UNION OF GREEK SHIPOWNERS

FOUNDED IN 1916

Survey of Alternative Fuels-Technologies for Shipping

May 2021

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Introduction

For centuries, sails were the primary form of marine propulsion. The first advanced mechanical means of propulsion was the coal-powered marine steam engine, introduced in the beginning of the 19th century. In the early 20th century, fossil fuel oil came into more general use and began to replace coal as the fuel of choice in steamships. In the second half of the 20th century, diesel engines almost phased out steam turbines. In fact, most new ships since the 1970s have been built with diesel engines, which run on Heavy Fuel Oil (HFO)[1], a residual product derived from the distillation and cracking process of petroleum. For six decades, slow-speed, HFO-burning two-stroke marine diesel engines dominated over other marine propulsion systems, fuelling a long period of robust growth in international shipping and keeping the cost of seaborne transportation low and stable in real terms for decades.

There are two constituent parts in this success story: on the one hand, a cheap (on account of it being a residual byproduct of the refining process), reliable and energy dense fuel that was widely available. On the other hand, a particularly reliable and remarkably efficient engine. Combined, these two elements are the lynchpins of today's universal marine propulsion system.

The fact that, for decades, the entire shipping industry has been using the same HFO and marine diesel oil package has led to the creation of an extensive bunkering infrastructure network worldwide to meet the needs of a global merchant fleet and its spectacular expansion since World War II.

In recent years, the growing momentum and regulatory drive towards a decarbonised future may have signaled the beginning of the end for the universality of HFO and distillates as marine fuels. While the search for new, environmentally sustainable marine fuels is still in its first stages, one thing is already clear: the era of the universal propulsion solution seems to be drawing to a close. However, candidate zero-carbon fuels have so far not been able to match the safety, reliability, cost-effectiveness, availability and energy density of HFO, leading experts to believe that the marine fuel landscape of the future will be a diverse one. Moreover, though new zero-carbon fuels are not yet technologically mature, they are more than likely to be considerably more expensive than HFO, not least because of the fact that shipping will, after decades of burning a residual fuel in low demand by other sectors, be in direct competition with land-based sectors and other transport modes. In addition, there is in still an abundance of fossil fuel reserves worldwide many of which have very low marginal costs of production.

1. Lighter fuel oils were initially consumed in marine diesel engines. Three factors led to the adoption of HFO: 1. Oil companies wish to sell residual products. 2. The use of heavy bunker C oil in steamships. 3. The swift realization that marine diesel engines could handle HFO.

As the shipping industry embarks on a long and uncertain period of transition into a multi-fuel future, shipowners will face the difficult task of deciding which fuel and marine propulsion technology to opt for or how to "future-proof" their fleets and assets.

Nowhere is the uncertainty greater than in the bulk/tramp shipping segment, which due to the service it provides and the cargoes it carries, is itinerant by nature and does not operate on the basis of a schedule or published ports of call. Thus, its *modus operandi* is inextricably linked to and heavily relies on a universal fuel being available globally, allowing ships to call at any port. A proliferation of new zero carbon fuels bodes ill for their global availability, which in turn casts doubts over the viability of the bulk/tramp shipping *modus operandi* and its ability to continue as it has for a century or so to serve seaborne trade and world economic growth in an incomparably cost-effective manner.

The changes in the bunkers supply market

Around 1970, almost all bunkers were sold by the oil majors, the so-called "7 sisters" (BP, Chevron, ESSO, Gulf, Mobil, Shell and Texaco). Changes that took place in the bunker industry altered significantly the structure of the bunkers market. Several new suppliers, such as traders and state-owned monopolies, entered the international market, in addition to the oil majors. Today, 1/3 of the bunkers market is composed of independent traders/brokers, while national oil companies and oil majors each control a 20% share[2]. The remaining 27% is composed primarily of independent local suppliers.

IMO regulatory framework - Emissions from international shipping

SOx emissions

The regulations of Annex VI of MARPOL: Prevention of Air Pollution from Ships[3], set limits on sulphur oxide MARPOL Annex VI, the main air pollutants contained in ships' exhaust gas, including sulphur oxides (SOx) and nitrogen oxides (NOx) and prohibits deliberate emissions of ozone depleting substances (ODS). SOx and particulate matter (PM) emission controls due to the sulphur content of conventional marine fuels apply to all fuel oil, combustion equipment and devices on board.

Emission Control Areas for SOx (SECAs) were introduced by the United Nations International Maritime Organization (IMO) - Marine Environment Protection Committee (MEPC) along the North American waters as well as in the North Sea and Baltic Sea in 2015. Starting on 1.7.2010, the sulphur content of fuels used in Emission Control Areas (ECAs) was reduced to 1.00% mass per mass (m/m) (from the original 1.50%). On 1.1.2015, the sulphur content of fuel in these areas was further reduced to 0.10% m/m.

Under the revised MARPOL Annex VI, the global sulphur cap in bunker fuels was reduced initially from 4.50% to 3.50% m/m effective from 1.1.2012. This was further reduced to 0.50% m/m on 1.1.2020, following a decision by the IMO (MEPC 70), based on the final report of the "Assessment of fuel

2. B. Stamatopoulos, D. Stamatopoulos – Marine Fuels, 4th edition, 2018.
3. First adopted in 1997, entered into force in May 2005 and its revised Annex VI as of 1.7.2010.

oil availability" undertaken by CE Delft[4]. Presently, the burning of HFO containing more than 0.50% m/m sulphur, with no maximum permissible sulphur limit, is allowed for vessels using scrubbers to clean the exhaust gas in order to achieve an equivalent level of sulphur emissions.

The universality of oil fuel-propelled vessels was first breached in the early 1980s with the introduction of Liquefied Natural Gas (LNG) tankers and the first LNG-fuelled ships, along with the significant increase in demand for LNG for industrial, commercial and domestic use as a cleaner and more efficient fossil fuel. In addition, the entry into force of the global IMO sulphur cap may have marked the end of the era of universal bunker fuel (i.e., one where all vessels burnt the same type of fuel). For more on this topic see the "Journey of shipping towards alternative fuels is uncertain" section below.

CO_2 emissions (a GHG)

Carbon dioxide (CO_2) emissions from international shipping represent approximately the same constant share of global CO_2 emissions over the period 2012 to 2018, i.e. approximately 2-3%[5], with bulk carriers and oil tankers having a much smaller share of CO_2 emissions, compared to container vessels, despite representing the industry's biggest segment in terms of the number of ships.

NOx emissions (a GHG)

Progressive restrictions in NOx emissions from marine diesel engines installed on board ships were included in the revised MARPOL Annex VI, with a "Tier II" emission limit for engines installed on or after 1.1.2011; followed by a more stringent "Tier III" emission limit for engines installed on or after 1.1.2016 operating in NOx ECAs. Moreover, in 2016, the North American waters and coastlines were declared as NOx-restricted areas, which means that ships with a keel-laid after 31.12.2015 must comply with Tier III NOx requirements when navigating in North American ECAs. The same restrictions will apply in the North Sea and the Baltic Sea from 1.1.2021 onwards.

Journey of shipping towards alternative fuels is uncertain

The shift to cleaner but pricier 2020-low-sulphur-compliant fuels has heightened interest in the energy efficiency of ships. Historically, the maritime shipping industry, where energy usually accounts for over half of operating costs, has responded to escalating fuel prices with innovative energy-saving strategies. To cite a recent example: in 2008, as fuel prices went through the roof, shipping lines cut their operating speeds by as much as 50%, helping many companies stay afloat amid one of the worst downturns in history. Implementation of IMO measures for the reduction of Greenhouse Gas (GHG) emissions adopted in 2011 includes the establishment of the "Energy Efficiency Design Index" (EEDI), the first globally binding climate measure. EEDI is an important mandatory tool that sets compulsory efficiency improvements of newly built vessels, with reduction targets recently being strengthened. The IMO Initial Strategy has set decarbonisation goals, which are not presently achievable with the available alternative fuels and technologies, which are discussed below. Moreover, it is not the shipping industry that can develop these and bring them on stream, but other stakeholders, such as fuel and energy providers, engine builders, shipyards etc.

4. Assessment of fuel oil availability – final report, July 2016, doc. MEPC 70/INF.6.
5. 4th IMO GHG Study, July 2020, doc. MEPC 75/7/15.

