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Applying Integrated Technologies for Ships to Meet Ghg Emission Reduction Strategies in The Shipping Industry

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ABSTRACT

The compliance options available to the global sulfur threshold are impacting greenhouse gas (GHG) and nitrous oxide (NOx) emissions from ships. The next regulation on GHG emissions, in addition to the ship's energy efficiency design index (EEDI) requirements, was agreed upon by IMO on its GHG emission reduction strategy in 2018. As a result, the compliance options presented in this review can highlight the role and influence of integrated fuel-to-emissions technology solutions on compliance with reduced GHG emissions regulations. Efforts to convert alternative fuels for marine engines for safe and reliable use of potential new fuels such as methanol, LNG and ammonia have been presented in this work. Furthermore, the latest technological solutions for the control of combustion products were also discussed to highlight their contributions in reducing harmful and GHG emissions from internal combustion engines. In order to comply with IMO's GHG emission reduction targets, maritime states are implementing a radical change in ship design and power generation to meet their emission reduction requirements with the challenge ahead to be solved is investment and infrastructure for production, storage and distribution of fuels to replace traditional fuels. This is a huge investment, a driving force to create a transport ecosystem to reduce carbon emissions in the future.

KEYWORDS

IMO, GHG reduction, alternative fuels, LNG, control emissions, marine shipping.

INTRODUCTION

Shipping has been and is contributing the most to global trade. By 2020, the global shipping fleet has transported 80-90% of cargo with more than 10 billion tons of bulk containers crossing the oceans to reach countries [1,2]. In the period from 2016 to 2019, the growth rate of world trade reached 18%. The increase in the volume of goods transported is also proportional to the amount of fossil fuels burned by the internal combustion engines installed on ships. According to the International Energy Agency (IEA), by 2040, the amount of fuel consumed by the world's fleet will increase by about 50% compared to today [3,4]. Moreover, the burning of petroleum fuels has been constantly releasing huge amounts of CO_2 into the atmosphere. It is forecasted that by 2050, the greenhouse gas emissions (GHG) of shipping activities will increase by up to 50% compared to 2018, despite the energy efficiency measures adopted as transport demand is expected to continue to increase [5,6]. The amount of GHG from the shipping industry (international, domestic and fishing) increased by nearly 9.6% between 2012 and 2018 (from 977 million tons to 1,076 million tons) [7].

The World Maritime Organization (IMO) has reported that GHG emissions from shipping will contribute 15% of the total emissions generated in the atmosphere by 2050 [8,8. Following a strategy to switch to using fuel oil with 0.5% sulfur content of the global shipping fleet was completed in early 2020. The next fuel-related challenge that the global maritime industry will soon face will be much more severe: the issue of greenhouse gases (GHG) [10,11]. At its 72nd session, the Marine Environmental Protection Committee (MEPC) adopted an ambitious strategy to reduce annual marine GHG emissions to 50% of 2008 levels by 2050 [8]. The ultimate goal is a carbon-free shipping industry by the end of the 21st century. For CO_2, the goal of the strategy is to reduce emissions by an average of 40% from 2008 levels by 2030, and further reduce emissions to 70% by 2050 [12,13]. In the short term, steps have been taken to enable the fleet to reduce GHG emissions. Operating trains at slow speeds is the easiest option right now, and in the near future we may see speed limits imposed on certain types of ships or in certain areas of the world [14].

However, with this approach, of course, ships' journey times will be longer and eventually, more ships will be on each route, thus increasing GHG emissions [15,16]. Moreover, the most radical solution is to decarbonize the shipping industry which will mean a shift to sustainable clean alternative fuels [17]. Through the regulation of the 0.5% sulfur threshold in global marine fuel oil from January 1, 2020, there are already a number of lower CO_2 emissions fuels used such as MGO or VLSFO. However, while using MGO or VLSFO on board ships can emit less CO_2 than HSFO, their production results in more GHG emissions at land-based refineries [12,18]. Some studies suggested that liquefied natural gas (LNG) could reduce emissions by about 20-25% compared to HSFO. However, the latest lifecycle analyzes show that only the high-pressure, 2-stroke dual-fuel engine contributed to a small reduction in GHG emissions. LNG used options, GHG emissions were equivalent to using MGO or HSFO [19,20]. On the other hand, secondary emission treatment technologies such as scrubber systems have allowed the continued use of HSFO while still helping to reduce CO_2 globally.

