Progress towards biofuels for marine shipping

Status and identification of barriers for utilization of advanced biofuels in the marine sector

IEA Bioenergy: Task 39

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Content

List of abbreviations

BAU	Business as usual
BTL	Biomass to Liquids
CARB	California Air Resources Board
CCAI	Calculated Carbon Aromaticity Index
CII	Operational Carbon Intensity Indicator
CO	Carbon monoxide
CO_2	Carbon dioxide
DC	Direct Current
DME	Di-Methyl Ether
DWT	Dead Weight Tonnage
ECA	Environmental Control Areas
EEDI	Energy Efficiency Design Index
EEOI	Energy Efficiency Operational Indicator
EEXI	Energy Efficiency Existing Ship Index
EGCS	Exhaust gas cleaning systems
ETS	European Emission Trading System
FAME	Fatty Acid Methyl Esters
FSC	Forest Stewardship Council
FT	Fischer-Tropsch
GHG	Greenhouse gas
GT	Gross Tonnage
GWP	Global Warming Potential
H_2	Hydrogen
HFO	Heavy Fuel Oil
HSFO	High Sulphur Fuel Oil
HVO	Hydrotreated vegetable oil
IEA	International Energy Agency
IFO	Intermediate Fuel Oil
ILUC	Indirect Land Use Change
IMO	International Maritime Organization
IMRB	The International Maritime Research and Development Board
ISO	International Organization for Standardization
LNG	Liquid Natural Gas
LUC	Land Use Change
MARPOL	The International Convention for the Prevention of Pollution from Ships
MEPC	Marine Environment Protection Committee
MGO	Marine Gas Oil
mmBTU	Million British Thermal Units
MOU	Memorandum of Understanding on Port State Control
MTBE	Methyl tert-Butyl Ether
Mtoe	Million ton of oil equivalent
NO_x	Nitrogen oxides
OEM	Original Equipment Manufacturer
PM	Particulate Matter
PSC	Port State Control
RED	Renewable Energy Directive
RFS	Renewable Fuel Standard

RNG	Renewable Natural Gas
SECA	Sulphur Emission Control Areas
SEEMP	The Ship Energy Efficiency Management Plan
SOx	Sulphur oxides
SVO	Straight Vegetable Oils
TEU	Twenty-Foot Equivalent Units
UCO	Used Cooking Oil
ULSFO	Ultra-Low Sulphur Fuel Oil
VLSFO	Very Low Sulphur Fuel Oil

Executive Summary

Biomass has the potential to fully supply the marine sector with sustainable fuel and is a promising solution for both reducing carbon emissions and meeting sulphur regulations, which were thoroughly described in the 2017 IEA bioenergy report on *Biofuels for the marine shipping sector*[1]. The benefits of biofuels have to some extent been recognized by the maritime sector, where the interest in biofuels in the last 5 years have been visible through progress in engine development, in sea-going biofuel trials of blends, as well as in 100% biofuel trials. However, greater use of biofuels in the sector is limited by the volumes presently available with delays in commercialization of technologies. This report seeks to uncover the largest barriers for the commercialization of biofuels for the marine sector, as identification of the current barriers will excel concrete actions from various stakeholders advancing the employment of sustainable biofuels in the maritime sector.

International shipping conveys the transportation of the majority the world's goods, with global shipping trade reaching $US 14 trillion in 2019. This service is facilitated by large marine vessels running primarily on heavy fuel oil, accounting for 2-3% of the global GHG emissions while being the largest source of anthropogenic sulphur emissions. The negative effects of these emissions extend to both terrestrial and aquatic life, including human health. In response to this, the International Maritime Organization (IMO) has established targets to decrease the carbon intensity of the shipping sector by 50% in 2050, and has from 2020 restricted the maximum allowed sulphur content of marine fuels used in international waters from 3.5 wt.% to 0.5 wt.%. Along with more stringent international regulations, stronger national and supranational regulations follows, resulting in a large pressure on the marine shipping sector to transition quickly to more sustainable fuel solutions.

To better understand the barriers for the commercialization of marine biofuels, interviews were conducted with 7 key stakeholders involved with the marine freight transportation sector. The interviews demonstrated the great complexity and many considerations related to transitioning marine fuels. It shows the overall barrier towards biofuel investment is the lack of economic incentives. Many stakeholders are also considering the overall level of uncertainty related to price development of biofuel feedstocks, sustainability criteria, as well as regulatory policies to be major barriers for major biofuel investments. However, among the interviewed stakeholders little concern was expressed towards the technical barriers of scaling-up, establishing supply chains, or adopting engine and fuel systems for new biofuels. In contrast, the common denominator for the largest identified barriers by the stakeholders (and this report in general) is the uncertainty of the future economic and political development.

Encouragingly, a number of shipping industry stakeholders, identifies biofuels as a the most promising short- to mid-term solution for both reducing carbon emissions and meeting sulphur regulations, which have been documented through interview presented in this report. Also, with increasing international stringency on sulfur emissions and ship energy efficiency, the price gap between fossil- and biofuels is declining. Especially in some local markets where elevated pricing – due to long distance to major fuel hubs – combined with CO_2 pricing and additional hedging cost savings, unite to provide a real opportunity for biofuels to compete with the fossil alternatives.

There seems to be a general demand among major maritime stakeholders to accelerate the transition towards sustainable solutions. This was clear from the stakeholder interviews, and is evident as industry coalitions are currently pushing international policy makers to create stronger policies towards realizing net-zero carbon vessels. However, several barriers for biofuel commercialization emerge as the landscape of technologies is revealed. The chemical complexity of different biofuels, variation and availability of biomass, and the plethora of biofuel production methods makes a 'one-biofuel-fits-all' scenario unrealistic and creates pressure on local solutions, while making the investment in any single biofuel technology risky.

The use of biomass as a sustainable source of energy has been target of international discussion as some biofuels are unsustainably produced, or are based on feedstocks competing with food production. This has led to policy fluctuation on the criteria of sustainability of biofuels. An internationally recognized standard defining the sustainability criteria of biofuels would thus support the further development of biofuel technologies. Likewise, other biofuel-promoting policies should focus on creating a predictable framework and long-term stability to lower the investment risk. Additionally, more national and supranational policies are needed to support local fuel demands and adapt to differences in biomass availability.