In this context, due to lower prices and downward revisions to demand resulting from the COVID-19 pandemic, fundamental efforts to diversify and reform the revenue streams of major oil and gas exporters look, more than ever, unavoidable. The U.S. shale industry has met nearly 60% of the increase in global oil and gas demand over the last ten years[6]. In 2020, investments in oil and gas supply fell by one-third compared to 2019 and the extent and timing of any pick-up in spending is unclear. So too may be the ability of the oil industry to meet demand in a timely way: this could presage new price cycles and risks to investment and energy security.

Use of LNG as a transitional marine fuel towards decarbonisation

Production and fuel supply infrastructure costs

As a result of increased global demand for LNG, U.S. LNG production, rose in 2018 to become the fourth-largest LNG exporter in the world, following Qatar (1), Australia (2) and Malaysia (3). Only three years prior, in 2015, the U.S. did not rank as an LNG exporter to put the rapid growth in U.S. liquefaction capacity into perspective[7]. Although the lack of infrastructure and the uncertainty of future prices have slowed the "dash to gas", many expect LNG to establish itself as one of the alternatives to HFO in the future. Shipping classification society, Lloyd's Register, expects LNG to take 11% of the bunker fuel market share by 2030[8]. Between the 1980s and the year 2000, the LNG bunkering infrastructure was initially developed on a conservative and rigid point-to-point basis to mitigate risks due to the high infrastructure costs and address financing constraints. LNG bunkering infrastructure still is in the early stages of development globally. Liquefied methane produced from biomass (LBG) can also use the expanding LNG infrastructure.

Storage on board and distribution issues

The evolution of LNG-fuelled engines to LNG carriers has been driven by efficiency in the past and now by efforts to lower GHG emissions. These efforts have led to the originally steam-turbine engines, shifting to Tri-Fuel Diesel Engine (TFDE) and now to slow speed diesel (MEGI or X-DF) engines. With high pressure DF engines, the combustion is nearly complete with nearly zero methane slip. However, this is not the case in low pressure engines where LNG is injected under low pressure and where GHG emissions can in fact be increased between 15 and 40% compared to using low sulphur fuels (i.e. MGO, Lindstad, 2020[9]). The Dual-Fuel Liquefied Natural Gas (DF LNG) engine is the prominent option for LNG carriers. A limited number of non-LNG carriers, less than 500, are using LNG as fuel today. Since methane is the main component of LNG, LBG should easily blend with LNG.

Life-cycle emission reduction potential

LNG can have 20-25% less tank-to-wake CO_2 emissions, a significant benefit for transitional compliance with increasingly stringent regulations. LNG is sulphur-free so there are no SOx emissions. LNG is mostly composed of Methane (CH_4). However, the comparative impact of CH_4 on climate change

6. International Energy Agency (IEA), World Energy Outlook 2020, October 2020.
7. BP – Statistical Review of World Energy, 2019 (for 2018)
8. The International Council on Clean Transportation, W. Wang, Article "The end of the era of heavy fuel oil", 9.10.2014 (https://theicct.org/blogs/staff/end-era-heavy-fuel-oil-maritime-shipping).
9. Elizabeth Lindstad (SINTEF Ocean, Marine Technology Centre, Trondheim, Norway): LNG and Cruise Ships, an Easy Way to Fulfil Regulations—Versus the Need for Reducing GHG Emissions,2020.

is more than 30 times greater than CO_2 over a 100-year period[10].Careful consideration needs to be given to methane slip (release of unburnt methane into the atmosphere). Varying and low engine loads also impact methane slip. In view of the above, using LNG as a transitional marine fuel towards decarbonisation presents challenges but should not be dismissed simply on account of the fact that it is a fossil fuel. "Green" LNG production and the liquefaction of natural gas to -173°C requires substantial energy input and storage capacity.

Limitations and challenges

Only a limited number of ports have established local rules for LNG bunkering, while there is an ISO Standard [ISO 20519:2017] "Ships and marine technology - Specification for bunkering of liquefied natural gas fuelled vessels". Lack of LNG bunkering infrastructure for LNG-fuelled ships in major ports of call worldwide is a market-barrier to further widespread use of LNG as marine fuel.

Safety challenges

With the adoption of the IMO IGF[11] Code for Liquefied Natural Gas (LNG) and Compressed Natural Gas (CNG), in effect since 1.1.2017, an international regulatory framework for the design and construction of LNG-fuelled ships has been well established. LNG–burning ships require specially trained crews. These officers are in short supply worldwide.

Conclusions on the use of LNG

According to data from Clarksons Research Limited 2020 Database[12], regarding non-LNG carriers, using LNG as fuel is more viable for tankers than for bulk carriers and general dry cargo ships, while for container vessels, LNG could be viable on certain routes. LNG is a better fossil fuel which is already in use but not viable for a significant portion of the world fleet. The energy density of LNG is 40-45% lower than that of HFO. There is high Capital Expenditures (CAPEX) cost of fuel storage and containment systems in non-LNG carriers. Therefore, the use of LNG as marine fuel can become a significant interim solution in conjunction with DF engines for some sectors only.

Biofuels

Production and fuel supply infrastructure costs

A sustained supply of efficient biofuels from renewable sources with worldwide availability for ocean-going shipping may not reasonably be expected. Certain renewable resources that can be used as biomass, such as fields, forests and crops, are needed to meet other, more basic human needs. Ethically, allocating resources is non-negotiable when planning biofuel supply chains and production. For these reasons, second and third generation biofuels show the most promise for marine propulsion.

There is a lack of global infrastructure and bunkering facilities for biofuels. Less than 1% of the global fleet currently runs on biofuels, despite increased

10. 4th IMO GHG Study, page 224, doc. MEPC 75/7/15.
11. The International Code for Safety of Ships using Gases or Other Low-flashpoint Fuels.
12. Clarksons Research Limited 2020 Database (as of October 2020): From 176 cargo capacity ships (non-LNG carriers) in total: Tankers: 26% (1/4 ships); (Chemical/Oil) Product carriers and chemical tankers: 33% (1/3 ships); Container ships: 24% (1/4 ships); Bulk carriers: 4.5% (1/20 ships); General dry cargo ships: 5.5% (1/20 ships); Other type of ships, such as cement carriers, multi-purpose ships: 7% (1/14 ships).

production and availability in Europe, North America and Asia. Biofuel is available in very few ports in countries such as the Netherlands, Australia and Norway.

HVO (Hydrotreated Vegetable Oil), a promising candidate as a “drop-in fuel” in most cases can be distributed using the existing Marine Gas Oil (MGO) and HFO distribution systems, although modifications are sometimes required. Using existing distribution systems for the type of biofuel classed as FAME (Fatty Acid Methyl Ester) is more challenging.

Life-cycle emission reduction potential

The actual GHG emissions from a given biofuel will depend vitally on the type of feedstock used and the fuel production process. Biofuels are often categorized by the biomass feedstock.

First generation biofuels are generally produced from food crops, such as corn, soy and sugarcane, which make them unattractive from a socioeconomic perspective. First generation biofuels have a relatively low CO_2 reduction potential. **Second** generation biofuels do not compete with food crops and are produced from lignocellulosic biomass, such as corn stalks or from food residues, such as HVO. A large variety of processes exist for the production of conventional (first-generation) and advanced (second and third generation) biofuels, involving a variety of feedstocks and conversions. **Third** generation biofuels come from microorganisms such as algae; oil is extracted from these organisms for use as biofuel.

The biomass used to make biofuels must itself be produced sustainably, as the first step in the biofuel supply chain. The use of renewable energy can further reduce the carbon footprint of such fuels during production. This technology is based on the premise that all biomass-origin energy can be classified as carbon neutral. However, there is currently no globally accepted ISO standard or certification available to verify the green production of biofuels from end to end.

HVO has higher reduction potential than FAME, with a life-cycle emission reduction potential of about 50% compared to diesel (IEA 2017). In general, HVO and FAME all produce very low SOx emissions. The PM emissions of biofuels are likewise lower than those of conventional marine fuels. The NOx emissions from HVO may be somewhat lower (about 10%) while those from FAME are considered to be higher compared to conventional marine fuels (about 10%). It is expected that significant amounts of carbon-neutral biofuels will be needed to meet the IMO GHG long-term target of 50% absolute reduction of CO_2 compared to 2008 levels.

Storage on board and distribution issues

Biofuels can be blended with conventional fuels or used as “drop-in fuels”.

In general, biofuel blends are expected to be able to be stored and handled by the same storage and machinery as that used for conventional ISO 8217 marine diesel fuel. Marine distillate fuels containing biodiesel blends should, as a minimum, be treated with the same attention as that of conventional marine diesel in all aspects of storage and handling, since these blends are still predominantly marine distillate fuels.

