.5} ship emissions ([Corbett et al., 2007](#)). In Europe, 5–10% of total PM emissions are derived from shipping activities, which are responsible for approximately 400,000 premature deaths annually ([Andersson et al., 2009](#)). Through the use of low-sulphur fuel, the reduction in PM_{2.5} emissions (by mass) by the year 2020, cleaner marine fuels will significantly contribute to the reduction of global ship-related morbidity and premature mortality by 54 and 34%, respectively ([Sofiev et al., 2018](#)). However, marine fuels with lower sulphur content will still significantly contribute to the number of related fatalities (~250,000 deaths) as well as ~6.4 million cases of childhood asthma ([Sofiev et al., 2018](#)). Therefore, a need for new regulations will be necessary, because reducing in-fuel sulphur will be insufficient to diminish emissions of ultrafine particle emissions ([Winnes and Fridell, 2012](#)). As noted in a further study by [Winnes et al. \(2016\)](#), the sulphur content of the fuel influenced the observed particle mass, but not the particle number emissions. Authors suggested that fuel chemical- and physical-related studies (e.g. metal and ash content, viscosity) are needed so as to understand this phenomenon.

2. Impact on marine fuel oil refining processes

Following the more stringent regulatory requirements, refineries bear the brunt of the increasing demand for low sulphur marine fuels. Around 2 million barrels of oil per day (bbl/d) of fuel oil will need to be switched to distillate fuels to meet the global sulphur cap in 2020, with an annual growth trend predicted at 500,000 bbl/d of distillate and a decline of 150,000 bbl/d in residual demand ([CONCAWE, 2016](#)). This requires significant changes to the refinery to increase the capacity of residue conversion processes to produce cracked gasoil, the development of larger sulphur-removal processes for residues ([IEA, 2016](#)), or the use of sweeter crude feedstock. An analysis of potential refinery modifications to meet the targets requires capital investments of \$2-5 billion for 350,000 bbl/d refinery, with payout periods of 4.2-5 years ([Abdel-Halim and Yu, 2018](#)).

Around 50% of crude oil usually proceeds to the heavy fuel fractions; however, with increasing light fuel (e.g. gasoline) demand and declining heavy fuel demands, complex refinery processes are often attuned to produce lighter components. Marine fuels are composed from diesel, kerosene, light and heavy gasoil, and atmospheric residue fractions. Kerosene can be used as feed for producing straight run marine gasoil and distillate marine diesel, and these products are used to decrease the viscosity of residues through blending. From the bottom of the atmospheric crude distillation part, the atmospheric residue proceeds to vacuum distillation, where it is further separated to a light fraction fed to a fluid catalytic cracker (FCC) and a heavy fraction that proceeds to a visbreaking process. The FCC process involves high temperatures and an aluminium silicate catalyst to produce more gasoline, light cycle oil (LCO), which is a distillate product, and heavy cycle oil (HCO), which is added to the visbreaker residue. The visbreaker uses a mild thermal cracking process to yield blendstock gasoil. Blending of these different product streams with streams of less desirable properties (i.e. high viscosity and density) to achieve marine fuel standards maximises total refinery yield. The blends consider the maximum density limit, which affects ignition quality; maximum aluminium and silicon limit, to avoid abrasive damage in the fuel system; and maximum total sediment aged

deactivation and maintain the reaction rates ([Takahashi et al., 2005](#)). The process also requires high temperatures and high hydrogen pressure, which contributes to high production costs ([Kressmann et al., 1998](#)).