The current marine (fossil) fuel standard ensures comparison and evaluation of fuel quality, fuel engine compatibility, safety and price. The complexity of the majority of biofuels associated with the wide range of feedstocks and production processes creates incompatibility with the current marine fuel standards. The lack of a dedicated marine fuel standard for biofuels obstructs their use, trade and production, and is therefore a barrier for commercialization. The establishment of alternative marine fuel standards is a long and complex task. The process requires large investment in R&D as well as successful sea-going trials involving several marine stakeholders including shipowners, fuel producers, bunkering companies, and engine and fuel system Original Equipment Manufacturers (OEMs). Initial trade and utilization of a new fuel technology can be accelerated by technical reports, publicly available or technical specification. The recent IMO interim guidelines on using ethanol and methanol as marine fuels is a great step in the right direction. It facilitates the usage of ethanol and methanol making them more attractive for ship operators. The perspectives of using sustainably produced methanol as an alternative marine fuel are promising. As the current production of ethanol and methanol from sustainable electricity is almost not existing, renewable ethanol or methanol will likely be dominated by biomass sources at least until the 2030s-2040s. Biobased methanol or ethanol fuels are therefore viable options for ship operators to reach the IMO 2030 emission targets.

Likewise, some stakeholders put emphasis on the advantages of HFO-compatible drop-in biofuels as they dramatically lower the capital investments associated with the required port infrastructure as well as reduces the need for vessel retrofits. Drop-in fuels based on existing waste streams would contribute to a circular economy without risking competition with food/feed or increase indirect land-use and can achieve significant emission reductions.

The crucial role of policies is to set the regulatory framework to encourage the implementation of maritime biofuels. Since biofuel technologies are diverse and the biomass type and availability differ greatly between nations, biofuel implementations rely on multiple stakeholders and supply chains. This makes establishment of national and supranational level policies particularly important, as these can more specifically support the local supply chains adapted to the technological maturity and biomass availability.

The current sulphur regulations and GHG targets made by IMO demand vessels to gradually increase their energy efficiency and lower their carbon intensity. The latter is defined as a CO_2

reduction per transport work, as an average across international shipping, by at least 40% by 2030 and 70% by 2050. This carbon intensity regulation will, according to IMO, lead to a reduction of total annual GHG emissions from international shipping by at least 50% by 2050 (compared to 2008). The shipping sector is not adapted to quick changes as the small margin business of deep-sea shipping require long-term stable policies to ensure minimal risks investing in new fuel technologies such as biofuels. Without policies targeting alternative fuel technologies more directly such as carbon taxation or renewable fuel mandates, the transition from fossil to alternative fuels will be slow.

Finding an economic and sustainable fuel solution to substitute current marine fuel technologies is a complex task on several levels. The field is experiencing intense research and political attention, creating a fast-paced environment with new research breakthroughs and changing policies. This is an indication of a positive global movement towards a sustainable maritime sector. However, it also creates a high-risk investment environment in a sector being aware of the fact that no single biofuel technology will fit all. In the light of the large investment risks associated with biofuel technologies, technical as well as regulatory actions towards lowering these risks are heavily needed to facilitate the fast-moving transition towards a sustainable marine sector.

1. Introduction

The shipping sector is responsible for transporting more than 80% of worldwide goods, and is often referred to as the ‘lifeblood of the global economy’. Despite being the least carbon intensive means of transport, international shipping vessels traditionally rely on ‘cheap and dirty’ heavy fuel oil (HFO) of which they annually burn 350 million tons, accounting for 2-3% of global GHG emissions. In addition, the shipping industry is the largest source of anthropogenic sulphur emissions, as well as a being a significant emitter of nitrogen oxide and airborne particle emissions. Serious negative effects on terrestrial and aquatic life, including human health are associated with these emissions.

International shipping is not included in national emission balances and is thus not covered by the Paris agreement (2015). On this foundation, the United Nations based agency, the International Maritime Organization (IMO), has introduced targets to decrease the carbon intensity of the shipping sector 50% by 2050 and mandates new ships to increase energy efficiency. To reduce sulphur emissions, on January 1st 2020 the maximum allowed sulphur content of marine fuels used in international waters (without the use of scrubbers) was reduced from 3.5 wt. % to 0.5 wt. %. This significant drop in sulphur content does not allow the continued use of high-sulphur heavy fuel oil without the installation of scrubbers, and forces international shipping companies to seek alternative solutions.

One option is to use more costly fuels with lower sulphur content. However, current oil refineries do not have the production capacity to produce enough low-sulphur fuels to cover the large market for heavy fuel oil. Alternatively, scrubbers – an exhaust cleaning system – can be installed in the ship to remove large amounts of sulphur from the exhaust material. This requires large investments, induces ‘down-time’ during installation, it takes up volume on the ship otherwise intended for cargo, and it prompt additional maintenance – all for a solution that does not support the GHG targets. Scrubbers is consequently only a viable option and a short time solution suitable for only few shipping companies.

Biomass has the potential to fully supply the marine sector with sustainable energy[2], and was through interviews with a number of shipping industry stakeholders, identified as the most promising short- to mid-term solution for both reducing carbon emissions and meeting sulphur regulations. Marine biofuels have varying degrees of emission reductions, supply and blending potential, and are divided in oleochemical fuels, thermochemical fuels, alcohols and gaseous fuels. There is currently no ‘one size fits all’ economical solution to reduce emissions in the marine sector. The large landscape of emerging alternative marine fuel technologies is difficult to navigate and involves risks for deep-sea shipping companies. These risks are not only related to technical challenges, but also to the uncertainty of long-term availability, future price fluctuations, and regulatory developments.

Biofuels are currently used in both aviation and road transport sectors. Bioethanol and biodiesel have been blended in gasoline since the end of the 1970s, and biobased jetfuel blends were approved for the aviation sector in 2011, with 5 different biofuel production pathways currently allowed[3]. Despite the great potential of bioenergy, biofuel technologies has yet only been commercialized to a very limited extend in the marine fuel market.

This report will attempt to understand why marine biofuels have not yet been commercialized and seek to identify its largest barriers. This report will also seek to identify possible promising pathways for biofuel production and research targeting the shipping sector, as well as other key developments which are necessary for the realization of commercial sustainable biofuels for the shipping sector.

