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Alternative Fuels – Prospects for the Shipping Industry

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ABSTRACT: Emissions from the sea transport sector are one of the major contributors to the climate change due to extreme dependency on fossil fuels. Environmental revolution has pushed shipping to focus significantly on the potential application of different cleaner fuels and sustainable source of energy solutions. The global shipping industry is considering alternative fuel options that meet economic feasibility and safety requirements. There is a variety of alternative fuel types available for shipping, such as liquefied natural gas (LNG), methanol, hydrogen, ethanol, ammonia and others. For many years, the advantages and disadvantages of using selected alternative fuels have been analysed from the point of view of sea transport costs. This paper presents the basic parameters for comparing different fuels, the characteristics needed to adopt alternative fuels in maritime transport. In addition, it provides an overview of the main technical challenges and drivers for the adoption of alternative marine fuels assessed through infrastructural, economic and environmental dimensions.

1 INTRODUCTION

With over 80 percent of world merchandize trade carried by sea. Maritime transport is considered the most attractive option for transferring commodities [1]. Maritime transport is as essential component of world economy is responsible for safe delivery of grains, food, solid and energy raw materials and consumer goods [2].

Climate change is becoming a growing global challenge, so reducing greenhouse gas (GHG) emissions is essential. At the same time, global energy demand is projected to increase by 28 % between 2015 and 2040. The sea transport sector is the largest user of fossil fuels. The fuel consumption of shipping is dominated by three type of ships: oil tankers, container ships and bulk carriers. Ships carry on-board thousands of metric tons of fuel for consumption, which is great source of strong environmental pollutants such as CO_2, NO_X, SOx, ozone, benzene and particulate matter (PM). At the same time, the fuel oil price is increasing and public is becoming more concerned about the environmental footprint of shipping. Global CO_2 emissions have exhibited a rapid increase. According to the International Energy Agency (IEA), CO_2 emissions from the transportation sector represented 24 % of global CO_2 emissions during the year 2016. Maritime transportation is a significant source of anthropogenic SO_x and NO_x emissions, which account for 13% of global SO_x emissions and 15% of global NO_x emissions. [3].

The contribution of global carbon dioxide emission from various sources is shown in Figure 1.

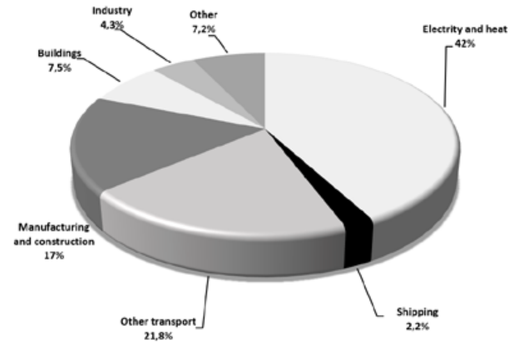


Figure 1. Shipping contribution to global CO_2 emissions. Source: [4]

If treated as a country, international shipping would have been the sixth largest emitter of energy-related CO_2, just above Germany, with total emissions in the range of 900 million tons of CO_2 per year [5]. A various parts of shipping industry are actively examining a number of ways to reduce emissions, which are primarily linked to reducing fuel consumption. In the longer time, the ship industry is also exploring a number of alternative fuel source. In April 2018 Marine Environment Protection Committee (MEPC) adopted a resolution on the IMO's Initial Strategy for reducing greenhouse gas (GHG) emissions from international shipping. To address such concerns, the International Maritime Organization has proposed measures to reduce greenhouse gas (GHG) emissions by at least 50% by 2050 [6]. International shipping needs to reduce its Carbon Footprint (CF) by 40 % by 2030, and by at least 70 % by 2050 compared to 2008. Reductions in carbon intensity are to be achieved by ships by implementing the next steps of the Energy Efficiency Design Index (EEDI) for new ships. On June 17, 2021 the IMO accepted amendments to MARPOL VI during MEPC 76, introducing provisions for the Energy Efficiency Existing Vessel Index (EEXI) and a requirements to reduce the carbon intensity of operations through the carbon intensity indicator (CII). The vessel’s achieved EEXI indicates its energy efficiency compared to the baseline. The ship’s achieved EEXI index will be then compared to the required energy efficiency index of the existing ship based on the corresponding reduction factor expressed as a percentage of the baseline value of the Energy Efficiency Design Index (EEDI. EEXI generally applies to any vessel of 400 gross tonnage and above, while CII applies to vessels of 5000 gross tonnage and above. As of January 1^{st} 2023 all ships are required to calculate the achieved EEXI to measure their energy efficiency and begin collecting data for annual operational CII. This means that the first annual reports will be completed in 2023, and initial CII assessment will be granted in 2024. To mitigate sulphur emissions, from January 1^{st} 2020, the limit for sulphur in fuel oil used on-board ships operating outside designed Emission Control Areas (ECAs) was reduced to 0.50 percent in global seas [7]. This will significantly reduce the amount of sulphur oxides emanating from ships and should have health and environmental benefits for the world, particularly for populations living close to ports and costs. There is an even stricter limit of 0.10 percent already effect in ECAs, which have been established by IMO. This 0.10 percent m/m limit applies in the four established ECAs: the Baltic Sea area; the North Sea area, the North American area (covering designated coastal areas of the U. S. and Canada); and the Caribbean Sea area (around Puerto Rico and the United States Virgin Islands). Annex VI of the International Convention for the Prevention of Pollution from Ships (MARPOL) also establishes limits for NO_x emissions from marine diesel engines. The IMO emissions standards are commonly referred to as Tier I, II and III. The Tier I standards were defined in the 1993 version of Annex VI, while Tier II and III standards were introduced Annex VI amendments adopted in 2008.