Various technologies are proposed for reducing sulphur to the required lower levels. Ebullated bed reactors with catalysts smaller than 1 mm can accommodate heavy feeds with high asphaltene, sulphur and metal content, and achieve up to 90% HDS conversion ([Rana et al., 2007](#)). Moving bed reactors, which can accommodate online catalyst replacement, have also been designed for partial removal of contaminants prior to processing in conventional fixed bed reactors ([Yuandong et al., 2009](#)). Another technique suggested is to ensure a low H₂S partial pressure towards the HDS reactor outlet to prevent inhibition of the desulphurisation reaction. Hydrogen with some amount of H₂S is recycled from the reactor outlet back to the inlet to maximise the hydrogen supply. This presents issues in the reaction at low sulphur levels, since the equilibrium can easily be tipped towards formation of sulphurous compounds if H₂S partial pressure is sufficient. Reactor configurations, such as interstage removal of H₂S, countercurrent feed-hydrogen flows, and a separate catalyst bed fed with fresh hydrogen are suggested to minimise the effect of H₂S ([Ancheyta and Speight, 2007](#)). Aside from HDS reactors, liquid-liquid extraction of the sulphur containing compounds has also been explored using organic solvents ([Kumar et al., 2014](#)), ionic liquids ([Chen et al., 2014](#)), and deep eutectic solvents ([Warrag et al., 2018](#)). The latter was developed as a less toxic, greener alternative to conventional solvents and ionic liquids, and can remove up to 99.5% sulphur in multistage reactors to 10 ppm. However, this has been demonstrated only for gasoline and diesel fuels ([Chandran et al., 2019](#)). A combination of conventional refinery processes of distillation, extraction and hydrotreatment, has also been proposed to facilitate deep desulphurization down to 73 ppm ([Kumar et al., 2018](#)).

A new technique proposed for removal of refractory sulphur compounds such as thiophenes, is oxidative desulphurisation (ODS). This process involves addition of an oxidising agent such as hydrogen peroxide, and a catalyst to convert aromatic sulphur to sulphones or sulfoxides, which can then be easily extracted by a polar solvent ([Ismagilov et al., 2011](#)). The use of oxygen in air as an oxidant with the use of cobalt and manganese oxide catalysts has also been explored to lower the cost of the process ([Sain et al., 2003](#)). The key advantage of ODS against HDS is the high reactivity of dibenzothiophenes in ODS, whereas in HDS they are the least reactive ([Ismagilov et al., 2011](#)). This process, combined with HDS has the potential to produce low-sulphur products because they target different sulphur species in heavy oil.

Another method that has been recently explored is biodesulphurisation, using bacteria that consumes dibenzothiophenes as substrates in mild conditions with low hydrogen requirements ([Chen et al., 2018](#)). High sulphur removal was reported up to 76% from crude oil and 98% from hydrodesulphurised diesel with a residence time of four days ([Adlakha et al., 2016](#)). There are challenges associated with the complexity and cost of cultivating bacteria in specialized culture media and isolating specific bacteria for the process, however, a more commercially-feasible bacterial consortium can be implemented ([Porto et al., 2018](#)).

The new technology introduced in refineries can suffer from unsustained reliability and lack of experience, which are both critical in production of large volumes of marine fuel. In order to avoid the complexities and costs of installing additional specialised refinery sections for the HDS of heavy fractions, residues are also blended with distillates. This is an established practice to extend the value of crude oil, however in this case, blending can also be done to meet new fuel standards. This affects refinery operations because there is added pressure to produce more distillates that can serve as blendstock. The processes to remove sulphur described above all require additional energy and hydrogen, and intensification of those processes to produce lighter, lower-sulphur marine fuels also increases energy and hydrogen consumption. This translates to potentially higher CO₂ emissions ([Silva, 2017](#)). However, new installations to cope with the higher demand for distillate fuels will have higher refinery efficiencies, which dampen the increase in energy and CO₂ emissions. A model by the Oil Companies International Study Group for Conservation of Clean Air and Water in Europe (CONCAWE) for the European scenario illustrates the effect of the new sulphur standard by showing the resultant marginal increase or decrease in the demands of marine fuels. Marginal increases (10-20%) in demand of low sulphur residual marine fuels cause small increases in energy requirements and CO₂ emissions. In contrast, a proportionate decrease in high sulphur marine fuel demand, also increases CO₂ emissions, due to the liberation of CO₂ in refining heavy fractions, which used to be a carbon sink. Furthermore, scenarios of switching to a 50% or 100% distillate marine fuel scenario show CO₂ emissions 7.5-15 times higher than the low sulphur residual marine fuel case. The model considers the balance of the entire refinery and economic optimisation, so the higher CO₂ emissions also reflect the difficulty of producing distillate marine fuels, which is already a high-demand product ([Dastillung et al., 2009](#)). On the global scale, a study estimates that a total switch from residual fuels to distillate fuels will increase total global anthropogenic CO₂ emissions by 0.01%, while decreasing total global sulphur emissions by 6% ([Corbett and Winebrake, 2008](#)), presenting a minor trade-off to mitigate the effect of sulphur in the atmosphere.