It is important to know the specific cold flow properties of biodiesel products and to keep storage and transfer temperatures above the cloud point. Water accumulation in biodiesel fuel can lead to microbial growth, which in turn can lead to excessive formation of sludge, clogged filters and piping. Frequent draining of tanks and the application of biocide (which should be environmentally friendly and should not pollute) in the fuel may reduce or mitigate microbial growth.

Biodiesel has a shorter storage lifetime compared to marine diesel or marine gas oil due to oxygen degradation. It is, therefore, recommended not to bunker the fuel for long-term storage before use, but to use it within a relatively short period of time (within 3-6 months). Alternatively, adding antioxidants (which should be environmentally friendly and should not pollute) to the fuel at an early stage may improve the ability of a somewhat longer time of storage without degradation.

Corrosion might also be an issue in higher concentration biofuel blends. Hence, it is important to verify that certain components such as fuel system hoses and gaskets and rubber sealings are durable and compatible with biofuel.

HVO is a high-quality fuel from which the oxygen has been removed using hydrogen, which results in long-term stability. The characteristics of HVO make it suitable as a “drop-in” fuel. In general, HVO is compatible with existing engine systems, subject to approval by the manufacturer.

FAME is not a “drop-in” fuel. FAME differs from MGO and Marine Diesel Oil (MDO) in terms of fuel stability, cold flow properties, compatibility with materials, durability and lubrication properties. Some tests have experienced increased corrosion and susceptibility to microbial growth. Knowledge regarding other potential effects of FAME is limited, as most of the tests performed to date studied the use of FAME for short time periods only. Using FAME may increase maintenance costs, such as costs of cleaning tanks, clogged filters and similar items.

Meeting the sulphur limits is normally not a challenge for biofuels, however the NOx emissions might be higher than with fossil diesel oils, due to possibly high oxygen content. To meet the requirements of MARPOL Annex VI, evidence must be provided to confirm that the diesel engine complies with the applicable NOx emission limits (which depend on the keel laying date of the vessel and the operational area) also when biofuels are used for combustion purposes. Providing evidence may be a challenge as it may require on board emission testing where the results should be presented in terms of g/kWh (not only in ppm concentrations).

The sixth edition of ISO specification 8217 may result in MDO or MGO fuels on board ship containing FAME[13] biodiesel up to 7%. Apart from this aspect, all other parameters of these grades are identical to those of traditional grades. The limitations mentioned above do not apply to HVO, which is classified as a DM (distillate) under the above-mentioned ISO standard, provided that certain conditions are met.

13. As DF (Distillate FAME) grades DFA, DFZ and DFB.

Regarding ISO 8217, a new work item proposal has not been submitted as yet within ISO and, therefore, a new specialized specification for biofuels will take a few years to be published. However, the provision in ISO 8217:2017 General Clause 5 states that “the fuel composition shall consist predominantly of hydrocarbons primarily derived from petroleum sources while it may also contain hydrocarbons from the following sources: synthetic or renewable sources such as Hydrotreated Vegetable Oil (HVO), Gas to Liquid (GTL) or Biomass to Liquid (BTL); i.e., co-processing of renewable feedstock at refineries with petroleum feedstock”.

Safety and regulatory challenges

“Drop-in” fuels (biofuel blends) present no safety risks, provided that they comply with specific ISO requirements. A decision was taken at IMO Maritime Safety Committee (MSC 99) to invite ISO to develop standards for methyl/ethyl alcohol as fuel for ships, with a flashpoint below the 60ºC required by SOLAS. As a result, draft technical provisions are currently being developed, aimed at addressing all safety-related issues of ships using methyl/ethyl alcohol as fuel, through proposed amendments to the IMO IGF Code (work is in progress at IMO)[14]. In addition, flag dispensation is needed for NOx emissions, whilst carbon factors for biofuels are not yet agreed.

Potential benefits of biofuels

- No CAPEX required in terms of engines, modifications etc.

- In general, the operational (OPEX) costs for biofuel machinery systems are expected to be comparable with those for HFO/MGO-fuelled vessels. However, additional costs for biofuels may result from monitoring, operational practice and staff training. This needs further investigation.

- They are compatible with modern ship engines (all vessel types – large or small, deep-sea or short-sea trading vessels – can burn biofuels without requiring technical, safety or design adjustments). In a pilot project between March and June 2019, a large container vessel fitted with a Multi-Fuel (Triple-E) Engine, sailed 25,000 nautical miles from Rotterdam to Shanghai and back on biofuel blends alone, using up to 20% sustainable second-generation biofuel, a world first on this scale. The 2nd generation biofuel used in this pilot project was produced from waste sources, in this case used cooking oil (UCOME oil)[15].

- They release no additional CO_2 into the atmosphere when burned, offering a significant advantage in terms of emissions reduction and improved carbon footprint.

Potential cost compared to HFO

HVO and FAME are currently more expensive than their fossil fuel counterparts. The market for these fuels is immature and information on prices is very limited. There are also great local and regional variations in price and availability. However, the biofuel market is expected to grow and the potential for reducing production costs is expected to be higher for

14. IMO Sub-Committee on Carriage of Cargoes and Containers (CCC).
15. Maersk/DSGC/Lloyd’s Register Pilot Project: Horizon 2020 Project, European Maritime Safety Agency (EMSA) and European Environment Agency (EEA), 2021, European Maritime Transport Environmental Report, Version 2.0, 5.11.2020 (under public consultation), page 186.

HVO than for FAME[16]. The reduction will be driven by continuous process improvements, technological developments and scaling of production. This does not mean that the prices will drop too because the latter will depend on demand.

The costs of “drop-in” fuel blends will eventually depend on the cost of the respective fossil fuel and the cost of the added amount of biofuels produced by PtoF processes[17] and on the demand for them.

Biofuels are more expensive than fossil fuels and may remain so. Numerous factors can affect the price of biofuels, including the price and availability of the feedstock, operating costs, production scale, availability of infrastructure and the cost of local resources. Until biofuel production becomes more uniform and common, it will be difficult to achieve competitive costs. The Netherlands is currently the only country with an incentive mechanism which makes pricing attractive. However, this mechanism expired at the end of 2020. In order to understand the impact of this incentive mechanism, in the Netherlands a supplier’s Marine Biofuel was sold at a premium of $5-10 per metric ton (PMT) over the price of the Very Low Sulphur Fuel Oil (VLSFO) 0.50%. The exact same product, with the same logistics, for delivery in Antwerp where the incentive mechanism was not applicable, brought the price to about $400 PMT over the price of the VLSFO 0.50%. Based on the above, suppliers are not actively pursuing the expansion of their supply in other ports/countries unless a relevant scheme is implemented there.

Conclusions on the use of biofuels

Biofuels can be mixed with fossil fuels (the “drop-in” fuel option), enabling ships to start limiting their emissions provided these mixes – blends are safe and fit for purpose.

Several studies predict that at most biofuels could supply fuel for 30% of the global fleet. Depending on their prices, this makes them a partial solution for meeting sustainable decarbonisation targets for shipping. Biofuels as “drop-in” fuels can be used in containerships, where cargo owners are increasingly requesting that shipowners use cleaner fuel and where ships have a fixed schedule or published ports of call. Ships operating near densely populated areas - e.g., cruise ships, ferries - can also benefit from biofuels, especially when operating in regions where biofuels are widely available and where passing on the cost is easier. For bulk/tramp shipping biofuels can also be a partial solution, provided it is the responsibility of fuel suppliers to make sure that when mixed with fossil fuels the blends are safe and fit for purpose.

16. Bill Stamatopoulos, Bureau Veritas, Verifuel, Presentation on Biofuel Types at UGS 21.12.2020.
17. Chemical synthetization processes known as power-to-liquid (PtoL) and power-to-gas (PtoG), summarily referred to as power-to-fuel (PtoF).

Synthetic fuels (ammonia, methanol and hydrogen)

Ammonia

Production and fuel supply infrastructure costs

Conventional ammonia (NH_3) is the most produced chemical in the world. Ammonia is not a “drop-in” fuel and marine engines that can burn it do not yet exist. So, a most substantial part of shipping’s operational infrastructure will have to be scrapped and replaced by new infrastructure around the world for ammonia to become the main fuel. Current lack of bunkering infrastructure also represents a barrier for using NH_3 as an alternative marine fuel (DNV GL, 2019).