Furthermore, hydrogen, may be a zero-emission fuel, but today 90% of global hydrogen production involves natural gas and energy-intensive production processes that release large amounts of CO_2. Methods of producing hydrogen by electrolysis of water using renewable energy are more environmentally friendly, but the technology is still very expensive [21,22]. "Power-to-X" technology is bringing promising effects in the GHG strategy [23,24]. This technology uses electricity produced from renewable sources (wind, waves, sun, etc.) that cannot be fed into the grid to produce gaseous fuels, liquid fuels or chemicals [25,26]. For example, in the electrolysis of water to produce hydrogen and oxygen, CO_2 is added to the hydrogen in a methane reactor to produce methane [27]. Methane is a carbon neutral syngas and a very important energy carrier of the future, perfectly suitable for both cars and ships. The use of carbon neutral fuels for vehicles reduces CO_2 emissions greatly. In addition, great advances in the development of batteries and vehicles using hydrogen fuel cells have been confirmed because it does not cause pollution but the cost is still very high [28,10].

Biofuels, which come in various forms, are one of the most promising options to replace existing marine fuels for accomplishing this in the short to medium term. Plant-based biofuels, such as fatty acid methyl esters (FAMEs), or hydrogen-treated vegetable oils (HVOs) are already another renewable fuel with significantly lower emissions than petroleum oils. traditional maritime material [29]. However, global biofuel production is still far below what is needed to support today's burgeoning shipping industry. At the same time, the aviation and auto transport industries also require a huge supply. Furthermore, depending on the plant source used, the production of these fuels could have created other environmental challenges due to deforestation and the heavy consumption of fresh water. On the other hand, much of the world supply of vegetable oils will still be needed as an important food source [30]. More interestingly, ammonia is another option that attracts attention.

If the substance is burned properly, only nitrogen and water are emitted, and NOx formation can be prevented. The downside is that ammonia is highly toxic, which can raise safety concerns far beyond conventional fuels. This can cause problems when ammonia is used in marine environments. Besides, technologies to capture, separate, filter, store and reuse CO_2 are also being considered for more application in production. However, to apply CO_2 capture and storage technologies on ships, there are still many challenges that need to be solved [31]. With the goal of providing an overview of CO_2 emission reduction technologies that have been and are being applied on the global shipping fleet. This work has reviewed typical emerging technologies such as using alternative fuels, emission control measures and GHG emission recovery technologies.

USE ALTERNATIVE FUELS

In the long-term strategy to meet IMO's GHG reduction targets, using alternative fuels is seen as a promising solution. Many alternative fuel candidates that can be considered for use in marine engines include nuclear power, LNG, biofuels, methanol, hydrogen and ammonia. In this section, the characteristics and applications of typical alternative fuels are analyzed and discussed.

METHANOL

Currently, methanol has become the most commonly produced organic chemical. In 2016, about 92 million tons of methanol were produced. The feedstock for methanol production can come from fossil fuels, biogas and biomass. However, fossil fuels are still the main source for methanol production, of which 65% is for natural gas and the rest is coal. Methanol is considered a biofuel if the production of methanol is from biomass sources [32]. At ambient pressure and temperature, methanol is the simplest alcohol that exists in liquid form which is flammable to form CO_2 without SOx or to reduce the formation of both NOx and PM emissions. According to calculations by Brynolf et al.[33], the amount of CO_2 produced is about 69 g for 1 MJ of fuel over the lifetime of emissions from the combustion of methanol. Meanwhile, when burning each kilogram of methanol fuel, 1,375 kilograms of CO_2 were formed. Methanol has been tested on spark ignition and combustion compression engines in onboard tests through pilot studies or commercial projects [34]. These studies confirmed methanol to be compatible with the fuel systems of the marine engines tested. With a bunker demand of up to 370 million tons/year for over 90,000 ocean-going vessels.