The increased sulphur removal is expected to increase nondiscretionary sulphur production only incrementally, similar to changes that occurred when road and jet fuel standards required lower sulphur content ([Ober, 2000](#)). Other factors such as the increased use of sour crude and gas, and improvement of environmental standards in developing countries can also contribute to an increase in sulphur production. This is expected to meet increasing demand in fertilizer processing and other industrial areas ([Apodaca, 2017](#)).

3. Impact on the future marine fuel mix for the shipping sector

To meet growing future demand and the regulated emissions reduction, it can be expected that the mix of marine fuels used will change. A forecast for shipping industry fuels has been recently reported by [DNV-GL \(2017\)](#). Several major types of cargoes, such as crude oil, oil products, natural gas, bulk, container and other cargoes have been included in the study as can be seen in Fig. 4. It has been predicted that demand for seaborne transport will increase 60% by 2050. The increase in demand of seaborne has also been reported in a two years study ([GMT, 2013](#)), which predicted that international seaborne trade will be nearly doubled by 2030 compared to 2010. It is hard to predict exactly the number, but overall an increase in the future seaborne demand has been predicted. It shows the important role of cleaner fuels for the marine sector in order to satisfy future seaborne demand and to mitigate emissions. The shipping fuel mix has been predicted up to 2050 as shown in Fig. 5. As can be seen in Fig. 5, alternative marine fuels, namely liquefied natural gas (LNG) and biofuel, may account for 50% of shipping energy demand, while the remainder will still be supplied by conventional HFO/MGO ([DNV-GL, 2017](#)). Similarly, LNG is predicted to reach the maximum of 11% in 2030, while 47-66% is of HFO ([GMFT, 2014](#)). It shows the vital role of emission regulations on shipping with the increasing utilization of alternative fuels.

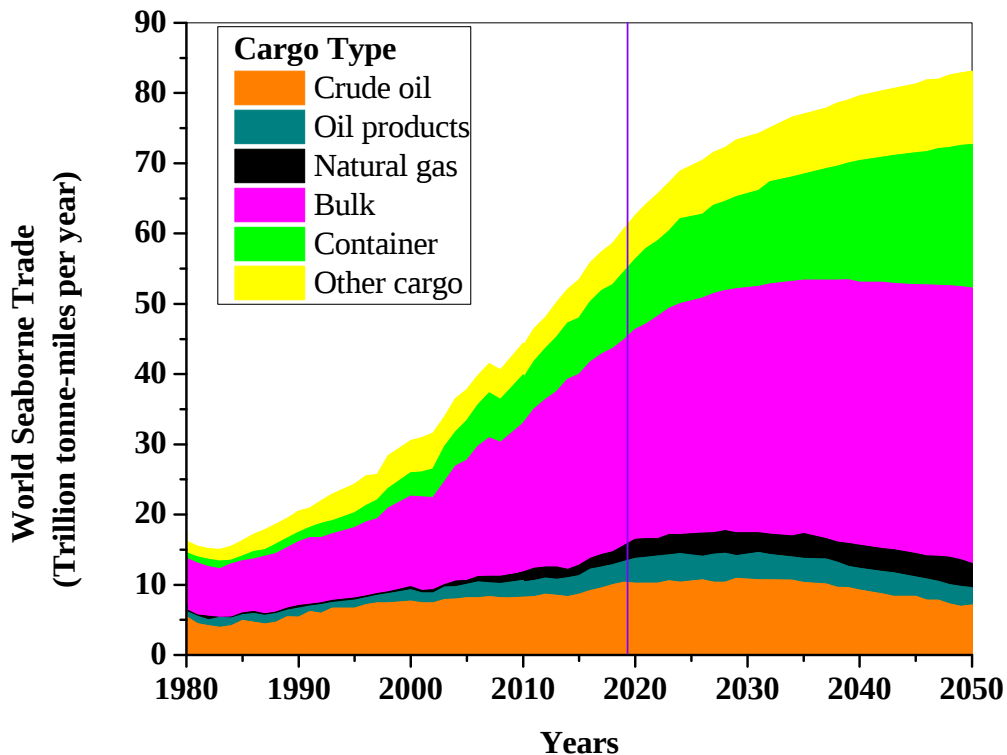


Fig. 4. Demand forecast for seaborne transport (adopted from [DNV-GL \(2017\)](#))