Today ammonia is mainly produced using liquified natural gas as feedstock. Ammonia can also be produced from a growing number of renewable resources, such as biomass, making the production chain of ammonia versatile. If produced by biomass gasification, it can be considered as a carbon-neutral fuel. **Hybrid green ammonia** can be produced by adding front-end electrolysis to existing ammonia plants. **Environmentally friendly (green) ammonia** is zero-carbon ammonia, that can be produced using sustainable electricity, water and air. The cost of producing green ammonia will be higher than that of conventional ammonia. The production of green ammonia by electrolysis on an industrial scale is not yet economically feasible. Haldor Topsøe of Denmark[18], one of the leaders in ammonia technology and in managing ammonia industrial plants worldwide, is working with solid oxide electrolysis cell (SOEC) technology to produce green ammonia by 2025. The specific energy consumption of SOEC-based ammonia is expected to be 30% lower than that of conventional ammonia plants or those using electrolysis.

Life-cycle emission reduction potential

Black (conventional) ammonia is produced using natural gas in the nitrate fertilizer industry. The future use of ammonia as a marine fuel presupposes a significant increase in global ammonia production, since its use in shipping will compete with the fertilizer industry using ammonia in agriculture and possibly other sectors also. **Blue** ammonia is produced combining natural gas with Carbon Capture and Storage (CCS) technology, minimizing carbon emissions by two-thirds[19]. It is more attractive, compared to conventional ammonia, because of reusing a significant part of the initially released CO_2 in the atmosphere. **Green** ammonia is zero-carbon ammonia, made using sustainable electricity, water and air.

Storage on board and distribution issues

On board ships, ammonia can be used in combination with internal combustion engines. The energy density of ammonia is approximately 43% of the energy density of MGO (18.6 MJ/kg compared with that of MGO which is 42.7 MJ/kg) (de Vries, 2019)[20]. Also, due to its toxicity and more stringent storage and handling requirements, ammonia engines are still at the development stage. The ammonia slip[21] from the combustion process will also need to be addressed and ships will need to be fitted with combustion aftertreatment systems to reduce potentially high NOx formation.

18. https://www.topsoe.com/processes/ammonia
19. Pat Han, R&D Director, Haldor Topsøe (https://marine-offshore.bureauveritas.com/magazine/shipping-industry-ready-ammonia).
20. Niels de Vries, TU Delft, Report (Thesis): Safe and effective application of ammonia as a marine fuel, 2019.
21. Ammonia slip: Preventing the escape of unburned ammonia, a non-methane Volatile Organic Compound (VOC) that burdens the atmosphere.

Ammonia in fuel cells

Fuel cell technology for ships is still in its infancy. Predicting the future development of fuel cells is challenging as the technology is not currently mature. In addition to technology maturation, a significant cost reduction is needed for fuel cells to become commercially viable (see below).

The requirements for fuel cell installations currently under development at the IMO might be integrated into the IGF Code in 2028 at the earliest. The fuels typically used in fuel cells eliminate emissions of NOx, SOx and PM nearly to zero. Due to the high efficiency of fuel cells, a reduction of CO_2 emissions by 30% is possible when using hydrocarbon-based fuels like natural gas or methanol. Use of fuel cells also minimizes vibration and noise emissions, a major feature of internal combustion engines. Hydrogen used in fuel cells as energy converters does not produce any CO_2 emissions and could also eliminate NOx, SOx and PM emissions from ships.

Limitations and challenges

Despite its high toxicity the use of NH_3 as fuel on board is currently not regulated. Ammonia Internal Combustion Engines (ICE) are still at the development stage. Due to low energy density, storage tank requirements will be almost three times larger than traditional conventional fuels. However, ammonia has higher energy density compared with Liquified Hydrogen (LH).

Safety and regulatory challenges

As ammonia has been widely used in refrigeration technology and carried on board as cargo, ensuring the ship’s safety is considered to be manageable. The crew’s safety is another key point, as ammonia is toxic in concentrated form, but this can be solved with careful engineering and crew training. MAN Energy Solutions has already begun developing a commercial, ammonia-fuelled, two-stroke engine. The first engine tests will begin in 2021. They expect to have a complete engine shipboard installation by 2024. It should be noted that an ammonia-capable engine, such as a DF Ammonia ICE, may still need fossil fuel as pilot fuel (DNV GL, 2020). Ammonia as marine fuel is not on the current agenda for the revision of the IMO IGF Code.

Potential cost compared to HFO

The capital investment needed for the worldwide supply infrastructure of ammonia by 2050, according to a study (UMAS, 2019)[22], depends on the production methods and the specific fuel production pathways and is estimated to be approximately USD 1.2-1.65 trillion. A recent Study by the World Bank[23] estimated that for Brazil, a country well positioned to produce blue ammonia for shipping, “The required capital investment ranges from $24 billion to meet two percent of global demand in 2050 to $107 billion of investment to meet nine percent of global demand in 2050”. Also, for India, in the said Study, given India’s potential as a supplier of “green ammonia”, “The required investment ranges from $147 billion to meet ten percent of global demand in 2050 to $385 billion to meet 27 percent of global demand in 2050.”

22. UMAS Study entitled: “Aggregate Investment for the decarbonization of the shipping industry”, January 2020, (https://www.globalmaritimeforum.org/content/2020/01/Aggregate-investment-for-the-decarbonisation-of-the-shipping-industry.pdf)
23. The Potential of Zero-carbon Bunker Fuels in Developing Countries, The World Bank, Version 1.0, 15.4.2021, https://openknowledge.worldbank.org/handle/10986/35435.

These figures are indicative of the capital investment needed for developing production of blue or green ammonia and do not include the investments required for introducing the required supply infrastructure worldwide.

Cost will also depend heavily on what kind of ammonia a ship may use in the future. Conventional ammonia currently costs about 250 USD/MT making it less expensive than heavy fuel oil but with 43% less energy efficiency. Cost of green (zero-carbon) ammonia is expected to be much higher, depending on the cost of using sustainable electricity.

Although there is no available data for the specific costs of the shipboard technology for using ammonia, Lloyd's Register has reported that the additional system costs are approximately 2-60% for internal combustion engines and 8-300% for a fuel cell ship, relative to a conventional HFO-fuelled vessel[24].

Conclusions on the use of ammonia

Availability in adequate quantities and at viable cost, development of new bunkering infrastructure worldwide and of suitable marine engines, lack of predictability of the regulatory framework and issues related to the exposure of crew to toxic ammonia vapours during storage and handling of ammonia as fuel on board need to be addressed. The method for producing ammonia with no carbon footprint has not been developed yet, neither for industrial use nor for shipborne application. Potential application in ammonia fuel cells is still under development. The marinization of the SOEC technology may stimulate use of ammonia in shipping as an alternative carbon-free fuel. Regulations for ammonia as a fuel will need to be covered by a future revision of the IGF Code within the 2030 timeframe (DNV GL, 2019).

Potential high cost of green ammonia is a major consideration. Low energy density must be factored in and the cost and space of bunker storage will impact negatively.

Methanol (Methyl alcohol)

Production and fuel supply infrastructure costs

The majority of methanol available in the market is produced from natural gas. Methanol can be produced from many different feedstocks, such as natural gas, biomass, or even carbon dioxide (CO_2). E-methanol[25] can possibly be produced by direct air capture of CO_2 (UMAS, 2019)[26]. The chemical composition remains the same, regardless of the source (IMPCA, 2008). If produced from biomass, it can be considered as a carbon-neutral fuel. Methanol is relatively easy to store and handle. CAPEX cost for the methanol supply infrastructure is estimated to be higher compared to hydrogen and depends on the methanol production methods (UMAS, 2019).

Methanol bunkering infrastructure is centred around methanol terminals only. Creation of the appropriate port infrastructure for the supply, storage and bunkering of methanol as marine fuel as well as its use for the ocean-going fleet presents considerable obstacles.

24. Lloyd's Register (2017), "Zero-Emission Vessels 2030. How do we get there?"
25. E-indicates a carbon-neutral electrofuel based on green hydrogen that can be synthesized from non-fossil carbon dioxide.
26. UMAS, Tristan Smith and Carlo Raucci: The zero GHG future and how to get there, October 2019.

Life-cycle emission reduction potential

Regarding potential contribution to GHG reductions, methanol produced using natural gas as a feedstock has Well to Tank (WtT) emissions similar to other fossil fuels such as LNG or MDO. Bio-methanol produced from biomass is a carbon-neutral fuel. Methanol does not contain sulphur and is relatively pure substance that is expected to produce very low PM emissions during combustion. In laboratory testing, emissions of SOx are reduced by roughly 99%, NOx by 60%, particles (PM) by 95% and CO_2 by 25% have been reported compared to fuels currently available (Ellis & Tanneberger, 2015)[27].