While the IMO has not entered into any binding agreements on decarbonisation, the European Union (EU) is pushing for stricter GHG reduction regulations within its jurisdiction. For example, the "Fit for 55" package launched in 2021 aims to transition the EU maritime sector to decarbonisation by reducing greenhouse gas emissions by at least 55% by 2030 compared to 1990 levels. In 2020 The European Parliament passed a resolution to include shipping in the European Emissions Trading System from 2023, with a goal of achieving a 40% reduction in CO_2 emissions by 2030 [1]. An alternative to reducing shipping emissions and meeting regulations is to switch from fossil fuels to new propulsion technologies, such as alternative fuels. A special topic of IMO discussion is the needs and possibilities of countries in the process of energy transformation towards low/zero –emission alternative fuels for shipping. The discussion emphasizes that the decarbonization of international shipping is a priority for IMO. The IMO Initial Strategy on the reduction of GHG emissions from shipping sets key ambitions. The IMO has set two main goals. The first is to reduce annual greenhouse gas emission from international shipping by at least half by 2050 compared to 2008 levels, and work towards phasing out GHG emissions from shipping entirely as soon as possible in this century [8].The second goal includes The Initial Strategy, which aims to reduce the carbon intensity of international shipping (to reduce emissions per transport work) by at least 40% on average in international shipping by 2030, aiming to reach 70% by 2050 compared to 2008. Policy recommendations comprise of increasing the stringency of operational carbon intensity standards to encourage the move to low-carbon fuels; an evaluation of well-to-wake emissions; the mandating of zero-emissions ships; and an acceleration of research, design and development. Activities are also focused on solutions to overcome barriers to global access to low and zero-emission marine fuels. Attention is drawn to the current scarcity of renewable fuels such as hydrogen, ammonia and methanol. The Initial Strategy will be revised by 2023.

The paper presents the basic parameters for comparing of the following alternative fuels: LNG, hydrogen, ammonia and methanol, the characteristics needed to adopt alternative fuels in maritime transport. In addition, it provides an overview of the main technical challenges and drivers for the adoption of alternative marine fuels assessed through infrastructural, economic and environmental dimensions.

2 CHARACTERISTIC OF ANALYSED FUELS

Currently, the dominant fuel in international shipping is Heavy Fuel Oil (HFO) (79% of total fuel consumption by energy value in 2018, based on cruise allocation). However, significant changes in the fuel mix have been observed in recent years. It was found that HFO consumption decreased by approximately 7% (absolute reduction of 3%), while marine diesel (MDO) and liquid nitrogen (LNG) consumption increased by 6 and 0.9% (absolute increase of 51 and 26 respectively %). It is estimated that methanol has become the fourth largest fuel consumption [9]. Different scenarios for climate targets and support for sustainable and smart mobility strategies assume that renewable and low-emission fuels should account for between 6% and 9% of all fuels in international maritime transport in 2030 and between 86% and 88% by 2050 to contribute to the achievement of EU-wide greenhouse gas emissions reduction targets [10]. There is a variety of alternative fuel types available for shipping, such as gaseous fuels such as LNG, LPG, methanol, hydrogen and ammonia, biofuels, fuel cells, among others. The industry must choose the future marine fuels by evaluating factors such as environmental impact, technical performance, availability, cost and infrastructure [11]. Among the proposed alternative fuels for shipping, IMO has identified LNG, hydrogen, ammonia, and methanol as a most promising solution.