According to Liu et al. [35] estimated, if 10% of the shipping ships use methanol fuel, then methanol distilleries need to produce 80 million tons/year. Indeed, many projects have been implemented on the use of methanol as fuel for marine fleets. Notable projects using methanol fuel have been recorded including 7 chemical tankers with a total design capacity of 70MW of Waterfront Shipping, Marinvest and MOL, marine methanol projects of Effship, Leanship, Methaship, SPIRETH, PILOTHy, MethShip and the Green Maritime Methanol Consortium project. In addition, projects using dual fuel methanol-diesel have been implemented such as the Stena Lines ferry equipped with a methanol-MGO dual-fuel engine with a capacity of 24MW [36]. According to the IMO report, methanol has become the 4th most common fuel used in shipping. In 2018, international shipping fleets consumed 160000 tons of methanol [12,37]. However, the calorific value of methanol is only half that of diesel, thus requiring ships to have twice the fuel tank volume or to receive fuel more frequently. Methanol is more corrosive than conventional fuels, so care should be taken in choosing the right material or using a special coating that is resistant to corrosion. Therefore, to be able to successfully apply methanol on board ships, it is necessary to have more specific regulations and instructions from the engine manufacturer as well as the registry.

LNG

The use of LNG as a ship's fuel is not new. It is LNG tankers that have used this gas to run ship engines since the early 1960s. According to marine engine manufacturers, the use of LNG can reduce CO_2 emissions by 20-25%. The biggest challenges when using LNG as marine fuel are the flammable nature of these gases [38]. Therefore, the ship's fuel systems are very complex and require specialized fuel supply and storage networks at ports around the world [39]. The use of LNG as an alternative fuel to comply with ECA emission restrictions is an option used on existing ships and is planned for new-build ships. Natural gas stored as LNG as an alternative fuel is considered the most likely option in the short to medium future because it can be easily accommodated by available engine and system technologies, regulated by law, and the worldwide operating and fuel costs of natural gas are feasible in terms of shipping operations [40].

LNG used for main engines on ships is usually stored in isolated and high-pressure tanks. These tanks are complex structures and require a lot of deck space that could instead be used for cargo storage. Liquefied natural gas is becoming increasingly popular as a marine fuel. From the years 2014-2020, the global investment of LNG in the maritime industry is expected to be 64.4 billion USD. The number of ships using LNG as fuel is growing rapidly, and an increasing number of infrastructure projects are planned or proposed along major shipping routes. More than 900 LNG-fuelled vessels were in operation and registered worldwide as of early 2020. According to a recent report by Pavlenko et al. [19], in the ferry, offshore, and tanker segments. and container ships have seen a steady increase in LNG-fuelled ships, as shown in Figure 1. The complete elimination of SOx and PM emissions, while reducing NOX emissions by up to 85% by using LNG, is a very solid basis for the use of LNG, especially in areas of strict emission control or coastal and sensitive ecological zones. In addition, LNG also reduces CO_2 emissions by at least 20%.

Table 1 shows the emission factors of HFO, MDO and LNG fuels. It is clear that LNG is an option that meets the criteria of protecting human health and the environment. Figure 2 shows the emission components for 2 types of MAN engines (6S70ME-C engine using MDO and HFO fuel, 6S70ME-GI engine using LNG fuel). Using LNG as fuel for ships will reduce SOx emissions by 90-95%. This reduction will also be mandated worldwide from 2020. Furthermore, the lower C content of LNG compared to conventional fuels allows for a 20-25% reduction in CO_2 emissions. New technologies have helped to lower the rate of methane emissions during combustion, so the use of LNG can help reduce GHG.