Storage on board and distribution issues

Methanol is a liquid fuel (alcohol) which has limited shipborne application on ocean-going vessels other than methanol carriers (Methanol Institute, 2020). It has a lower heating value (energy content) compared to MGO or LNG, resulting in lower performance when compared to other marine alternative fuels, such as LNG. Fuel is stored in liquid form at atmospheric pressure and temperature of 20°C, a particular advantage when compared to LNG. Investment costs for on board storage solutions for these fuels are lower than for others, such as hydrogen. ICE engines running on LNG are estimated to be more expensive than those running on methanol. Likewise, storing methanol as a fuel on board a vessel is assumed to be cheaper than storing LNG, although bunkering requires use of non-corroding hoses and stainless-steel fuel tanks (DNV GL, 2020). Methanol on the MAN ME-LGI dual fuel engine requires fuel oil as pilot fuel (Methanol Institute, 2020).

STENA Germanica (51,000 GT, 240 meter long), the world's second largest Ro-Pax carrier, operating between the ports of Gothenburg, Sweden and Kiel, Germany in Baltic Sea, has undertaken retrofit conversion for the use of methanol as an alternative fuel. The engine type selected for the project is a Wärtsilä-Sulzer engine (eight-cylinder, offering a combined propulsion power output of 24MW). The upgraded vessel had to be fitted with dual-fuel injection nozzles, capable of injecting both methanol and MDO.

Limitations and challenges

Safe storage, handling and on board use of methanol needs particular attention due to safety considerations. The viscosity of methanol is lower than that of MDO by a factor of about 20 and this may lead to potential increased amount of leakage in pumps and fuel injectors[28]. In addition, methyl alcohol is toxic to humans when ingested or when their vapours are inhaled. The toxicity characteristics of methanol coupled with its flammability/explosivity properties pose challenges to fire detection and firefighting techniques. As a colourless liquid with a flame which can hardly be seen, it is important to develop easy-to-use thermal imagery for fire visualization.

Safety and regulatory challenges

While interim guidelines for methanol as fuel were agreed and approved at IMO (MSC 102, November 2020)[29], detailed provisions for using methanol as marine fuel are not yet under discussion. A limited number of Recognized Organizations (ROs) have issued class rules for the use of methanol as marine fuel on board (DNV GL, 2020).

27. Joanne Ellis (SSPA Sweden AB), Kim Tanneberger (LR EMEA): Report (Study) prepared for the European Maritime Safety Agency (EMSA) on the use of ethyl and methyl alcohol as alternative fuels in shipping, https://eibip.eu/wp-content/uploads/2018/01/Study-on-the-use-of-ethyl-and-methyl-alcohol-as-alternative-fuels.pdf
28. EMSA and EEA, 2021, European Maritime Transport Environmental Report, Version 2.0, 5.11.2020 (under public consultation), page 98.
29. Interim Guidelines for the Safety of Ships using Methyl/Ethyl Alcohol as Fuel (MSC.1/Circ.1621/7.12.2020).

Potential cost compared to MDO

Conventional methanol currently costs about 600 USD/MT and is more expensive than MGO (with a price of 700 USD/MT) on an energy equivalency basis[30]. Due to the lower energy content of methanol, the energy content of 11 tonnes of methanol is equal to approximately 5.5 tonnes of oil[31]. Cost of green (zero-carbon) methanol is expected to be much higher, depending on renewable pathway, such as sustainable biomass or carbon dioxide and hydrogen using renewable electricity.

Conclusions on the use of methanol

Notwithstanding the absence of bunkering infrastructure and the lack of information regarding the future cost of carbon-neutral methanol, dual-fuel methanol engine and fuel-supply systems (DF methanol ICE) are an option being examined. The STENA Germanica Pilot Project (2013-2015) proved the feasibility of methanol as a future marine fuel for a certain segment of short sea shipping, given the very limited number of vessels (approximately 10) running on methanol globally (DNV GL, 2020). However, methanol can provide a very good stable and safe hydrogen carrier since it is the simplest alcohol with the lowest carbon content and highest hydrogen content of any liquid fuel. It can be used to produce hydrogen for fuel cells and the methanol industry is working on technologies that would allow methanol to produce hydrogen for fuel cells (see below).

Safety concerns, lower energy density of methanol and increased costs of the fuel storage system continue to make this fuel unattractive for the oceangoing bulk fleet.

Hydrogen

Production and fuel supply infrastructure costs

Hydrogen is a widely used chemical commodity and an energy carrier. Today, 95% of hydrogen is produced from fossil fuels, mainly natural gas. Only 5% of current hydrogen production uses electrolysis. Since there is currently little demand for marine hydrogen fuel, there is no distribution or bunkering infrastructure for ships in place. Liquefied hydrogen (LH) could be distributed in a similar manner to LNG.

In the future, LH might be transported to ports from storage sites where hydrogen is produced using surplus renewable energy, such as wind power, whenever energy production exceeds grid demand. Most commonly, it is stored either as compressed gaseous (CGH) or cryogenic hydrogen (LH)[32]. Transport of hydrogen as CGH or LH could be by road, ship, or pipeline depending on the site, volume and distance.

30. Methanol Institute, Methanol as a Marine Fuel, Compliance Cost Comparison, January 2020 (https://www.methanol.org/wp-content/uploads/2020/01/Methanol-as-a-marine-fuel-january-2020.pdf)
31. DNV GL – Maritime: Assessment of selected alternative fuels and technologies, April 2018.
32. DNV GL, Comparison of Alternative Marine Fuels, September 2019.

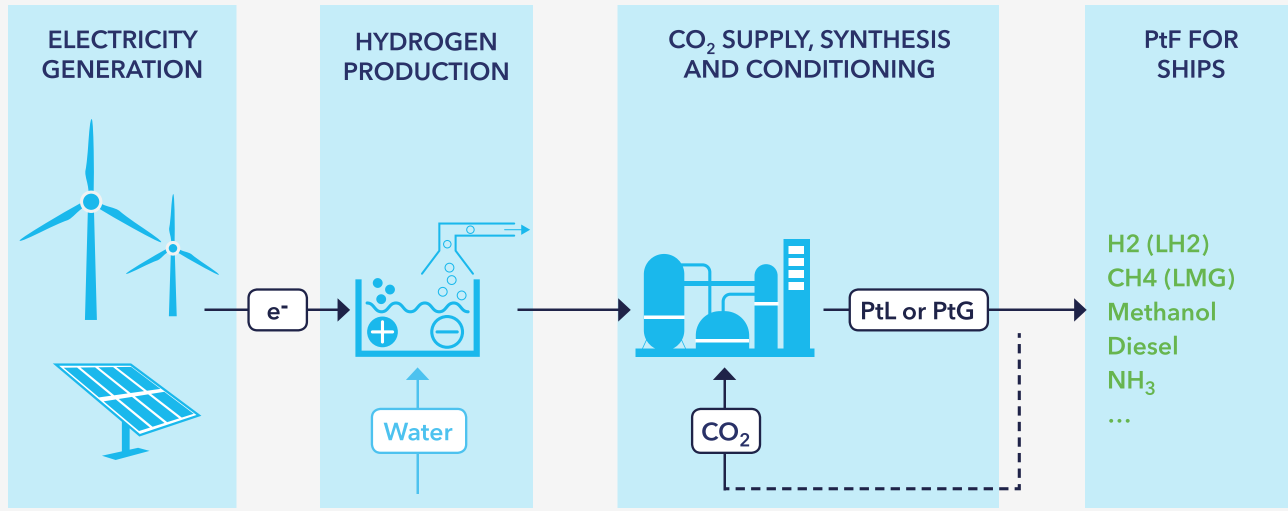
There would be the need for substantial hydrogen supply, distribution and bunkering infrastructure to make it viable for the marine industry. Production costs presently pose a challenge to hydrogen viability as an alternative fuel, especially when compared with other fuels.

The cost of hydrogen production by reforming natural gas or biogas varies greatly, ranging from around 1.51 to 6.5 USD per kg (800 to 2,170 USD per ton of fuel oil equivalent, foe)[33]. These cost estimates include production, compression, storage and transport.

Life-cycle emission reduction potential

The carbon footprint of hydrogen produced from natural gas is larger than those of HFO and MGO. The cleanest fuel is green hydrogen produced using renewable energy. Production of hydrogen by electrolysis is viewed as an opportunity to store and transport surplus renewable energy, thereby stabilizing the energy output of solar or wind power plants (see figure 1 below). If the electricity used to produce H2 is green, the corresponding GHG emissions reduce by more than 85% compared to conventional fuels (Lindstad, 2020)[34].