2.1 *LNG*

Natural gas, in the form of Liquefied Natural Gas (LNG), is the most frequently used alternative fuel in shipping [12]. LNG has been used to power the diesel propulsion systems since the delivery of the Provalys vessel in 2006.

LNG is a colourless and non-toxic liquid, that is formed when natural gas is cooled to -162°C. During this process, the volume of gas is reduced 600 times, facilitating safer storage and transportation. LNG is a cryogenic liquid that rapidly evaporates, when exposed to normal atmospheric conditions. Such a rapid phase transition phenomenon can lead to critical risks, and the ignition of this flammable gas mixture can cause catastrophic events in particular fire and explosion [13]. LNG combustion is as operationally efficient as HFO. LNG is considered one of the most viable solutions, because it is the cleanest fossil fuel used in shipping. The use of LNG as a fuel for marine transportation will result in environmental benefits, including a reduction of carbon dioxide (CO_2) emissions by 25%, nitrogen oxides (NO_x) by 90%, sulphur dioxide (SO_2) and fine particles by 100% [14]. Although LNG is the cleanest fossil fuel available, but the slippage of methane may offset its beneficial effect on GHG reduction [15]. In addition, the global warming potential of natural gas is an aspect that may reduce the attractiveness of natural gas as a fuel. The Tables 1 provides an overview of advantages and disadvantages of LNG.

Table 1. An overview of advantages and disadvantages of LNG as an alternative fuel

Advantages	Disadvantages
the fastest growing gas supply source globally	high flammability
technology of gas engines is mature	methane slip- reduction of CO_2 is limited
the cleanest fossil fuel available today	40% lower volumetric energy density than diesel
high energy density – approximately 18 % higher than that of HFO	limited infrastructure-necessary investment in LNG infrastructure
measurable reduction of CO_2, SO_x, NO_x, and particles emissions	treated as a short-term solution, especially when the goal is zero-emission shipping

Source: [13-16]

In marine transportation, there are currently two different options for operating engines with LNG: engines that run solely on natural gas, and dual-fuel engines that either run on a mixture of diesel and natural gas, or switch between diesel and natural gas operation.

2.2 *Hydrogen*

Hydrogen (H_2) is currently an energy option in the context of decarbonisation in various sectors of the industry, as it has the greatest potential for zero emissions, especially when produced from renewable resources. The use of hydrogen as ship fuel represents a significant opportunity for clean energy production; however, it comes with significant implementation challenges. With the tightening of IMO regulations to reduce greenhouse gas emissions from ships, liquefied hydrogen has been recognized as an alternative to marine fuels.

Hydrogen is a colourless, odourless, tasteless, nontoxic, relatively unreactive and flammable gas with a wide flammability range. Hydrogen is commonly produced by converting natural gas or coal into hydrogen gas and CO_2. For long-term sustainability goals, it should be generated from renewable energy through electrolysis [17]. To obtain liquid hydrogen, the fuel must be stored at temperatures below -253°C, which requires a large input of energy. Hydrogen is flammable over a wide mixing range with air, the flammability range is from 4 to 74% by volume [18]. Hydrogen (in the gaseous phase) is lighter than air, which means that in the event of a leak, the gas will quickly rise and be diluted, reducing the risk of accidental ignition and combustion.

Two types of hydrogen are currently being studied as fuel options: compressed hydrogen and liquefied hydrogen. These options have the advantage of an uncomplicated fuel production process, as only one additional step (liquefaction or compression) is needed to produce the final fuel. However, the energy density of these fuels is lower than alternative fuels. The low energy density makes the use of hydrogen make the most sense for short shipping application, where the amount of fuel that needs to be stored on board is the smallest. The advantage of hydrogen options is that none of them require reforming or cleaning on board before use. Some applications of hydrogen are currently being considered, such as gas turbines, fuel cells or internal combustion engines in stand-alone operations [19]. The Tables 2 provides an overview of advantages and disadvantages of hydrogen.