2. The shipping sector

2.1 A BRIEF HISTORY OF SHIPPING

The first sea-going ships in history are believed to be catamarans propelled by sails built by the peoples of Austronesia around 3,000 BC[4]. This invention led to the Austronesian expansion – the colonization of an area spanning almost half of the globe. It was not before 1200 BC the first big merchant hull ships were built. These were able to carry a significant amount of cargo and were able to be steered. Sails were the dominant propulsion technology until the invention of the steam engine in the 19th century, whose invention contributed to a huge increase in international trade[5]. In the beginning of the 20th century the British Royal Navy introduced diesel engines which soon after led commercial ship operators to transition to the use of fuel oil from coal. From the mid-20th century, new ships have almost exclusively been constructed with diesel engines, with only some military or specialized vessels using steam turbines. Today, all large merchant ships are built with a two- or four-stroke diesel engines.

Shipping has been the largest carrier of freight throughout human history, surpassing both that of air and land[6]. There has been a long-term increase in international trade-volume following the industrialization and liberalization of national economies, and the growing global population. The continuous increase in the sector has led to the Invention of new propulsion technologies and ship designs, along with greater efficiency in terms of speed and larger cargo volumes[1]. Nothing indicates this trend will stop as the global emerging economies continue to increase their consumption of commodity goods as their standards of living increase. Even though sea transport is regarded as the most environmentally friendly means of cargo transportation, the current merchant shipping sector burns roughly 350 million tons of fuel annually[7]. The associated sulphur oxides (SO_x) and nitrogen oxides (NO_x) emissions are associated with harmful effects to both humans and the environment[8]. The international shipping sector is therefore in the middle of the next big transition in the history of shipping - the transition towards sustainable shipping.

Shipping in numbers

In 2018 shipping accounted for:

- 2-3% of GHG emissions
- 4-9% of SO_x emissions
- 10-15% of NO_x emissions
- 350 million tons of combusted fuel, where HFO accounted for 79% of total fuel consumption on an energy basis
- Around 80% of total export/import by volume, but only 50% by value.

11 billion tons of goods are transported globally each year

1.5 tons per person based on global population

World shipping trade reached $US 14 trillion in 2019

Sources:[168, 7, 138]

> *"We are in the middle of the biggest change since shippers went from break bulk to intermodal containers, or since ship propulsion went from coal to oil."* **Tim Reeve**, Senior Project Manager at Maersk.

2.2 THE DIVERSITY OF SHIPPING VESSELS

Only a few decades ago, the main role of the shipping sector was the transportation of people - now the shipping sector is dominated by the movement of goods. The modern shipping sector has increased not only in size and number of vessels, but also in the diversity of roles it covers in the modern society. The shipping sector is dominated by the merchant shipping with large tankers, container, and bulk cargo ships responsible for more than 70% of maritime GHG emissions. An increasing number of large specialized vessels have recently entered service, such as gas carriers, specialized in carrying liquid natural gas (LNG), reefers that specialize in transporting refrigerated goods and roll-on/roll-off (ro-ro) ships designed to carry vehicles.

The vessel types of the global merchant fleet can be categorized into 9 types, outlined in table 2.1.

Table 2.1 Ship types in the global merchant fleet[9]

Vessel type	Purpose	% of merchant fleet by	
		Gross tonnage	Number
General cargo ships	Multipurpose. Transport non-bulk cargo	5%	14%
Container ships	Transport non-bulk cargo in containers	18%	4%
Ro-ro Cargo ships	Carry wheeled cargo	4%	1%
Bulk carriers	Transport bulk cargo (ore, grain, coal etc.)	34%	10%
Oil and chemical tankers	Transport fluids (crude oil, gasoline or chemicals)	25%	12%
Gas tankers	Transport gas (mainly LNG)	6%	3%
Passenger ships	Transport passengers.	3%	6%
Work and service vessels	Offshore service vessels and tugboats	5%	28%
Fishing vessels	Vessels associated with the fishing industry	1%	21%

The Gross Tonnage (GT) of a vessel is a dimensionless measure based on the moulded volume of all spaces in the vessel. The GT is a broadly utilized measure relevant for example for port dues or safety regulations. The largest vessel categories by number are work and service vessels, fishing vessels and general cargo ships in the small to medium size category. However, these vessels only account for a small part of the total GT of the merchant fleet, which is dominated by container ships, bulk carriers and tankers primarily in the large to very large category (Figure 2.1). Dead weight tonnage (dwt) is a measure of the maximum carrying capacity (by mass) a vessel can safely carry. There is a big variation of dwt within vessel types, but generally container ships, bulk carriers and tankers have the largest dwt of up to 550,000 dwt. The size of a vessel greatly influences its CO_2 emissions. It is estimated that half of the maritime CO_2 emissions is associated with vessels larger than 60,000 GT, corresponding to only 5% of the merchant fleet by numbers[9]. GHG reduction strategies should therefore primarily target large and very large ocean-going vessels.

Vessel size	
Small	<500 GT
Medium	500 - 25 000 GT
Large	25 000 - 60 000 GT
Very large	>60 000 GT

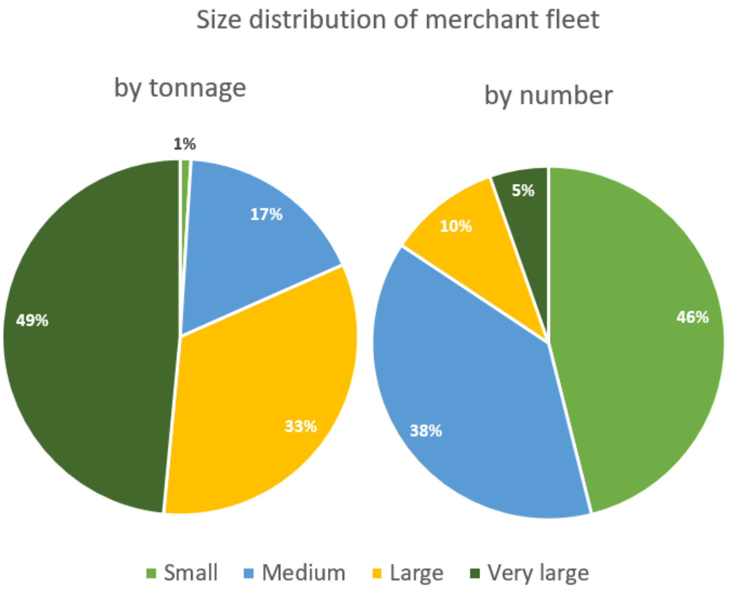

Figure 2.1 Size distribution of ships in the global merchant fleet by tonnage and number[9] Size distribution of ships in the global merchant fleet by tonnage and number[9]

Short-sea vessels (size typically range from 1,000 to 15,000 dwt) move cargo and passengers in fixed routes in environmentally sensitive areas such as coastal waters, lakes, inland rivers and urban areas. Short sea shipping is thus competing with ground transportation on both freight price and sustainability. Concerns about air-pollution in populated coastal areas and meeting potential environmental control areas (ECA) restrictions makes short sea vessels usually fueled by marine gas oil (MGO) (see section 4). Short-sea shipping dominates European trade and transport in the Black Sea, Mediterranean, Baltic and North Seas as well as in rivers to serve the continental European countries. The vessels are commonly owned by small to medium-sized companies and subsidized by local governments. Short-sea shipping has a good combination of strict environmental regulations, short routes, many stopovers, and local governmental funding that lowers the economic and technical barriers for testing and adopting new marine propulsion technologies such as biofuels, or fully electric powered engines[10]. Almost all marine biofuel trials have therefore been conducted in the short-sea shipping sector.