Figure 1: Principal production pathway for Power to Fuel
Power to Liquid (PtL), Power to Gas (PtG) = Power to Fuel (PtoF)



Source: DNV GL, 2019

33. Pat Han, R&D Director, Haldor Topsøe (https://marine-offshore.bureauveritas.com/magazine/shipping-industry-ready-ammonia).
34. Elizabeth Lindstad (SINTEF Ocean, Marine Technology Centre, Trondheim, Norway): LNG and Cruise Ships, an Easy Way to Fulfil Regulations—Versus the Need for Reducing GHG Emissions, 2020.

Storage on board and distribution issues

For use on ships, as a cryogenic liquid, hydrogen must be liquefied at very low temperatures up to -240°C by increasing the pressure towards the "critical pressure" for hydrogen, which is 13 bar. Therefore, safe storage, handling and on board use of LH needs particular attention due to safety considerations. The low volumetric energy density of LH which is approximately 23% compared to MGO (8.5 GJ/kg compared with that of MGO which is 36,6 GJ/kg) (de Vries, 2019)[35] requires more than five-times[36] the volume of the same amount of energy when compared to HFO. The higher energy content of H2 by mass, is penalized by the low volumetric energy density. Therefore, it is very difficult to use liquefied hydrogen in deep-sea shipping. When stored as a compressed gas, its volume is roughly 10 to 15 times (depending on the pressure) the volume of the same amount of energy compared to HFO, which makes it inappropriate to use hydrogen as fuel (compressed gas) in deep-sea shipping.

Limitations and challenges

Even though hydrogen is today largely understood and dealt with under very strict safety measures, it is still a gas with a very low Lower Flammable Limit (LFL) (4% in air) and with the largest flammability range LFL (from 4% to around 70% up to Upper Flammable Limit – UFL). Hydrogen is a low-flashpoint fuel subject to IMO IGF Code. The current edition of the IGF Code does not cover hydrogen storage. Rules for the use of hydrogen in fuel cells are under development and will be included in a future amendment to the IGF Code.

Potential cost compared to HFO

Today, nearly all hydrogen is produced from natural gas and, therefore, is more expensive than natural gas. When hydrogen is produced using renewable energy, it can be assumed to be more expensive than VLSFO/ MDO/MGO. It would only be competitive under the assumption of massive subsidies, or of heavy taxes on conventional fuels. It has been estimated that renewable hydrogen could cost USD 1,000 to 2,000 per tonne of oil equivalent (toe) [Dena (2018) and Brynolf et al. (2018)].

Conclusions on the use of hydrogen

The low volumetric energy density of liquefied hydrogen (LH) and the high cost of the fuel storage system make it very difficult to use LH in deep-sea shipping. The situation is different for LH in short-sea shipping on fixed routes covering limited distances with frequent port calls, which due to their relatively low energy demand, are more likely candidates. DNV GL is working with the Norwegian Government on putting a new hydrogen-powered ferry into service by 2021[37].

If a renewable source of electricity is used, electrolysis is almost a carbon-free process to produce hydrogen[38] (Figure 1 above). Potentially using green hydrogen to make green ammonia, has the advantage of making another fuel which can be either combusted or used in a fuel cell. However, the

35. Niels de Vries, TU Delft, Report (Thesis): Safe and effective application of ammonia as a marine fuel, 2019.
36. Gaseous hydrogen (CGH) has a very high energy content by mass, but it is a very light gas with 1 Kg occupying 5.4 m^3 at standard temperature and pressure (STP).
37. DNV GL, Assessment of Selected Alternative Fuels and Technologies, June 2019.
38. EMSA and EEA, 2021, European Maritime Transport Environmental Report, Version 2.0, 5.11.2020 (under public consultation).

extra step to convert hydrogen to ammonia using renewable electricity will make ammonia more expensive (BBC, 2020)[39].

Hydrogen can be considered a zero-carbon fuel with no carbon emitted when converted to electrical energy in fuel cells (section below).

Several technical arrangements exist where different fuels are directly fed into the fuel cells, such as LNG or Methanol, which are used as chemical carriers/sources of the hydrogen. (More information is presented under Section below "Ongoing Projects using on board capture and storage technology".)

Hydrogen (LH) – burning ships will require specially trained crews.

Fuel cells

Fuel cells convert the chemical energy contained in a fuel directly into electrical and thermal energy through electrochemical oxidation. All fuel cells need a hydrogen-rich fuel for the chemical process. Apart from the use of pure hydrogen, chemical reactors (fuel reformers) are used to convert other fuels such as natural gas (methane-CH_4), methanol (CH_3OH) to hydrogen-rich fuel for the cells. This direct conversion process enables electrical efficiencies of up to 60%, depending on the type of fuel cell and fuel used. There are various fuel cell technologies under development. The chemical mechanism, working temperature, efficiency and fuel suitability depend on the material used in the fuel cell. Maritime development projects and feasibility studies have shown that from the three most promising fuel cell technologies for maritime use [low-temperature proton exchange membrane fuel cell (LT-PEMFC), high-temperature proton exchange membrane fuel cell (HT-PEMFC) and solid oxide fuel cell (SOFC)], the latter is being tested for marine application with ammonia.

Air pollutants emission reduction potential

The fuels typically used in fuel cells eliminate emissions of NOx, SOx and PM nearly to zero. Due to the high efficiency of fuel cells, a reduction of CO_2 emissions by 30% is possible when using hydrocarbon-based fuels like natural gas or methanol. Use of fuel cells also minimizes vibration and noise emissions, a major characteristic of internal combustion engines. Hydrogen used in fuel cells as energy converters does not produce any CO_2 emissions and could eliminate NOx, SOx and PM emissions from ships.

Ongoing Projects for Fuel Cells

Several projects are under way for demonstrating viability of fuel cell technology for shipborne application, such as the following:

ShipFC Horizon Project (2020-2025)[40]: The project will see an offshore vessel, Viking Energy, owned and operated by Norwegian Company Eidesvik AS to have a large 2MW ammonia fuel cell retrofitted, allowing it to sail solely on ammonia for up to 3,000 hours annually.

39. Article "The fuel that could transform shipping", BBC Future, 30.11.2020 (https://www.bbc.com/future/article/20201127-how-hydrogen-fuel-could-decarbonise-shipping).
40. ShipFC Horizon Project: Horizon 2020 Project, EMSA and EEA, 2021, European Maritime Transport Environmental Report, Version 2.0, 5.11.2020 (under public consultation), page189.

Maranda Horizon Project (2020-2025)[41]: A 165 kW (2x82.5 kW AC) fuel cell powertrain (hybridized with battery) will provide power to the research vessel's electrical equipment as well as dynamic positioning during measurements, free from vibration, noise and air pollution (dedicated application as an auxiliary power unit).

HySeas III Project (2017-2021)[42]: It is aimed at demonstrating that fuel cells may be successfully integrated with a proven marine hybrid electric drive system by developing, constructing, testing and validating a full sized (hydrogen/electric) drive train on land. Should this test be successful, Scottish Transport have agreed to fund the construction of a Ro-Ro passenger ferry, which will integrate the entire powertrain.

As a comparison, a large tramp merchant vessel would need 5-30MW for at least 7,000 hours annually for main propulsion.

Safety and regulatory challenges

Fuel cells based on Proton Exchange Membrane (PEM) are predicted to run on hydrogen (DNV GL, 2019) whilst safety provisions for the use of fuel cells in shipping are still under development. The safety of hydrogen fuel cells, due to the presence of hydrogen in the fuel poses significant challenges. High efficiency in fuel cell technology, comes from achieving high temperatures in fuel cells. The most efficient ones with temperatures in excess of 1,000°C require careful assessment of the safety-related aspects (Source: European Maritime Transport Environmental Report, Version 2.0, November 2020).

The requirements for fuel cell installations currently under development at the IMO might be integrated into the IGF Code in 2028 at the earliest.

Conclusions on the use of Fuel Cells

A ship running on fuel cell technology in the future will not necessarily have to have an internal combustion engine. However, fuel cell technology for ships is still in its infancy. Predicting the future development of fuel cells is challenging. The technology is not currently mature enough and cannot provide a solution for large ocean-going ships in the foreseeable future. In addition to technology maturation, a significant cost reduction and size up-scaling is needed for fuel cells to become commercially viable. Specialised crew will be required.