Table 2. An overview of advantages and disadvantages of hydrogen as an alternative fuel

Advantages	Disadvantages
carbon and sulphur free-reduction of emission electrolysis process is mature and available very high gravimetric energy density suitable for relatively short distance	low volumetric energy density – efficient storage of fuel is high low temperatures below -253°C to liquefy a flammable gas with very low activation and ignition energy lack of marine transport experience permeability – material challenges high fuel cost high cost of bunkering infrastructure lack of safety regulation for bunkering a lack of standardised design and fuelling procedures

Source:[17-19]

With properly advanced technology, there are not principal limitations to production capacity that could restrict the amount of available hydrogen to the shipping industry.

2.3 *Ammonia*

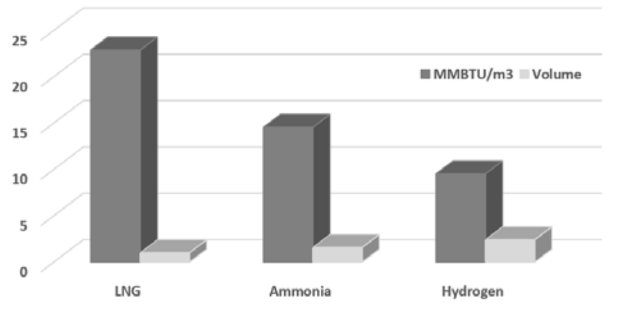
In the Full Report of the Fourth IMO GHG Study 2020, it was assessed that ammonia is one of the promising alternative fuels. Ammonia is an important option for zero-carbon fuel, because it can be used either directly as a fuel in internal combustion engines or as a chemical carrier for hydrogen to be used in fuel cells [20]. Around 80% of the world’s production of ammonia is as a widely used chemical and its production amounts to approximately 200 million tons yearly and is used as feedstock for the production of fertilizers [21]. Unfortunately, currently most of the hydrogen used to produce ammonia is produced using fossil fuels such as natural gas and coal, and only a small portion is produced from other sources such as electrolysis. Although large quantities of anhydrous ammonia are now being sold and handled around the world it is not considered one of the most toxic cargoes handled in shipping. The risk of fire and explosion is lower than with other fuels due to its low flammability limit and strict ignition conditions. Nonetheless, with the right conditions there exists a potential for ammonia to ignite. Thus, in principle ammonia is required to be isolated from any ignition source on-board vessel, when used as a marine fuel. Small fires involving ammonia can be extinguished with dry chemicals or CO_2 and large ammonia fires can be extinguished through water spray, fog, or foam emissions [22]. The main risks associated with ammonia are due to its toxic and corrosive nature. Thus, liquid ammonia allows storing more energy per cubic meter than liquid hydrogen, and moreover, without the need for cryogenic temperature storage - as is the case with liquid hydrogen. Storing ammonia at -33.4°C is technologically easier and cheaper than storing hydrogen at -252.9°C [23]. There is therefore no need for a cryogenic system to store ammonia. In principle, therefore, ammonia storage is much less complicated than hydrogen and LNG. Ammonia can be stored at ambient temperature (20°C) at a pressure of just 10 bar. Liquid ammonia has a higher energy density (12.7 GJ/m3) than both liquid and compressed hydrogen, which benefits fuel storage [24]. Ammonia can be decomposed to produce hydrogen, and can also be burned directly [25]. Ammonia offers the possibility of storing more hydrogen in liquid form without the need for cryogenic storage (-33.4°C for ammonia versus -252.9°C for hydrogen), thus NH3 is a suitable hydrogen carrier [26]. This is an important consideration because hydrogen is much more expensive to store than ammonia, despite the fact that the two fuels have similar energy densities. They have already begun work on ammonia-powered marine engines; the first ammonia-powered marine engine is expected to enter service around 2024 [25]. The Tables 3 provides an overview of advantages and disadvantages of ammonia.