The short-sea biofuel trials should provide the technological and economic experience to become a springboard for the implementation of alternative fuel technologies in deep-sea shipping. A graphical illustration of the large amount of short-sea shipping can be seen in figure 2.2 exemplified with Europe.

Figure 2.2 Graphical illustration of the large amount of short-sea shipping in Europe based on marine vessel traffic July 3rd 2012. White lines represent ship traffic. Made by Kiln.digital.

Deep-sea shipping refers to intercontinental shipping, which represents the largest percentage of the global fleet by GT. Around 80% of the global deep sea shipping fleet consists of vessels larger than 25,000 dwt. Tankers, dry bulk carriers and container ships dominate this segment and are owned by a few large private companies, which account for 95% of the industry revenue. An overview of the largest shipping companies can be seen in Table 2.2, while a graphical representation of the marine vessel traffic is seen in figure 2.3.

Table 2.2 ***List of the 5 largest shipping companies*** *on the basis of cargo carrying capacity*[11]*. TEU stands for twenty-foot equivalent units, the standard length of a container.*

Company	Country	Number of container Ships	Total fleet carrying capacity [TEU]	Market share [%]
Maersk Line	Denmark	711	2,921,125	15.5%
Mediterranean Shipping Company S.A.	Switzerland	524	2,550,147	13.6%
CMA-CGM Group	France	505	1,628,269	8.7%
Hapag-Lloyd	Germany	231	965,168	5.1%
Evergreen Marine Corporation	Taiwan	178	948,220	5.0%

Figure 2.3 Graphical illustration of the marine vessel traffic July 3rd 2012. Colour indicates vessel types. Yellow: containers, blue: Dry cargo, red: Liquid cargo, green: Gasous cargo, purple: Vehicles. Made by Kiln.digital.

2.3 EMISSIONS REGULATIONS

The exhaust gasses from the burning of fossil fuels for marine shipping produces a large amount of pollutants, and shipping alone represents 2-3% of global GHG emissions. The exhaust material of diesel engines consists primarily of nitrogen, carbon dioxide (CO_2) and water. Carbon monoxide (CO), sulphur oxides (SO_x), nitrogen oxides (NO_x) and particulate matter will also be part of the exhaust material to varying amounts, depending on factors such as the chemical composition of the fuel, engine combustion efficiency and combustion temperature. The emissions of these compounds have serious negative human health and climate impacts, including terrestrial and aquatic acidification, lung cancer and premature deaths[12-14]. Therefore, these cumulative emissions represent a real threat the environment and the climate and must be reduced.

Due to its transnational nature and existence primarily on the high seas and beyond national borders, global shipping has not been accounted for in individual countries' GHG and pollution emissions reduction targets and regulations. Therefore, international regulation is necessary to control emissions and pollution from the shipping sector. International shipping including both short-sea and deep-sea shipping is under the jurisdiction of the International Maritime Organization (IMO), covering all of the sea and coastal areas of the world[15]. According to the latest GHG study from IMO, the current 2050 GHG emission projections for the shipping sector vary from 90-130% of 2008 emissions[16]. As international trade expands, the climate impact of the maritime shipping sector will not improve unless direct actions are taken to reduce maritime GHG emissions. Policies in the form of tax incentives, mandates or subsidies have played a central role in bringing biofuels to the aviation and road sectors. One of the most important driving forces for GHG reduction in shipping is legislation.

IMO develops international regulations and takes action to reduce the environmental impact of shipping through reduction of emissions, where biofuels can contribute to reduce these emissions. The strict limits on sulphur content in fuels that came into force January 1st 2020 will be addressed in detail in this section. However, other emissions also fall under the scope of the IMO's jurisdiction where targets and objectives are being developed similar to the aviation sector (although at a slower pace)[17].

2.3.1 The International Maritime Organization

The IMO is a specialized agency of the United Nations responsible for the global regulative framework surrounding international shipping[15]. The IMO regulates all aspects of safety, environmental concerns, legal matters, technical co-operation, maritime security, and efficiency within shipping. The IMO was established following agreement at a UN conference held in Geneva in 1948 and met for the first time in 1959. Similar to the International Civil Aviation Organization (ICAO), the IMO jurisdiction encompasses international shipping that falls outside the scope of domestic jurisdictions (inland waters). The IMO initiatives on emissions cover air pollutants (such as SO_x and NO_x), including greenhouse gas emissions.

The International Convention for the Prevention of Pollution from Ships (MARPOL) incorporates regulations to restrict air pollution from ships (Annex VI) and was first adopted in 1997[18]. A revised Annex VI came into force in 2010, regulating a reduction of SO_x and NO_x emissions for vessels in international waters.

The IMO Working Group on Greenhouse Gas Emissions from ships took place in 2008, but an initial strategy on reducing GHG emissions was only adopted in 2018. Although the IMO participated in the 2015 United Nations Climate Change Conference in Paris, the IMO was not part of the Paris agreement on climate change and must self-regulate on issues like GHG emissions. Although accused of inaction after the Paris agreement, the IMO Marine Environment

Protection Committee (MEPC) finally adopted a strategy reducing of GHG emissions from ships in 2018, including a vision to reduce and phase out emissions as soon as possible[19]. A revised strategy on further GHG reduction is planned for 2023.

2.3.2 SO_x regulations and abatement technology

The first regulations to reduce SO_x emissions from ships formed part of the MARPOL Convention which came into force in 2005. This convention mandated the reduction and regulation of the amount of sulphur emitted by ships in various geographies, either through instituting sulphur fuel limits or by mandating that SO_x scrubbers be installed on ships to reduce SO_x emissions (Table 2.3).