41. Maranda: Horizon 2020 Project, EMSA and EEA, 2021, European Maritime Transport Environmental Report, Version 2.0, 5.11.2020 (under public consultation), page188.
42. HySeas III: Horizon 2020 Project EMSA and EEA, 2021, European Maritime Transport Environmental Report, Version 2.0, 5.11.2020 (under public consultation), pages188-189.

Electrofuels

The recent announcement by U.S.-based company Infinium Electrofuels™[43] for the successful fund-raising, bringing together a consortium of investors including Amazon's Climate Pledge Fund, Mitsubishi Heavy Industries (MHI), AP Ventures, Neuman & Esser and the Grantham Environmental Trust, is promising. The proceeds are expected to be used to advance the development of commercial scale applications to decarbonize the transportation sector, given the "drop-in" aspect of electrofuels. Electrofuels based on "green"-hydrogen – from electrolysing water with renewable electricity – that can be synthesized with nitrogen or non-fossil carbon dioxide can make green alternative fuels. No information is readily available on the likely cost of these electrofuels as "drop-in" fuels, which are at a very early stage of development.

Electricity production from renewable sources for 2019 was of the order of 21% in the EU and 11% in the U.S.[44], while the needs of the transportation sector as a whole (land, sea and air) are most substantial. At this stage, it is not clear what infrastructure is necessary and in what locations for the production of these electrofuels nor is there any information provided on their thermal efficiency, storage on board characteristics and safety aspects.

Different levels of technical and regulatory maturity of alternative fuels

LNG DF engines can currently provide a transitional solution for certain segments of the industry, provided that LNG bunkering infrastructure will be established in major ports of call worldwide. "Drop-in" fuels, which are compatible with all modern ship engines (all vessel types irrespective of trade) that can burn biofuels without requiring technical, safety or design adjustments, can also be a partial solution to oceangoing bulk shipping. Biofuels will need to be made available in sufficient quantities in ports worldwide.

Alternative fuels such as ammonia, methanol or hydrogen need a new generation of internal combustion engine and advancements in technology not yet developed for ocean-going ships and will need to be developed by out of sector stakeholders such as energy providers, engine-builders and shipyards.

Most new and alternative fuels have properties posing different safety challenges from those of conventional fuel oils. This requires the development of regulations and technical rules for safe design and use on board ships in parallel with the technological progress needed for their uptake. Many low carbon alternative fuels require pilot fossil fuels to be carried onboard.

Crew costs and crew training are a significant factor for all alternative fuels except sustainable biofuels.

43. Infinium Electrofuels™ Closes Funding to Decarbonize Transportation Sector with Electrofuels Solution, 26.1.2021. (https://infiniumco.com/infinium-closes-funding-to-decarbonize-transportation-sector-with-electrofuels-solution/).
44. BP Statistical Review of World Energy 2020, 69th edition, page 63 (https://www.bp.com/content/dam/bp/business-sites/en/global/corporate/pdfs/energy-economics/statistical-review/bp-stats-review-2020-full-report.pdf).

Propulsion Technologies

Alternative ship propulsion technologies (also mentioned as Energy Recovery or Energy Harvesting): all available alternative propulsion technologies other than the conventional ones using shaft and/or propeller for the main and auxiliary engines or those being developed, can offer improvements in fuel consumption but cannot replace conventional internal combustion engines. Currently, the main available alternative propulsion method is wind-assisted propulsion (WASP) and its main forms are: Fixed Sails or Wings, Kites and Flettner rotors. For seagoing vessels, according to GL-MMEP[45], all wind propulsion technologies are characterised as **"Not mature"**[46] (See figure 2).

Figure 2: Extract of GL-MMEP table of Energy Efficiency Technologies

ENERGY RECOVERY

NAME	FUNCTION	TECHNICAL MATURITY*	APPLICABILITY
Fixed sails or wings	Use sails or wings to replace some of the propulsion power needed	Not mature	Vessels with enough place on deck (general cargo, tankers, bulkers)
Flettner rotors	Use Flettner rotors to generate power from wind energy	Not mature	Dependent on trading area and sufficient free deck-surface
Kite	Use a kite to replace some of the propulsion power needed	Not mature	All vessels
Solar panels	Install solar panels for conversion of solar energy to electricity	Not mature	Dependent on trading area and sufficient free deck-surface

Source: GL-MMEP Project

In IMO 4th GHG study, the immaturity of these technologies is confirmed by the zero per cent penetration rate they had in shipping in 2018 (same applies to Solar panels which is an alternative energy source to existing propulsion systems) (see figure 3).

Figure 3: Extract of table from IMO 4th GHG Study with penetration rates of propulsion technologies in ships

Group		Penetration rates (% of ships applying a technology)				
		2018	Scenario 1		Scenario 2	
			2030	2050	2030	2050
Group 12 Reduced auxiliary power demand	Reduced auxiliary power demand (low energy lighting etc.)	50.0%	100%	100%	55.0%	80%
Group 13 Wind power	Towing kite Wind power (fixed sails or wings) Wind engine (Flettner rotor)	(0.0%)	(100%)	(100%)	(5.0%)	(30%)
Group 14 Solar panels	Solar panels	(0.0%)	(100%)	(100%)	(5.0%)	(30%)

Source: 4th IMO GHG Study, July 2020

For Flettner rotors, their immaturity is indicated also by the fact that while the first modern ship has installed such rotors in 2008, up to now, only 5 more vessels have installed these devices. With current technology, Flettner

45. GL-MMEP Project is the GEF-UNDP-IMO project for the supporting of the uptake and implementation of energy efficiency measures for shipping.
46. https://glomeep.imo.org/technology-groups/#EnergyRecovery

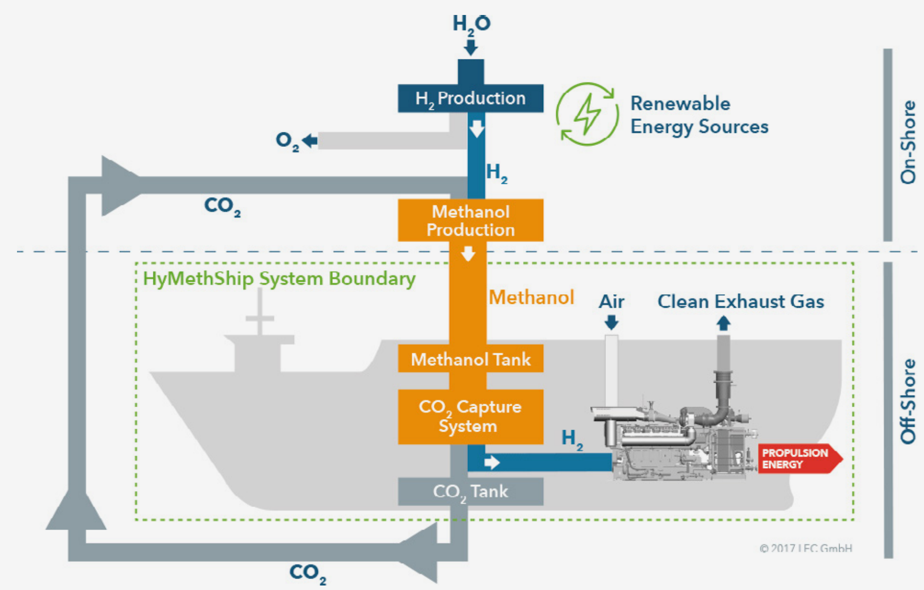
rotors could have a measured fuel saving effect from 3 to approximately 8%[47,48], and should always be used as auxiliary to the main propeller or water-jet propulsion systems.

Bulk/tramp vessels navigate varying routes at different times of the year. Therefore, the benefits from WASP systems are limited.

Ongoing Projects using on board capture and storage technology

a. The HyMethShip project (2018-2021)[49] is developing the first internal combustion engine for a marine propulsion system capable of CO_2 emissions reduction of more than 95%. The project will achieve this goal by using renewable methanol as the energy carrier and implementing pre-combustion carbon capture. The system will be demonstrated onshore at full scale. The HyMethShip system innovatively combines a membrane reactor, a CO_2 capture system, a storage system for CO_2 and methanol, as well as a hydrogen-fuelled combustion engine into one system, comprising cryogenic hydrogen stored at -173°C. The proposed solution reforms methanol to hydrogen, which is then burned in a reciprocating engine that has been upgraded to burn multiple fuel types and is specifically optimised for hydrogen use. The new concept allows for a closed CO_2 loop ship propulsion system while maintaining the reliability of well-established marine engine technology. The HyMethShip project will undertake risk and safety evaluations, as well as life cycle costing (LCC) and life cycle assessment (LCA) to ultimately optimise economic and environmental performance for different ship types and operating scenarios (see figure 4). The CAPEX and OPEX of the commercial application of this project are so far unknown.