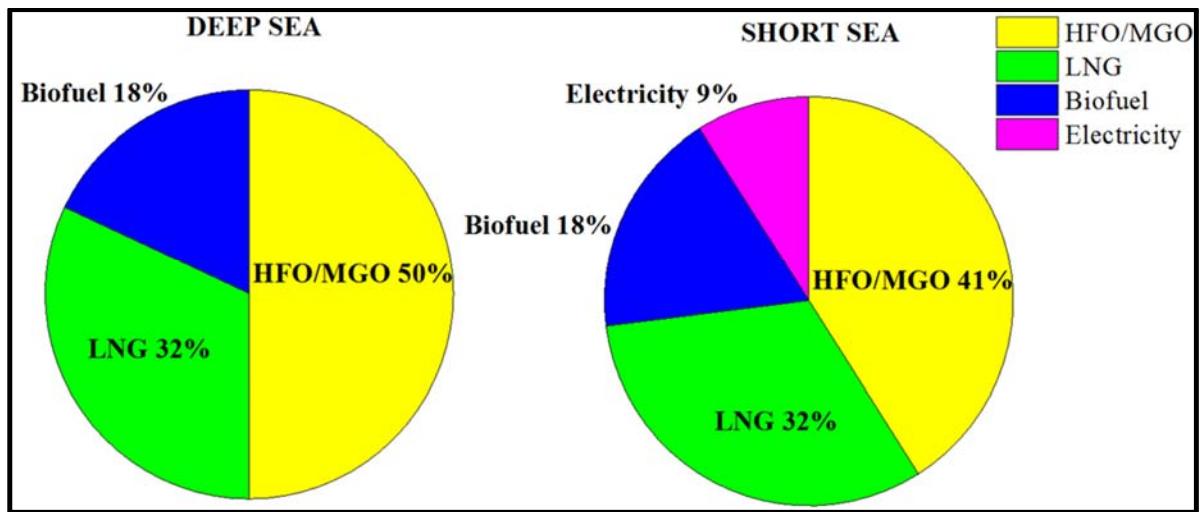


Fig. 5. Shipping fuel mix 2050 (DNV-GL, 2017)

Alternative fuel potential for use in the marine sector will need to satisfy the required reduction in coastal area air pollutants and greenhouse gas emissions, and to comply with IMO regulations (Gilbert et al., 2018). A recent study assessed the full life-cycle air emissions of a set of alternative shipping fuels, including LNG, methanol, liquid hydrogen, biodiesel, straight vegetable oil and bio-LNG. Results showed that no available fuel exists to meet both short-term and long-term ship emission reductions (Gilbert et al., 2018). Residual fish oil and MGO blends have been used in a recent study to investigate combustion and emission profiles (Ushakov et al., 2013). Burning fish oil showed a reduction up to 56% of CO, 70% of HC, and 70-90% of total number and PM mass compared to MGO, which may be strongly associated with high oxygen content and lack of aromatic compounds in fish oil. However, the lower heating value of fish oil resulted in an increase in specific fuel consumption observed at all load conditions (Ushakov et al., 2013). Recently, a study suggested that waste cooking oil biodiesel (fatty acid methyl esters-FAME) blended with MGO can be considered as an alternative fuel for auxiliary marine engines because it helps to reduce NO_x emissions (Wei et al., 2018).

Methanol has recently been given attention by researchers as a low carbon alternative fuel to conventional fuels. The total life-cycle emissions of methanol use were compared to MGO and HFO in order to identify the environmental benefits of using methanol (IMO, 2016b). Generally, emissions of SO_x, NO_x, PM and GHGs (CO₂, CH₄ and N₂O) were used in the total life-cycle model. It is reported that although methanol's cost is slightly lower than that of MGO, it is not a preferable fuel for shipping in the long-term. This is because its use neither gives a favorable payback period for the capital investment of its propulsion, nor meets the price of its production. The Stena Germanica ferry is reported as the first large marine vessel running methanol after a conversion in 2015 in Poland. Methanol use is expected to reduce emissions for SO_x, NO_x, CO₂ and PM by up to 99%, 60%, 25% and 95% respectively (MKC, 2018). It is obvious that methanol has a lower investment and space requirement, making it attractive compared to LNG, however a major barrier to its use is its high fuel cost (Motorship, 2018).