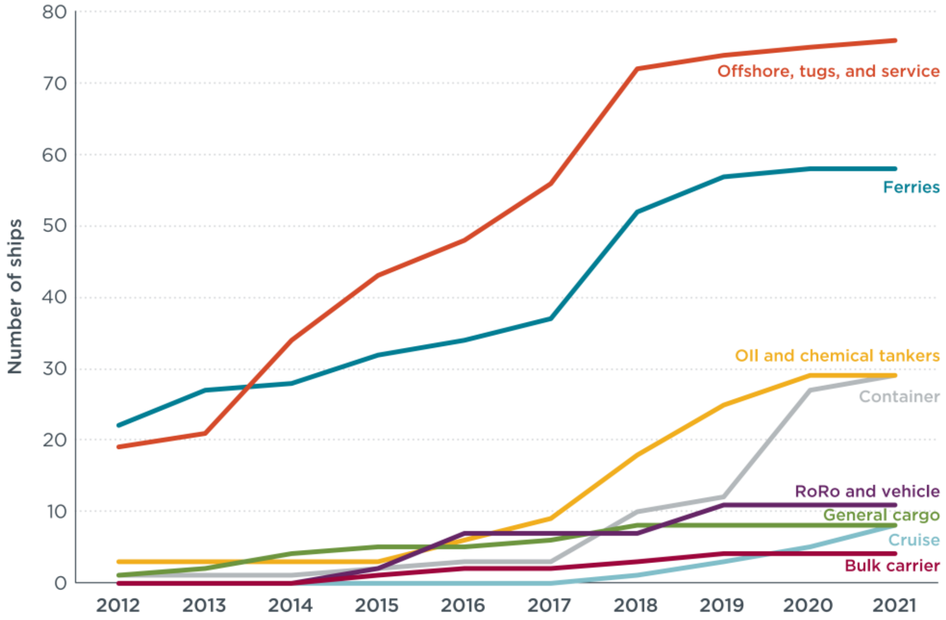

Figure 1. Growth of international commercial fleet using LNG [19]

Table 1. Emission factors of HFO, MDO and LNG fuels [41]

Emission (g/g)	HFO	MDO	LNG
SOx*	0.049	0.003	-
CO_2	3.114	3.206	2.750
CH4	-	-	0.051
NOx	0.093	0.087	0.008
PM	0.007	0.001	-

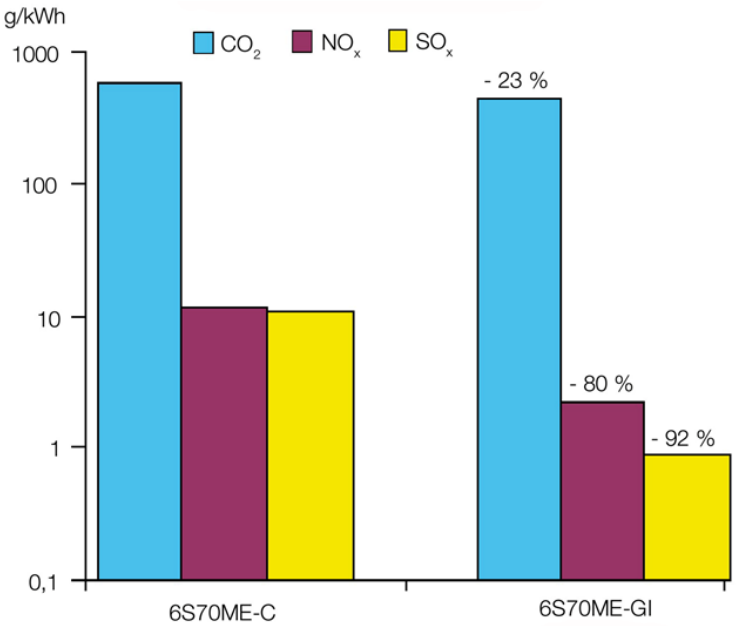

Figure 2. Comparison of emission composition of engines using conventional fuels and LNG [42]

Ammonia

Ammonia is a common chemical compound used mainly in the production of fertilizers for the agricultural industry. However, in recent years, ammonia is becoming a widely used chemical to serve new requirements in the shipping sector. First of all, ammonia has been used extensively in selective catalytic reduction (SCR) systems to remove emission components such as NOx and PM from the exhaust gas. Besides, it is the source of hydrogen modulation for fuel cells [43]. Recently, the increasing pressure of GHG reduction strategies posed by IMO has forced designers and researchers to switch to using fuel from ammonia, a fuel that does not emit GHG [44]. Ammonia can be used as a potential alternative fuel for marine engines through pure fuel, dual fuel or emulsion. However, using pure ammonia is very difficult and requires modification of the engine configuration. Moreover, with its properties as an additive, it can stimulate complete combustion, improving fuel efficiency. Therefore, the research directions focus mainly on the use of dual fuel and three-phase emulsion fuel [45].