Table 3. An overview of advantages and disadvantages of ammonia as an alternative fuel

Advantages	Disadvantages
carbon free fuel stored as a liquid at ambient temperature low flammability-low risk of ignition commonly shipped around the world available port loading infrastructures-commonly traded commodity storage is easier and less expensive than H_2 experience in handling – established safe handling procedures	toxic properties-the need for a safety equipment NO_x and N_2O are generated when burned slow flame propagation speed corrosive nature-incompatible with various industrial materials larger storage tanks lack of regulations issues of toxicity, safety, and storage production reliant on natural gas

Source:[20-26]

LNG, liquefied ammonia and liquefied hydrogen have different physical properties. Analysis has shown that liquefied ammonia and liquefied hydrogen were disadvantageous as far as maritime transportation cost is concerned due to calorific value and density per unit. However, price competitiveness of ammonia and liquefied hydrogen may vary in the future based on policy support for carbon trading schemes or subsidies [27]. On an equal volume basis, LNG transports 22.88 MMBTU/m3 of energy, 14.53 MMBTU/m3 of liquefied ammonia, and 9.51 MMBTU/m3 of liquefied hydrogen. In order to transport the same amount of energy, assuming that the cargo hold size for LNG is 1.00, a cargo hold about 1.57 times larger and about 2.41 times larger is required for liquefied ammonia and liquefied hydrogen, respectively (Fig.2.).



*Volume: Require volume for transporting the same energy
Figure 2. Physical properties of gas fuels. Source: [27].

2.4 *Methanol*

Methanol (MeOH) is a substance commonly used in the chemical industry to make consumer and industrial products, but is also used as an alternative marine fuel. Methanol is also well known as a fuel for cars and similar engine applications. Every year over 70 million tons of methanol are produced globally.

Methanol is produced mainly via catalytic conversion of synthesis gas (CO and H_2) from natural gas reforming, coal gasification or synthesis from biomass. Currently, many research and production initiatives are being undertaken that treat solid and liquid forms of forest biomass (such as pyrolysis liquid, forest residues, black liquor, etc.) as raw materials for methanol production [28]. Methanol can also be produced by catalytic synthesis of carbon dioxide (CO_2) and hydrogen obtained via electrolysis. Methanol was classified, as per European classification (modified 67/548/CEE and 1999/45/CE directives), as an easily flammable fluid. Following the European Classification (modified 1272/2008 Regulation), methanol is classified as a toxic substance of category 3, and as a hazardous substance for health of category 1.

There are also fewer challenges in adopting methanol as a marine fuel compared to LNG or hydrogen. Investigations shows that the handling and installation of a liquid like methanol had clear advantages over gas or cryogenic fuels regarding fuel storage and bunkering. Because methanol is a liquid, it is very similar to marine fuels such as heavy fuel oil (HFO). This means that existing storage, distribution and bunkering infrastructure could be used for handling of methanol. Only minor modifications of infrastructure are required [29]. From an environmental perspective, methanol is readily biodegradable in both aerobic and aquatic environments.

Methanol requires larger storage volumes or more frequent bunkering as compared to conventional fuel oils. As with other fuels, methanol's future will be determined not only by the upscaling of its production, but also by its availability at various ports and the future cost of the fuel. The Tables 4 provides an overview of advantages and disadvantages of methanol.

Table 4. An overview of advantages and disadvantages of methanol as an alternative fuel

Advantages	Disadvantages
liquid at ambient temperature	lower volumetric energy density than diesel
potential of widespread availability	central nervous system toxic fuel
retrofitting ships is not expensive	highly flammable – low flash point, require more extensive monitoring
the same bunkering and safety standards as conventional marine fuels	
easier to store and handle than hydrogen and ammonia	
low investments and bunkering infrastructure	

Source:[28-29]

3 POTENTIAL AND LIMITING FACTORS

Alternative fuels have great advantages as well as their own problems. An important aspect of the use of alternative fuels is the identification of barriers that hinder their use in maritime transport. The possibility of using alternative fuels in the maritime sector strongly depends on the type of fleet, technical parameters of ships, ship operation, investment costs, environmental impact and geographical location, which determines the availability of alternative fuels. Several important criteria have been identified, which are used in the selection of alternative fuels (Fig. 3.).