Figure 4: HyMethShip System



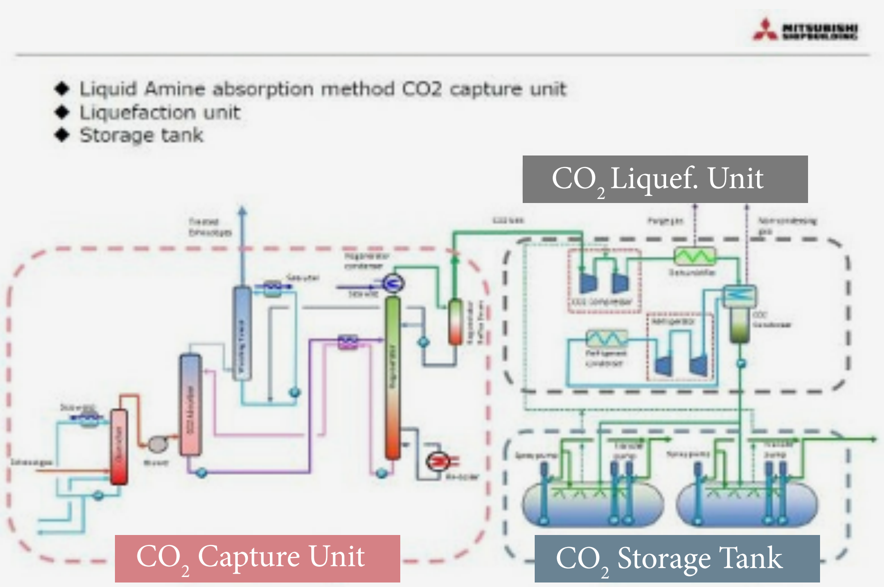
Source:
EMSA/EEA "European Maritime Transport Environmental Report", 2021, Version 2.0, 5.11.2020 (under public consultation)

47. https://research.tudelft.nl/en/publications/case-study-wind-assisted-ship-propulsion-performance-prediction-r
48. https://www.norsepower.com/tanker
49. Horizon 2020 Project Hydrogen-Methanol Ship propulsion system using on board pre-combustion carbon capture; EMSA and EEA, 2021, European Maritime Transport Environmental Report, Version 2.0, 5.11.2020 (under public consultation), pages 187-188.

b. A Japanese concept study by Mitsubishi Heavy Industries (MHI)[50] has identified certain technical challenges of using on board carbon capture and storage to drive down emissions from big ships. According to MHI's calculations, the system would add more than USD 45 million to the cost of a conventional VLCC, with the methane fuel system costing around USD 15 million and the carbon capture and storage plant around USD 30 million. Even with a carbon tax of around USD 200 a tonne and with a price of electricity nearly 10 times lower than Japan's cheapest wind-generated power today, payback would take 20 years.

Return on investment is just one obstacle in a project designed to highlight, *inter alia*, the technical challenges that shipping's decarbonisation poses for larger vessels. One problem is the size and weight of the carbon capture units. The system envisioned for MHI's project uses the amine treatment method that has been deployed on land. Each of the four towers is around the size of a scrubber unit and the weight of the whole system would be over 4,500 tonnes, or nearly 2% of the vessel's deadweight. Another stumbling block is the fact that the carbon capture is not totally effective, with a capture rate of around 86%. Despite these considerable hurdles, it is envisaged that the production of either methane or methanol fuel by combining hydrogen and on board carbon capture could be feasible in principle for large ocean-going vessels (see figure 5).

Figure 5: MHI: System Composition of CCS on board



Source: www.rivieramm.com article, June 2019

c. A first systematic study[51] analysed and obtained key insights for the integration of a ship energy system with post-combustion carbon capture (PCC). The reference cargo ship is of 35,000 gt and has a propulsion system consisting of two four-stroke reciprocating engines at a total power of 17 MW and aimed at providing a solution which would capture 90% of CO_2 emissions from ship energy systems.

50. https://www.rivieramm.com/opinion/opinion/could-onboard-carbon-capture-really-work-55436
51. A compact CO_2 capture process to combat industrial emissions, Meihong Wang, The University of Sheffield, Article in Applied Energy, June 2017.

On board carbon capture

Using amine solvent to absorb CO_2 from flue gases is a proven technology for use onshore although great amount of thermal energy is required for rich solvent regeneration which results in high cost of carbon capture and preventing its commercialization. However, its application for capturing CO_2 from ships encounters several challenges because ships are constantly moving vessels with limited space as well as limited supply of utilities. Table 1 summarizes the limitations of on board CCS considering several features of ships. It is easy to understand that storage tanks are required for both solvent make-up and captured CO_2.

Table 1. Limitations of on board CCS in a typical marine vessel

Features of marine vessel	Limitations of onboard CCS
Offshore	Tank storage of solvent and captured CO_2
Limited space	Sizes of equipment
Limited utilities	Supply of heat, electric power and cooling utilities
Constant movement	Construction limitation (such as heights of the columns)

Source: Applied Energy, June 2017

Limitations for use of CCS on board

For on board application, captured CO_2 stored in tanks as a cryogenic liquid will occupy considerable space and will have to be unloaded when ships reach a port. In terms of cooling utility on board, seawater is a good source for cooling down the hot stream to atmospheric temperature. However, it is not suitable for cryogenic process, in which the target operating temperature is lower than -50°C (Kvamsdal et al., 2010).

Another main limitation is that the equipment size of CCS system should be minimized to occupy less space and less weight. One special consideration is about the height of the absorber and the stripper, which are two main pieces of equipment of this carbon capture process. Previous studies showed that for CCS onshore applications, the total height of the columns could be around 50 meters. Even for large size vessels, such a packing height is not realistic from ship's design point of view.

Technologies such as CCS onshore would possibly allow bridging the current technological gap between fossil fuels and the zero-emission fuels needed to decarbonise shipping. However, this technology (CCS) has not been fully developed yet, neither for industrial use, nor for shipborne application.

Concluding Remarks

Decarbonisation requires a wholly new generation of zero-carbon fuels and propulsion technologies that do not yet exist. The investments in fuel production and in supply infrastructure represent by far the major share of the total cost of decarbonisation for the shipping sector. Consequently, the greening of fuels and ships is the responsibility and area of expertise of out of sector stakeholders, who must provide the international shipping industry with safe and fit for purpose propulsion technologies and maritime fuels available worldwide. Shipowners cannot carry these tasks out unilaterally.

In general, the alternative energy source to be selected and carried on board must have a sufficiently high energy density, compared to the energy density of VLSFO and MDO/MGO to maximize the available cargo space, but crucially without compromising safety. These efforts require the active contribution of all actors in the maritime value chain, especially energy providers and the fuel supply chain, shipyards, engine manufacturers, but also classification societies, ports and charterers.

Research, innovation and investments, in aspects such as availability in sufficient quantities and applicability, are needed to ensure that shipowners can use these fuels safely on a global scale in the near future. The first priority should be a massive effort in R&D and a shift of technological paradigm towards safe and future-proof alternative fuels. Once new and economically viable fuels are developed, fuel and energy suppliers will have to start producing them and ports will need to have the right infrastructure in place.

Nevertheless, in the coming decades, fossil fuels will likely remain much cheaper than zero-carbon alternatives, unless the former are heavily taxed or the latter heavily subsidized (or both). In general, the question of the macroeconomic implications of fuels for ships becoming much more expensive (as will ships themselves) is a major one, along with the disruption and economic implications of the departure from one universal fuel for shipping which fossil fuels have been over the last 70-80 years and the introduction of a number of new fuels and technologies. It seems *prima facie* that technologies that capture most or all of the CO_2 from fossil fuels will cause less disruption and should be investigated further.

It is noteworthy that orders for newly built vessels with delivery dates in 2023/2024 are mainly comprised of "dual-fuel ready" and NOx Tier III compliant ocean-going vessels although they are no doubt more expensive.

Depending on the extent of the fragmentation of the fuel landscape of the future and the length of the transition period towards a new situation, the shift to a multi-fuel future may in fact herald the end of low-cost seaborne trade and its mainstay, the international bulk/tramp shipping model which is responsible for over 84% of global tonne-miles.

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