Recently, NH_3 has attracted extensive attentions thanks to its high hydrogen content and ease of liquidation at mild conditions [46][47]. More countries have begun to feature ammonia for a low carbon fuel in their energy-related policies. Very recently in January 2020, the US House of Representatives published a draft legislation that specifically defined ammonia as a “low-carbon fuel” [48]. One month later, the UK’s Royal Society published a policy briefing titled “Ammonia: zero-carbon fertiliser, fuel and energy store”, bringing information and analysis to assist the development of regulatory policies for using ammonia within the clean energy technology portfolio [46]. Clearly, the potential of ammonia for a clean energy future has been increasingly realised and finally reached a higher level within policymakers. Application of ammonia as a marine fuel is noticeably attracting attention of the shipping industry, as a response to recent mandates by the International Maritime Organization regarding lowering of sulfur content of fuels and also the ultimate decarbonization of shipping by 2050.

Marine industry experts from AP Moller - Maersk A/S, Fleet Management Limited, Keppel Offshore & Marine, Mc-Kinney Moller Zero Carbon Shipping of Maersk, Sumitomo Corporation and Yara International ASA announced that the parties have signed a Memorandum of Understanding in the establishment of a comprehensive and competitive supply chain for the delivery of ship-to-ship green ammonia silos at the Port of Singapore [45]. Keppel Offshore & Marine will develop and design Ammonia transport and LPG storage vessels, which can be modified and converted into tanks containing ammonia. In addition, Keppel will cooperate with the Singapore maritime authority to issue regulations and guidelines for the exploitation and use of ammonia fuel for the marine industry.

Further more, MAN Energy Solutions, which is part of the Volkswagen Group, is currently developing an ammonia-fueled marine two-stroke engine and has published a perspective document concerning [49]. The European-based Transport and Environment Group has estimated potential ammonia usage in marine applications of at least 1.2 PWh/year in Europe alone by 2050. The report puts this in the context of current EU electricity generation in 2015 of 3.2 PWh/year [50]. A detailed comparative analysis with traditional fuels also shows that the use of ammonia as a fuel results in a lower environmental impact in terms of overall ecotoxicity and ocean acidification.

CONTROL EMISSIONS

Exhaust gas return to the intake manifold is a method of extracting part of the exhaust gas from the engine back to the intake manifold, where it mixes with the intake air before being loaded into the engine's cylinders. The purpose is to reduce the oxygen content, increase the amount of inert gas such as CO2 in the intake air of the engine cylinder, reduce the combustion speed, reduce the maximum combustion temperature thereby reducing the NOx content generated [51,52]. The results of many studies have shown that the use of an exhaust gas return system can reduce the amount of NOx by up to 80%. If the exhaust gas recirculation is combined with the humidification of the intake air, the NOx concentration is further reduced. However, the exhaust gas returns to the intake manifold changes the fuel-air ratio of the combustion mixture, the combustion process in the engine cylinder is changed in a bad direction, increasing the amount of soot (PM), the unburnt hydrocarbons (HC) and increased COx emissions. These problems have been significantly overcome by Yanmar through the installation of a DPF (Diesel Particulate Filter) soot filter on the discharge line.

The optimization of the fuel injection process is through an electronically controlled fuel injection system used in conjunction with the exhaust gas return system to the intake manifold [53-55]. HSFO fuel remains the main fuel for marine operations after 2020. Therefore, in order to comply with emission control requirements, ships must be equipped with a wet exhaust cleaning system. However, when installing exhaust gas cleaning systems, factors such as time, installation costs, costs arising from system waste should be taken into account [56]. Liability stakeholders for maintenance and repair in the event the exhaust gas cleaning systems fail to function. Dry exhaust gas cleaning systems require the use of very expensive reagents such as urea, calcium hydroxide. It requires large storage space, so it is rarely chosen by ship owners [57,58]. Similar to the TWC fitted to gasoline engines, the Diesel Oxidation Catalyst (DOC) has proven effective at removing UHC and CO from diesel exhaust. Further development of these catalysts today mirrors that of TWCs, with focuses on low temperature conversion and reduction in precious metal requirements [36,59].