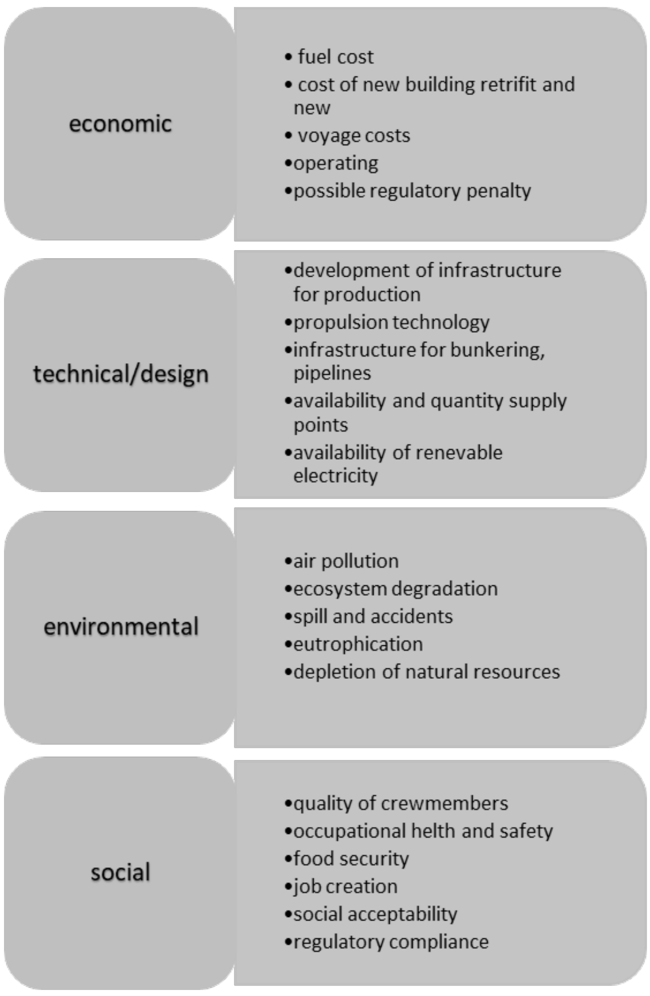


Figure 3. Main aspects important for evaluation of alternative fuel solutions for shipping

It is recognized that the cost of fuel is the main criterion for evaluating alternative marine fuels and that significant increases in fuel costs will be borne by ship owners, ship operators, shippers and, consequently, end consumers. The total cost for a fuel includes the production cost, transportation, storage cost and possible regulatory costs in the future (such as carbon tax). Compared to hydrogen and ammonia, LNG currently has a lower cost, as among alternative shipping fuels, it is widely available shipping fuel today [30]. Alternative fuels not only vary in price among themselves, but also independently vary considerably from port to port around the world. Therefore, fleet operators are making decisions not only about what to bunker with, but also where to bunker. Available data indicate that estimated prices for fuels derived from natural gas, such as LNG and methanol, trough 2030 are associated with less uncertainty than fuels derived from renewable sources, including hydrogen and ammonia [31].

Each type of alternative fuel requires specialized infrastructure for its production, storage, delivery and combustion at port, terminals and ships. Building and testing alternative-fuel ships involves large capital expenditures [32]. The development of alternative fuel infrastructure is hampered by economic consideration, as fleet operators choose not to make the necessary retrofits to ship engines and fuelling systems and build new vessels, fearing the high cost of both upgrades and alternative fuel. They are also concerned about the low availability of alternative fuels in ports [33]. An important aspect of fuel infrastructure construction, in addition to capital investment, is the availability of standards for fuel quality and production. To ensure the safe operation of fuels, it is necessary to standardize them. Parameters such as energy density and storage volume are important in the selection of alternative fuels for marine sector, because they affect the endurance range of ship and the frequency of bunkering. Alternative fuels with lower volumetric energy density than HFO require a larger fuel volume to provide the same cargo work, This either reduces the volume of space available for cargo transport or will reduce the vessel’s range between bunkering [34]. Increasing vessel fuel storage capacity is therefore costly and reduces the amount of space available for cargo transportation. Different solutions are currently available or under development to carry out the fuelling of LNG ships. These differ mainly due to the availability of LNG supply infrastructures and the ship type. The LNG bunkering methods currently in use are truck-to-ship (TTS), ship-to-ship (STS) and pipeline-to-ship (PTS) [12]. The most widely accepted LNG bunkering method is to use pipelines to transfer the fuel from an LNG depot to a receiving point on ships, known as pipeline-to-ship (PTS). Unfortunately, there is a lack of infrastructure in the terminals for this type of bunkering and therefore alternative methods are used. Hydrogen storage is one of the main obstacles for its wider application in the marine sector. It is estimated that new infrastructure would cost over several billion dollars in the coming decade. Ammonia is already a widely traded commodity with established supply chains and availability at most ports around the world. Compared to hydrogen, there is an extensive ammonia distribution network, and port infrastructure is available. At the same time, possible accessibility problems are pointed out, particularly in terms of geographic locations for ammonia bunkering. Methanol as an alternative fuel solution is a readily available fuel solution as there is a global production infrastructure and the potential as a fully renewable fuel of the future. Since methanol is a well-known and widely used substance, distribution infrastructure already exists, as well as experience in handling it. Bunkering infrastructure is also available, but may not be sufficient given the use of methanol as a marine fuel.