Natural gas in the form of LNG is an alternative fuel for shipping is considered the most likely option in order to comply with IMO regulations and to reduce air pollution and climate change (IMO, 2016c). Table 1 reveals that the use of LNG as a marine fuel for shipping would be preferable from an environmental perspective; however other factors such as finance need to be considered to choose the compliance strategy for a vessel. A recent study investigated both particulate and gaseous emissions from an LNG-powered vessel (Anderson et al., 2015a). Results showed that a significant reduction of particles, NO_x, SO₂, and CO₂ was observed for LNG use compared to MGO, while emissions of HC and CO showed the opposite trend. HC analysis also revealed 90% of HC was unburnt methane, which shows the need to control and limit methane slip when using LNG (Anderson et al., 2015a), since the global warming potential of methane is 25 times higher than that of CO₂ over a 100-year scale. The energy policy requirements are necessary in order to reduce methane leakage through better processing infrastructure designs and during engine combustion (Thomson et al., 2015). A total life-cycle emission inventory for air emissions from two vessels operating between China and Taiwan using both HFO and LNG for each ship was conducted (Hua et al., 2017). Both ships present a considerable decrease in the total fuel life-cycle emissions of NO_x (38-39%), CO (42-43%), SO₂ (99.8%) and PM₁₀ (97.5%), however methane emissions were significant in the case when LNG was used compared to HFO. This study also indicated that LNG as a marine fuel enables improved life-cycle GHG emissions and reduces SO_x and PM across the Taiwan Strait (Hua et al., 2017). Recently, the assessment on using LNG as an alternative marine fuel has suggested there is a need for regulating methane slip from LNG engines (Brynolf et al., 2014). In addition, uncertainties related to future price and global availability of LNG, methanol and MGO are actually questionable, while issues with HFO/Scrubber are located at the reliability/corrosion during operation. Infrastructure development for bunkering and safety in use would also be considered as uncertainties since LNG and methanol are used.

Table 1. Comparison between the alternatives: LNG, Methanol, MGO and HFO/Scrubber with HFO (IMO, 2016b, c)

Fuel types	Environmental factors				Other factors		
	SO _x	NO _x	PM	CO ₂	Cargo capacity	Capital investments	Operating costs
LNG	++	++	++	+	Restricted	Very high	Very low
Methanol	++	+	++	++	Restricted	Very high	High
MGO	+	-	-	-	Unrestricted	Low	Very high
HFO/Scrubber	+	--	+	-	Slightly restricted	High	Medium
HFO	--	--	--	--	Unrestricted	Low	Low

++ very positively, + positive, - negative, -- very negative.

Biofuels are of increasing interest and a promising alternative for both road and seawater transport sector. Potential biofuels should be required to provide no competition with food crops or land use and to offer a reduction in greenhouse gas emissions (Obeid et al., 2019). Microalgae-based biofuels have recently received great attention from researchers because of their potential for large-scale fuel production on non-arable land (Islam et al., 2017). Oil extraction from microalgae can be obtained through a variety of methods

such as mechanical disruption, ultrasonic-assisted extraction, solvent extraction, hydrothermal liquefaction (HTL) and supercritical fluid extraction. Among these, HTL has been identified as a very promising method to convert biomass into biofuels owing to its high energy efficiency (Islam et al., 2017) and ability to process a wide variety of locally available waste biomass (Kosinkova et al., 2017). Physicochemical properties of microalgae biofuels resulted in engine combustion reaction changes, which consequently will have a large effect on engine performance and emission profile (Hossain et al., 2018b). These properties are dependent on microalgae species (Islam et al., 2013), process conditions (e.g. temperature, pressure, retention time and the choice of catalyst) (Ross et al., 2010; Xu et al., 2015). The variation of microalgae biofuel properties also affects their potential application. In particular, microalgae HTL bio-crude may be more suitable for low-speed marine diesel engines because its properties are similar to HFO (Hossain et al., 2018b). In contrast, microalgae biodiesel consisting of FAME mostly can be used as an alternative fuel for high speed diesel engines (cars, buses and vehicles) owing to its properties being similar to that of conventional diesel (Islam et al., 2015). HTL bio-crude is a dark and energy-dense liquid with high viscosity (Hossain et al., 2018b; Kosinkova et al., 2015), and is comparable with HFO as regards fuel properties. The fuel property comparison between microalgae FAME, HTL bio-crude, tyre oil, MGO and HFO is presented in Table 2. It can be seen that HTL bio-crude properties are closer to that of HFO, which reveals the promising low-sulphur alternative fuel for shipping in the future. This fuel can also be upgraded to reduce oxygen content and improve calorific value (Ramirez et al., 2015) and can be used as alternative fuel for auxiliary marine diesel engines. The storage stability of HTL bio-crudes must also be considered to anticipate the effects of long-term storage of fuels (Kosinkova et al., 2016).