Table 2.3. Sulphur limits on fuel oil outside and inside ECAs showing the dates as they came into force

Outside an ECA established to limit SO_x and particulate matter emissions	**Inside an ECA established to limit SO_x and particulate matter emissions**
4.50 wt. % prior to January 1st 2012	1.50 wt. % prior to July 1st 2010
3.50 wt. % on and after January 1st 2012	1.00 wt. % on and after July 1st 2010
0.50 wt. % on and after January 1st 2020	0.10 wt. % on and after January 1st 2015

ECAs were established where different limits for sulphur emissions were required within vs outside the ECAs.

The ECAs and their regulated pollutants were established as follows:

- Baltic Sea area (SO_x only)
- North Sea area (SO_x only)
- North American area (entered into effect 1 August 2012) (SO_x, NO_x and particulate matter (PM))
- United States Caribbean Sea area (entered into effect January 1st 2014) (SO_x, NO_x and PM).

The sulphur limits apply to the fuel oil used in ship propulsion and the progressive phased-in limits are shown in Table 2.3 and Figure 2.4[20].

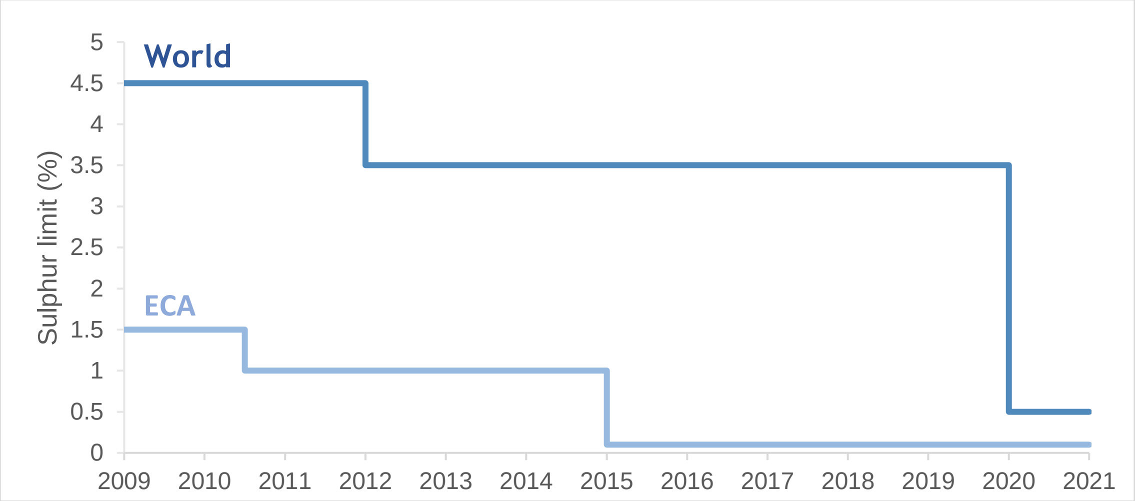

Figure 2.4 IMO MARPOL Annex VI Sulphur limits timeline

Vessels traveling both inside and outside the ECA would generally have a dual fuel system to allow switching from heavy fuel oil (which has sulphur content up to 3.5 wt. %) outside of the ECA's, to a compliant fuel to meet the regulations within the ECA. On January 1st 2020, strict regulations came into force limiting sulphur in fuels to 0.50 wt. % at a global level, restricting the use of heavy fuel oil to vessels equipped with an exhaust cleaning system (scrubber). Within the Sulphur Emission Control Areas (SECAs), the requirement was set at 0.10 wt. % sulphur limit in the North American, US Caribbean, North Sea and Baltic. Figure 2.5 shows the regional and global limits in 2020.

Figure 2.5. IMO world map for emission control areas in 2020. Globally there is a 0.5% sulphur limit. Sulphur emission control areas (SECAs) include the Baltic- and The North sea area (blue) with a 0.1% sulphur limit, the North American ECA (green) with a 0.1% sulphur limit, Chinese National waters (red) additional restrictions for open loop scrubbers, and discussed future ECA (grey)[21].

Apart from the differential cap on sulphur content in fuels in the SECAs, additional, specific regulations apply in other areas (as shown in Figure 2.5). The European Union Sulphur Directive stipulates a maximum of 0.10 wt. % sulphur content in fuels for ships in EU ports. China also expanded the 0.50 wt. % sulphur fuel limit areas to a 12 nautical mile zone covering the entire Chinese coastline. Furthermore, the California Air Resources Board (CARB) enforces a 0.10 wt. % sulphur fuel limit within 24 nautical miles of the California coast[21].

To comply with the 0.5 wt. % sulphur regulations outside ECAs, ships have turned to four options:

- Using Marine Gas Oil (MGO) consisting of exclusively distillate oil.
- Using desulphurized fuel oil - Very Low Sulphur Fuel Oil (VLSFO).
- Using LNG requiring a retrofit of the vessels engine and fuel system
- Installing exhaust gas cleaning systems (scrubbers) allowing the continued operation on High Sulphur Fuel Oil (HSFO)[21]

Switching to MGO entails a significant increase in fuel cost, as these fuels are more expensive than HSFO. The increased use of VLSFO requires refineries to adapt their crude oil refining processes to increase fuel desulphurization. The investment required for expanding or implementing more desulphurization units largely depends on the price gap between VLSFO and MGO with natural sulphur content of 0.1%. In the past 2 years this price gap has been low holding back further expansion[22].

The fourth option to mitigate the 0.5 wt. % sulphur regulations is through installing exhaust gas cleaning systems (EGCS) – also known as scrubbers. The exhaust is mixed with water to turn SO_2 into water-soluble sulphates. Scrubbers exist in both open- and closed-loop configurations including a combination where vessels can use the open scrubber configuration at open sea, and closed configuration in more sensitive areas. Scrubber installation is not a practical or economical solution for all vessels since scrubber installation requires a large volume and additional maintenance, an investment between US$ 2-10 million as well as 2-3% increase in fuel consumption[21]. However, scrubbers can provide SO_x emissions reduction with lower well-to-wake energy consumption and GHG emissions than using low sulphur fuels[23]. According to DNV GL approximately 2500 ships were equipped with a scrubbers in the beginning of 2020 corresponding to 10-15% of the entire marine fuel consumption[21]. The majority of ships equipped with scrubbers are large bulk carriers and tankers retrofitted with open-loop scrubbers.