The shipping industry faces the challenge of choosing alternative fuels to decarbonize its operations, while renewable fuels and related infrastructure remain under development. Shipping companies choose multiple fuels to diversify. The most common scenario envisioned by 2050 is ships simultaneously fuelled by variants of diesel/biodiesel, methane, methanol and ammonia. This represents a significant increase in complexity compared to today's fleet, where simultaneous management of the consumption of more than one fuel type within a fleet is rare. Compliance with regulations and practical needs affect the technological potential of alternative fuel. Most metals corrode over time when in contact with fuel. Uncertainty about current and future marine fleet that may be susceptible to high levels of corrosion when using alternatives fuels shrouds the potential for adoption.

Developing a legal framework for the introduction of alternatives fuels is a challenge and requires both scientific knowledge and practical information. It is essential for a systematic and consistent evaluation in the selection of marine fuels. The ideal marine fuel will the one with the best properties that coincide with the concept of sustainable development (in terms of economic, environmental and social aspects), that contribute to the goals of decarbonisation of the maritime transport, while recognizing the pace of technological development. In addition, there is a need for international harmonization of safety standards, as well as national regulations, for both the production of fuels and their operation on-board ship.

From the environmental perspective, the amount of emissions generated by the use of a particular fuel indicates environmental friendliness. The emissions greenhouse gases and other emitted substances from fuel production and use have a direct impact on climate and thus are very important when comparing the environmental impact of different fuels. However, the emission associated with any fuel are not limited to those generated in the process of consuming it. The production of fuels contributes significantly to the total gasses emissions and should be considered together with fuel combustion. A significant portion of the emissions generated along the entire value chain of a given fuel is generated during the transportation phase. Therefore, Life Cycle Assessment (LCA), which considers environmental aspects and potential environmental aspects throughout their life cycle can be used to support analysis for the whole life benefit of the fuels. There are two primary factors that make LNG appear to be an attractive alternative for meeting Annex VI fuel sulphur content requirements. LNG enables ships to meet MARPOL Annex VI requirements in global trade, because LNG's sulphur content is significantly lower than Annex VI requirements for ECAs areas, as its sulphur content is significantly lower than Annex VI requirements for ECAs. In addition, LNG reduces NO_x emissions to a level that will meet MARPOL Annex VI requirements. In some markets, natural gas and LNG are cheaper than high-sulphur marine fuel oils, based on heating value. Currently, ammonia faces several barriers before it can be used as an energy carrier on a global scale. As a result, ammonia as a fuel still requires further research and analysis that takes into account all the effects in both the production and use of ammonia produced by different methods. First, ammonia should be produced cheaply. Current methods still rely on hydrogen production contributes significantly to climate change. Globally, about 420 million tons of CO_2 are emitted into the atmosphere during ammonia synthesis, and it is estimated that ammonia production accounts for more than 1 % of total energy-related CO_2 emissions [35. A significant contribution of the marine sector is only possible with ammonia produced by electrolysis from renewable source. All changes in ammonia production and operation technology must be cost-effective. Burning ammonia leads to elevated levels of emissions of nitrogen oxides, which are environmental pollutants, and nitrous oxide, which is a greenhouse gas. As a result, ammonia cannot be considered a "greenhouse gas-free" or environmentally friendly energy source unless steps are taken to reduce emissions. Ammonia is also labelled as highly toxic to aquatic organisms with long-lasting effects. Most liquid ammonia spilled directly into water, dissolves forming a balance of mostly ammonium hydroxide and a little ammonia depending on the pH and temperature of the water. Dissolved ammonia poses a serious threat to aquatic organisms, killing most of them in close proximity, as lethal concentrations can be easily exceeded. The long-term effects of an ammonia spill are related to the time required to restore the original state through the nitrogen cycle [36]. Leaks or incomplete combustion can contribute to ammonia emissions into the atmosphere and, consequently, would contribute to acid deposition and eutrophication, which could harm soil and water quality. However, with careful operation and control of the combustion system, these emissions can be prevented. Currently, hydrogen produced mainly by steam reforming of natural gas, which is a fossil fuel. A by-product of this process is CO2, which is a greenhouse gas. It is estimated that hydrogen produced from fossil fuels contributes to global warming at a similar rate to the direct burning of fossil fuels. In contrast, hydrogen derived from renewable energy, such as solar power, is environmentally clean both in its generation and combustion. The actual CO_2 emissions from burning methanol result from the carbon content of the fuel as well as depending on the purity of the fuel. CO_2 from burning bio-methanol is considered climate neutral and therefore not considered a GHG gas. CO_2 emitted from biomass-based fuels is assumed to be removed from the atmosphere when new biomass is grown to replace the biomass used to produce the fuel.