Table 2. Microalgae FAME, HTL bio-crude, Tyre oil and Licella properties in comparison with the conventional marine fuels: MGO and HFO.

Fuel Parameter	Unit	Microalgae		Tyre Oil (Hossain et al., 2018a)	Licella (Nabi et al., 2015)	MGO (Nabi et al., 2012)	HFO (Chu-Van et al., 2018a)
		Biodiesel (FAME) (Islam et al., 2015)	HTL bio-crude (Hossain et al., 2017a)				
Density at 15 °C	kg/L	0.912	0.97-0.104	0.847	0.89	0.855	0.986
Viscosity at 40 °C	mm ² /s	5.06	73.8	3.43	5.11	2.60	377*
Calorific value	MJ/kg	39.86	30-35	42.28	42.63	42.8	42.74
Cetane number		53	N/A	51	N/A	47	N/A
Sulphur (S)	% mass	7.5x10 ⁻⁴	0	0.35	0.010	0.005	3.13
Carbon (C)	% mass	78.41	75.56	84.1	84.46	86.2	88.14
Hydrogen (H)	% mass	11.12	10.14	15.9	12.66	13.6	9.36
Oxygen (O)	% mass	10.47	10.33	N/A	2.88	N/A	N/A
Nitrogen (N)	% mass	0	3.97	N/A	0.05	N/A	0.68

*measured at 50 °C; N/A: not available.

Tyre oil may also be a promising fuel for marine diesel engines. The physicochemical properties of the tyre oil are similar to MGO and this fuel can be miscible with conventional diesel in any blended ratio. A very recent study investigated engine performance and emissions from a non-road diesel engine using tyre oil ([Hossain et al., 2018a](#)). The results showed a significant reduction in NO_x, PM mass and number, while CO emissions slightly increased. Tyre oil is produced from end-of-life tyres (ELTs). It has been reported that 1-1.5 billion tons of ELTs are generated annually around the world ([Hossain et al., 2018a](#)). The ELTs to fuel technology not only can help to deal with problem-related waste disposal from ELTs in the world, but also offers a potential fuel solution for the marine sector.

Companies such as Licella, which convert numerous low-cost products, waste and non-edible biomass residues through thermochemical conversion processes, are helping to produce renewable fuels that can be used for the transportation sector. A previous study investigated fuel characterisation, engine performance and exhaust emissions with a new renewable Licella biofuel ([Nabi et al., 2015](#)). The renewable component of the Licella biofuel in this study was made from Australian pinus radiata wood flour by using the HTL conversion method. Results showed a reduction in both PM mass and PN emissions for all Licella blends, with no significant changes in engine performance compared to conventional diesel. However, HC and NO_x emissions were observed to be higher for the Licella biofuel. This study also highlights a need for further studies on the future use of Licella biofuel in marine and stationary generation applications ([Nabi et al., 2015](#)).

4. Potential impact to ship emissions

To mitigate emissions from ships, the IMO has issued and implemented more stringent regulations related to marine sulphur content and NO_x emissions. IMO compliant fuels or marine fuels with low sulphur content normally refer to marine gas oil (MGO), marine diesel oil (MDO), and low-sulphur residual fuel (LSHFO), which have been used to meet fuel sulphur content IMO regulations. For the reduction in NO_x, the use of fuel additives can be considered as a feasible measure though it did not be officially recognised by IMO. In this section, the effect by using these fuels compared to heavy fuel oil (HFO) on engine emissions will be thoroughly investigated to assess the efficiency of IMO regulations. A number of recent on-board and test-bench measurements will be used in the present study.