The effect on vessel GHG emissions of these four options are estimated to be ± a few percent which considering the larger uncertainties of the models can according to the IMO be regarded as having no net impact on CO_2 emissions[16,24]. In contrast, biofuels have the potential to greatly reduce GHG emissions as well as reducing SO_x emissions, as they contain little to no sulphur.

2.3.3 Enforcement of IMO regulations on sulphur

Enforcement of sulphur regulations will take place by Port State Control (PSCs) authorities through the inspection of foreign vessels in national ports. They verify the condition of the vessel and assess if its equipment, staff, and operation comply with the requirements of international and or national regulations. Thus, the IMO itself is not responsible for enforcement of the regulations. Uniform penalties for non-compliance have not been determined and sentencing/penalizing will be up to every PSC to decide. As a minimum, it is expected that the PSC will require ships to offload non-compliant fuel. However, actions will likely vary significantly between port states. From March 2020, a general ban on carrying high sulphur fuel oils on board vessels unequipped with a scrubber was implemented. This was done to close an enforcement loophole related to proofing the ship actually used such fuel.

The IMO can adopt conventions on any relevant matter, but the convention only comes into force once a minimum number of member states (the IMO consists of 174 member countries) have ratified the convention. Once ratification has taken place, every member country must incorporate the convention into their own legislation. The IMO does not have any authority to enforce regulations. Enforcement is carried out by member states in accordance with domestic legislation and regulations. Penalties for non-compliance are therefore part of domestic laws and this may differ from member state to member state[25]. The IMO has not specified any fines or sanctions for non-compliance, and it is up to the discretion of individual member states to determine penalties. MARPOL only states that penalties should be '*sufficient to discourage violation … irrespective of where the violations occur.*' In practice, the 0.5% requirement will be enforced globally by PSC authorities that is permitted to inspect any vessel for compliance.

Port State Control is established in a region under a Memorandum of Understanding on Port State Control (MOU). The Paris MOU, for example, incorporates 26 European countries and Canada. Similarly, other regional MOUs were established, Tokyo MOU (Pacific Ocean), Acuerdo Latino or Acuerdo de Viña del Mar (South and Central America), the Caribbean MOU, the Mediterranean MOU, the Indian Ocean MOU, the Abuja MOU (West and Central Atlantic Africa), the Black Sea MOU, and the Riyadh MOU (Persian Gulf), Figure 2.6.

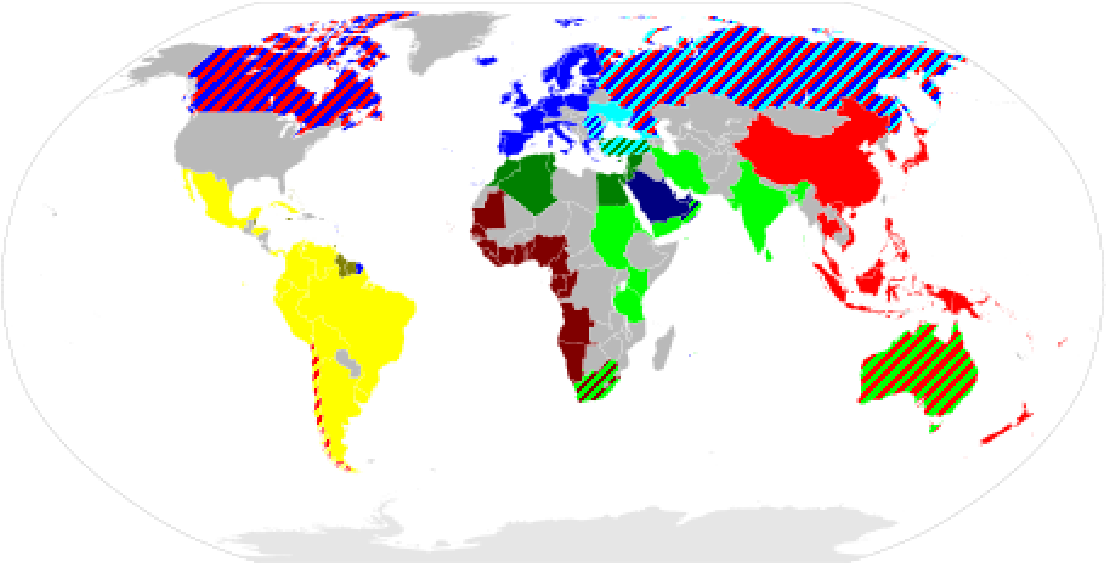

Figure 2.6. Map showing jurisdiction of regional Port state control authorities and signatories. Paris MOU (blue), Tokyo MOU (red), Indian Ocean MOU (green), Mediterranean MOU (dark green), Acuerdo de Vina del Mar (yellow), Caribbean MOU (olive), Abuja MOU (dark red), Black Sea MOU (cyan) and Riyadh MOU (navy) (Source: Wikipedia)

By January 1st, 2020 when the IMO's sulphur cap entered into force, several Asian countries had already implemented similar ECAs. At the start of April 2020, the Port Authority of Singapore, announced that, from the start of 2020, captains and owners of vessels that burn high sulphur fuel in the Asian country's territorial waters, without using sulphur-reducing technology such as gas scrubbers, could face as long as two years in prison[25]. Ship owners and operators could also face detention of ships[26]. In January 2019, Taiwan and Hong Kong implemented regulation enforcing a 0.5 wt. % sulphur limit on ships operating in national waters. Hong Kong enforce this by making non-complying vessel owners pay a fee up to 200,000 HKD (approx. $US 25,000) and up to six months of imprisonment[27].

In the United States, enforcement measures could include letters of warning, notices of violation with penalties up to $US 10,000, civil penalties up to $US 74,552 per violation and criminal enforcement[28]. In August 2019, two shipping companies were convicted and sentenced to pay $US 3 million for violations of Annex VI, namely use of non-compliant fuel in the Caribbean ECA, failing to maintain an accurate oil record book, maintaining false bunker delivery notes, and obstructing justice[29]. In 2019, the US Coast Guard and US Department of Justice fined two Greek vessel operators $US 1.5 million each and senior crew members were sentenced to three years' probation under the first criminal prosecution of a violation under MARPOL Annex VI[28]. Chinese regulations allow for fines ranging from 10,000-100,000 yuan (approx. 1,500-15,000 $US) for IMO 2020 violations[30].