NOx removal from diesels has been an area of intense focus particularly because a TWC cannot typically be used on diesels as their lean operation means a TWC would not be effective in reducing NOx. In common with all other pollutants, NOx can be controlled using both engine methods or after-treatment. On all modern vehicles the two approaches are used together [60,61]. A modern after-treatment system would include a Lean NOx Trap (LNT) [62], which can store NOx at low temperature, and a Selective Catalytic Reduction system (SCR) which can reduce NOx at temperatures higher than ~200 °C [63]. SCR systems are complex and expensive, requiring an aqueous urea solution injection upstream of the catalyst – and hence a separate tank and injection system for the DEF. An SCR is typically followed by an Ammonia Slip Catalyst (ASC) in order to remove any ammonia, required for the SCR reaction, from the engine exhaust. In common with all other catalyst technologies, current development includes reducing the precious metal requirements and reducing light-off temperatures [64]. Additionally, for NOx reduction, combinations of technologies including more than one SCR as well as an LNT are being considered in order to meet the most stringent legislative requirements [65].

The Open-loop Scrubber system is designed to be simple, easy to install on board. Operation, testing and maintenance are simple for this system. Furthermore, the system does not require waste storage space. However, some of its disadvantages can be listed as system cooling requirements, operation depends on the alkalinity of the water, requires a very large volume of water to clean, so the system consumes a lot of energy [66]. The Closed Loop Scrubber system is self-contained, requires little maintenance, but requires a large wastewater storage space. In addition, installation and operation difficulties can be faced with multi-fuel engines [19]. Finally, there is the Hybrid Scrubber system, which is suitable for many different types of ships and operating areas, but this system requires many modifications to the ship structure.

Besides, more storage space for chemicals, additives and wastewater is required, resulting in higher installation time and costs. Therefore, the shipowner choosing the most suitable exhaust cleaning system should consider factors such as: available installation space on board, operating area and chartering plan, capacity of engines and boilers on board, availability of fresh water and power to operate on board. Currently, two ship exhaust cleaning systems Closed-loop scrubber and Hybrid Scrubber have been approved by many countries for ships to use in port waters and equipped with equipment to receive sediment from these systems at the port [67]. In deed, in 2018, most of the exhaust cleaning equipment in the world has been installed or ordered for cruise ships and passenger ships operating in ECAs [68][69]. Up to 50% of these equipment systems are closed-loop or hybrid designs to ensure operation in restricted areas such as certain ports in North America. But these trends have been reversed in the past few months, with bulk carriers, tankers and container ships being the three segments that order the most exhaust cleaning equipment. Open-loop systems are by far the most popular design, due to their relative simplicity, especially as retrofits on existing ships [70].

CONCLUSION

World shipping annually emits about 940 million tons of CO_2 and accounts for about 2.5% of total global GHG. The IMO's ambitious strategy to reduce GHG emissions in the maritime sector is to reduce emissions by an average of 40% from 2008 levels by 2030, and further reduce emissions by up to 70% by 2050. In deed, there are concerns that improving ship design and operation through energy-efficient technologies may not be enough to meet the goals outlined above. Therefore, it is necessary to convert most of the energy used for ships from fossil fuels to alternative low-carbon energy, which includes clean and sustainable energy in the future. Several different types of alternative fuels have been discussed and analyzed in this review including methanol, LNG, and ammonia fuels. On the other hand, technological solutions to reduce secondary emissions from marine engines were also discussed at the end of this work.

LNG is commercially attractive and is available worldwide in quantities that could meet shipping fuel needs in the coming decades. Demand for LNG as a specialty fuel is expected to increase for vessels that regularly operate in North American and Nordic waters with existing and future stringent NOx emissions regulations. Alternative fuels, such as methanol and biofuels, are expected to only be able to serve a small portion of the market in the short term. They will be an alternative in some local areas, where supply matches our commercial operating model. Looking further into the future, hydrogen as fuel, with fuel cell technology combined with batteries, is an emerging alternative. Especially for small ships operating on fixed routes and with a secure power supply.

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