Switching to low-sulphur fuels such as MGO, MDO or LSHFO from HFO results in a variety of fuel properties changing, and consequently may affect ship emissions because these are significantly affected by fuel type, fuel quality and fuel properties ([Winnes et al., 2016](#)). It is evident that fuel sulphur content has a strong impact on PM mass, particle number (PN), and particulate matter chemical composition. On-board measurements were carried out on a ship operating in the Baltic Sea (an SECA) ([Zetterdahl et al., 2016](#)). This study investigated the impact of 0.1% sulphur content fuels (LSHFO or hybrid fuel called RMB30) on emissions compared to HFO. This fuel change from 0.48% to 0.1% sulphur content resulted in a reduction of nearly 67% PM mass, and 80% SO₂ as well as a reduction in total volatile organic compounds (VOCs)

(Zetterdahl et al., 2016). This is in agreement with the results of other on-board measurements (Moldanová et al., 2013), which showed that HFO emitted the higher PM mass compared to MGO. Particulate organic carbon (OC) emissions for HFO combustion were three times higher than that of MGO, while elemental carbon (EC) revealed no significant differences between the two fuels. A recent test-bed study investigated the effect of sulphur- and vanadium-spiked fuels on particle characteristics and engine performance (Chu-Van et al., 2018a). This study found that higher sulphur content leads to significant increase in PM mass, PN and sulphate fraction. However, PN results in this study are in contrast with previous on-board measurement (Zetterdahl et al., 2016), which showed unchanged values of PN for both LSHFO and HFO. It indicates the uncertainty in PN emission measurement results which highly affected by other factors such as dilution systems used, engine types and engine load conditions. In the case when HFO was used, the major components of PM_{2.5} are hydrated sulfates, OC and trace metals, which accounted for 80-97% of total PM_{2.5}. However, changing fuel from HFO to MDO revealed that OC is the main component of PM_{2.5}, accounting for 65% of PM_{2.5} (Celo et al., 2015), and over 90% of PM found was OC for both MGO and LSHFO (Gysel et al., 2017). It indicated that using IMO compliant fuels will result in a significant reduction of sulphate and trace metal proportions of PM_{2.5}.

In addition to the impact on PM mass and PN, switching to IMO compliant fuels strongly affects particulate matter chemical composition. A previous on-board measurement found that metals detected in exhaust when using HFO were dominated by compositions from both fuel used (V, Ni, Fe) and lubricating oil (Ca, Zn), while for MGO use, most metals from exhaust emissions were associated with lubricant compositions (Moldanová et al., 2013). These findings are in good agreement with a very recent test-bed study (Chu-Van et al., 2018b). In this study, a detailed investigation into the metallic elemental composition at different particle diameter sizes was undertaken. A multivariate statistical analysis was performed to elucidate relationships between the measured engine performance (engine power, thermal efficiency, specific fuel consumption,...), engine emission variables (gaseous and particle emissions) and particular test conditions such as different engine load conditions, the fuel sulphur and vanadium contents, and experimental replication. The major sources of metallic elements in the emitted particles are considered in this study, including the fuel and lubricating oil compositions, engine wear emissions and metal-containing dust in the ambient air. Solid ultrafine-particles (Dp < 100 nm) are strongly associated with metallic compounds derived from lubricating oil (Ca, Zn, Mg and K), while the fuel-related metallic compounds and engine wear emissions are represented in the coarse particle fraction (Dp > 1 µm) (Chu-Van et al., 2018b).

In the case both ECA-compliant fuels used, it showed the difference in particle emissions. Particularly, MGO and LSHFO have been used in a recent on-board measurement to provide insight into particle emissions from a very large crude vessel (Gysel et al., 2017). These two fuels have small sulphur and no ash or vanadium content. The significant difference between the two fuels is in their viscosity, with a 4-times higher viscosity for LSHFO compared to MGO. Results showed that MGO emitted 5% higher NO_x but three times lower for PM_{2.5} compared to LSHFO combustion. It can reveal the important role of fuel viscosity on engine

emissions, however further study is needed to make this clear.