The IMO has set strict limits on sulphur in fuels used by shipping vessels, the enforcement of these limits is a source of concern. While the measures came into force from January 1st, 2020, many member states have yet to ratify the Convention, and many have not implemented domestic legislation to incorporate these measures. In addition, consistency of enforcement is a concern. A world map of States that have ratified Annex VI of the MARPOL Convention can be seen in figure 2.7.

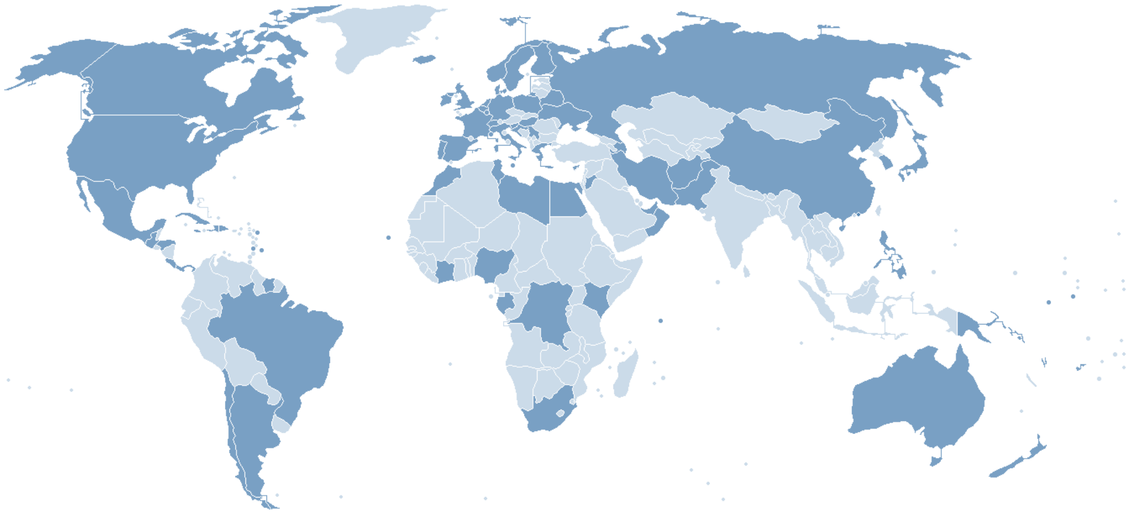

Figure 2.7. Map showing States have ratified Annex VI of the MARPOL Convention (Source: Wikipedia)

2.3.4 GHG reductions - regulations and targets

In 2018, the IMO adopted a strategy for the reduction of GHG emissions including specific reference to the Paris Agreement temperature goals[31]. The targets for emission reductions included:

- Reducing the average carbon intensity by at least a 40% by and 70% in 2050 (compared to 2008 levels).
- Reducing the total GHG emissions from international shipping by at least 50% by 2050 (compared to 2008 levels)
- Review of the Energy Efficiency Design Index (EEDI)[31]

Figure 2.8 below is a graphical illustration of current emissions and targets. A baseline, representing a Business as usual (BAU) case, is shown.

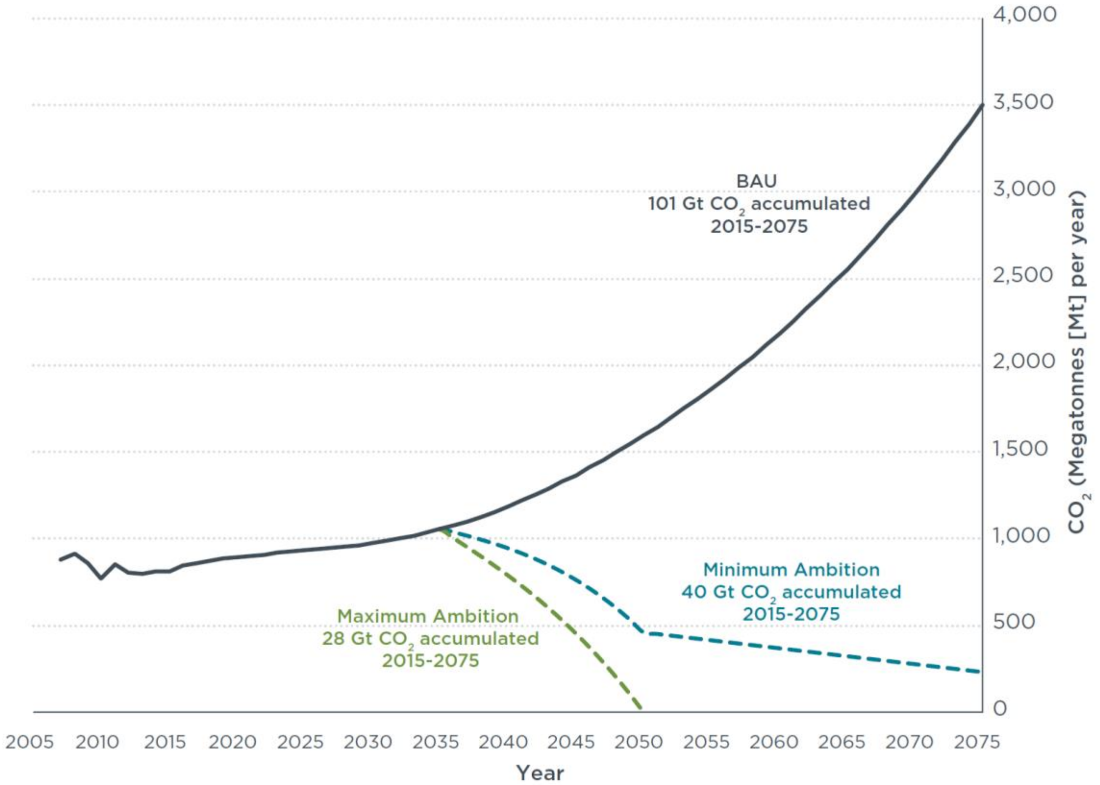

Figure 2.8 Cumulative CO_2 emissions from international shipping under IMO's initial GHG strategy (blue and green) versus business as usual (BAU in black)[31]. Cumulative CO_2 emissions from international shipping under IMO's initial GHG strategy (blue and green) versus business as usual (BAU in black)[31], Reprinted with permission from the authors[31].

Different measures can be taken to achieve these targets. Easier methods in terms of cost and technical feasibility, is to improve the energy efficiency through hull design, improved engines, ship maintenance, route optimization, as well as reducing fuel consumption via slow steaming[32].