Methanol has a much lower environmental impact in the event of a spill or leak than conventional hydrocarbon fuels. Methanol in case of spills into the aquatic environment is fully soluble in water, biodegradable and non-bioaccumulative. Only very high concentrations in the environment pose a lethal threat or affect local marine life. This means that a methanol spill would cause limited damage to the environment.

The impact of the use of alternative marine fuels on human health and occupational safety is important, as potential problems associated with alternative marine fuels (e.g., toxicity, flammability, explosiveness) can lead to occupational health risks for ship crews and shore personnel. The hazards posed by the properties of ammonia mean that safety principles used in the ammonia industry should be implemented on ships and the crew on board must be equipped with appropriate chemical-resistant protective clothing and breathing apparatuses.

There are a number of significant barriers that need to be overcome before ammonia can be more widely used in the shipping industry. Ammonia as a fuel can compete with fertilizers in food production, which can have serious socio-economic consequences. The question remains to be resolved: Will ammonia production be sufficient to meet the demands of agriculture and the maritime economy? Globally, ships in operation consume about 300 million tons of fuel annually. In order for ammonia to completely replace diesel fuel its production would have to be twice as large, or about 550 million tons. This is because the energy density of ammonia is half that of diesel fuel. Another important socio-economic issue in the future may be the need to support the economic transition after the reduction of coal mining and exports in the some regions of the world.

4 CONCLUSIONS

Protection of environment and sustainable growth of international sea transportation is the unquestioned goal and a common understanding for the countries as well as various stakeholders of shipping industry. To achieve the ambitious emission reduction targets set by IMO and the EU, alternative fuels within the maritime industry are receiving attention over the years from state administration, shipping company, industrial partners and academic researchers. A successful transition from fossil fuels to renewable fuels in the maritime sector requires simultaneous attention to regulation, production, distribution and ships.

In the search cleaner fuels in shipping, several solutions to find new alternative fuels that could replace fossil fuels are currently being explored. Alternative fuels such as ammonia, methanol and especially hydrogen are currently being explored by the maritime sector. Currently, the lack of infrastructure for alternative fuels is the main obstacle to the development of alternative fuel-powered maritime transportation.

The use of LNG provides a readily available transition fuel for the maritime industry. Of the alternative fuels analysed, natural gas has the least potential as a long-term solution. This is due to its characteristics, as it is susceptible to constraints and changing prices. It can be concluded that while LNG allows for air pollution reduction, it is certainly not an option for decarbonizing shipping.

Hydrogen is the most promising zero-emission fuel of the future. However, there are still some barriers and limitations that need to be addressed before its global deployment. Among others, the need to develop a production base and distribution infrastructure, as well as to further improve hydrogen storage technologies, remain among the key obstacles at present. Hydrogen is being considered as part of an intensive energy transition effort, which will only become profitable when production and demand increase significantly as costs fall. Methanol and ammonia are fuels that are cheaper to produce and easier to store then hydrogen and can be considered as potential substitutes for it. Both hydrogen and ammonia have promising potential to replace conventional fuels, because only hydrogen and ammonia have the potential for zero carbon emissions. Moreover, of the alternative fuels, methanol, hydrogen and ammonia can be produced using renewable electricity. This is expected to happen in the future due to increasing global energy demand and the time required to develop supply chain and the infrastructure for these alternative fuels.

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