BC, a component of elemental carbon (EC), is an important climate forcing agent ([Lack et al., 2008](#)). BC emissions from marine traffic in the Arctic also greatly influences climate warming through direct light absorption and increase of surface albedo through darkening of snow ([Bond et al., 2013](#)). A reduction in aromatic and long chain hydrocarbon constituents of fuels owing to switching to low sulphur marine fuels (e.g. RMB30) may be associated with a decrease in BC ([Lack et al., 2011](#)). However, a previous study found that using low sulphur distillate fuels emitted higher EC than HFO, although a reduction of hazardous species such as PAHs, Oxy-PAHs, N-PAHs and transition metals was observed ([Sippula et al., 2014](#)). To make the BC emission mechanism clear, [Jiang et al. \(2018\)](#) investigated the effects of BC measurement method, fuel type and engine loads on BC emissions from a 187 kW, 2-stroke high-speed marine engine. The variation in BC concentration due to different measurement methods ranged by a factor of 2, and did not be responsible for a ten-time range of BC suggested in the literature review. Jiang and co-workers' view is that fuel properties, engine load and engine characteristics are most likely to be the driving factors towards a large variation in BC emissions ([Jiang et al., 2018](#)). Surprisingly, RMB30 or LSHFO, a new low-sulphur residual fuel widely used in SECAs and NECAs, presents the highest level of BC emissions among three tested fuels. There is not a clear link between BC and fuel properties like fuel sulphur content, viscosity and carbon residue. Consequently, this calls for a need of further study on fuel parameters. In addition, this study shows a positive trend, that using distillate fuels may help to reduce BC emissions from ships ([Jiang et al., 2018](#)).

Using fuel additives in order to obtain both fuel savings and environmental benefits, so adding additives to HFO, has been attractive to both shipping companies and researchers recently. One study used oil-soluble Ca- and Fe-based organometallic compounds as fuel additives in HFO ([Ryu et al., 2016](#)). Both reductions in fuel consumption and exhaust emissions were observed. In particular, 23-32.6% and 16.5-19.7% reductions in NO_x emissions obtained for Ca- and Fe-related additives, respectively. Similarly, for PM, added Ca-based compound resulted in a 57.4-59.7% reduction, with 38.9-40.9% reduction for Fe-related additive ([Ryu et al., 2016](#)). Similarly, dispersant cetane and combustion improvers showed an improvement in fuel stability during storage and a significant reduction of PM emissions ([Jang and Choi, 2016](#)). However, this method is not considered as an alternative method to satisfy IMO regulations. Official alternatives to meet the SO_x and NO_x limits set by the IMO are to use the approved exhaust cleaning systems.

In summary, the potential impact of IMO regulations on ship emissions can be seen through switching the fuel from HFO to low sulphur fuels. This changing in the fuel resulted in a significant reduction of overall engine emissions including PM mass and number emissions, sulphate fraction and BC. In addition, the fuel change has strongly influenced to engine emission characteristics such as particulate matter chemical composition. In the future, switching the fuel combined with the modification of marine engines such as using electronic fuel injection system (common rail system) can help to save fuel consumption and further

reduce engine emissions.

5. Conclusion

In this study, an overview of the context and global impacts of recent IMO regulations implemented on the marine oil refining industry, future marine fuel mix and ship emissions has been investigated. The marine fuel limit of 0.1% (wt. %) in both Sulphur Emission Control Areas (SECAs) and Nitrogen Oxide Emission Control Areas (NECAs), and of 0.5% globally are in force by 2015 and 2020, respectively. Moreover, new vessels which built on or after 2016 and operate in SECAs must also comply with the NO_x emission limit. It has been reported that the new implemented IMO regulations will be beneficial for both public health and environment. Owing to IMO impact, the demand for low sulphur marine fuel is increasing, which requires significant changes to the refinery to increase the capacity of residue conversion processes to produce cracked gasoil, the development of larger sulphur-removal processes for residues, or the use of sweeter crude feedstock. These changes to the refinery processes can lead to an increase in greenhouse gas emissions and high capital investments. Alternative marine fuels consisting of LNG and biofuel may be suitable fuels to meet the required reduction in coastal area air pollutants and greenhouse gas emissions. It has been predicted that these two fuels can account for 50% of shipping energy demand by 2050 while the rest will still be fulfilled by conventional HFO/MGO. Switching from HFO to low sulphur fuels under IMO impact resulted in a significant reduction of engine emissions and emission chemical characteristics.

Acknowledgement

The first author gratefully acknowledges the financial support from the Government of Vietnam for a PhD scholarship and QUT for a fee-waiver.

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