The life cycle of large container ships requires an investment of at least 15 years and can typically be operational for 20-25 years. The long life-span makes it important for ship owners to ensure engine technology compatibility with accessible future marine fuels. Vessel energy efficiency is of great importance and is continuously improving as even small enhancements lead to long-term fuel and emissions savings. To ensure new ships are designed for high energy efficiency regulations were introduced through the EEDI and was in 2011 made mandatory for all new ships built from 2013. The index applies to the technical aspects of the ship and depends on installed power, hull and propeller design, speed, dwt as well as fuel type[33]. The index is adjusted for vessel type and estimates grams of CO_2 emission per tonne-mile. The EEDI requires a minimum energy efficiency level with increasing requirements every five years. In the initial phase, a 10% reduction is required and after 2025, a 30%. About 85% of GHG emissions from international shipping is expected to fall under this regulation[34].

The Ship Energy Efficiency Management Plan (SEEMP) and Energy Efficiency Operational Indicator (EEOI) are other IMO initiatives to facilitate good practices for ship maintenance related to higher fuel efficiency. Examples are vessel speed and route optimization depending on weather, reduction of waiting time in ports, reducing drag by removing barnacles or cleaning the propeller.

In the most recent MEPC 75, the prohibition of use and carriage of Heavy Fuel Oil (HFO) in Arctic waters was approved. The Polar Regions consist of vulnerable ecosystems where a potential oil spill would have devastating consequences to the environment including wildlife. The limited infrastructure and the navigational challenges of sea ice and heavy weather conditions makes oil spills extremely problematic. A ban on carrying HFO in the Antarctic has existed since 2011. The new regulation will come into action July 1st, 2024 or in 2029 for vessels with existing fuel oil tank protection (with for instance double hull). The usage of highly biodegradable biofuels such as biodiesel in the polar regions have several environmental advantages, besides their low GHG and no sulphur emissions, spills would be much less harmful to the environment.

The latest MEPC also approved three draft amendments to the MARPOL Annex VI introducing new regulations on GHG emissions from ships with expected adoption at next MEPC session in June 2021 that will put them into force on January 1st 2023[35]. One amendment is Energy Efficiency Existing Ship Index (EEXI), a one-time certification for all existing vessels regardless of built year to meet energy efficiency targets. Operational Carbon Intensity Indicator (CII) is another amendment affecting all vessels above 5,000 GT. The CII is an annual rating program measuring the operational carbon intensity of the vessel (measured as grams of CO_2 per dwt per mile) giving a rating from A to E. This rating threshold is planned to continually increase stringency to meet GHG reduction targets of 2030. For ships with an E rating or with three consecutive D ratings, an action plan for improvement needs to be approved and integrated as part of the SEEMP. Ships not complying with the SEEMP will not receive a statement of compliance and could be detained by port authorities. More detailed enforcement strategies could be seen closer to 2023. The continuous pressure on the industry to make more efficient vessels through EEDI, EEXI as well as CII are important measures towards lower emissions. However, using technical and operational optimization alone is a game of diminishing returns and will require fuel transition to meet the IMO GHG[36-38]. Considering the emission reductions associated with biofuels, these regulations could promote vessel owners to retrofit their existing vessels with more fuel-flexible engines compatible with biofuels.

The international GHG reducing mechanisms are targeting single vessels only and does not include mechanisms covering the GHG emissions of entire fleets. This could remove incentives to start producing zero-carbon vessels, which is the aim of the '*Getting to Zero Coalition*' consisting of more than 120 companies such as Maersk, Shell, and Cargill aiming to get zero emission vessels commercially viable in 2030[39]. Another criticism is that even with new more efficient ships, the growth in demand for shipping will easily outstrip the efficiency gains achieved by the IMO policy[40]. More 'radical' changes such as market-based mechanisms (carbon pricing), alternative fuels, including LNG, biofuels, and development of zero carbon fuels are needed[41].

While there has been an increase in ships operating on LNG, only limited emission reductions can be achieved (~15%), and problems with methane leakage can negate the benefits[42]. It is argued that LNG vessels may not offer any GHG emission benefits over the long-term, particularly if methane slips cannot be controlled[42]. However, biofuels that can be used in the existing engines or used with minimal modifications, can achieve significant emission reductions[43]. Greater use of biofuels in the sector is limited by the volumes available at present with delays in commercialization of technologies. Some technical challenges remain, but the delays of the sector to set emission reduction targets and the absence of supporting policies to facilitate a significant expansion of these biofuels have played an enormous role. The cost of reaching the IMO targets of 50% GHG reduction in 2050 has been estimated to be $US 1-1.4 trillion or $US 1.4-1.9 trillion to fully decarbonize[37]. To put the number into perspective, the global investment in energy in 2018 was $US 1.85 trillion[44]. All biofuels have been developed through strong policy support and thus this is also most likely necessary in the shipping sector. The debate and discussion around appropriate policies have been ongoing in the international aviation sector and the Carbon Offset and Reduction Scheme for International Aviation (CORSIA) commencing in 2021 has been a significant step for the aviation sector[45]. Although the price of offsets will influence its impact, the scheme is an important step towards carbon pricing. Discussions in the shipping sector for pricing carbon emissions have been focused on two aspects, a carbon levy on fuel to be placed in a fund for research and development of new technologies, and a market-based measure in the form of a carbon tax on emissions[46]. These two proposals and their potential impact emission reduction targets, and the promotion of biofuels will briefly be discussed.

2.3.5 International Maritime Research and Development Board

The International Maritime Research and Development Board (IMRB) is an industry submitted suggestion to accelerate decarbonization of the shipping industry and was submitted for discussion at the MEPC 75th session in November 2020[47]. Some of the largest international shipping associations were behind the suggestion covering around 90% of the merchant fleet includes The Baltic and International Maritime Council, Cruise Lines International Association, The Internal Chamber of Shipping, The International Association of Dry Cargo Shipowners, The International Ferry Association INTERFERRY, International Association of Independent Tanker Owners, The International Parcel Tankers Association, and The World Shipping Council. They suggest a carbon levy of $US 2/ton of consumed marine fuel for ships larger than 5,000 GT. Proceeds of this levy will go into a new entity, the International Maritime Research Fund (IMRF) for the purpose of funding the research and development of zero-emission vessels by 2030 and beyond. Spending of funds will be coordinated by the IMRB. The 2 $US amount was based on an annual fuel consumption of 250 million tons, which would result in a total of $US 5 billion by 2030. This levy is not intended as a market-based measure or a carbon tax, although this was heavily discussed during the MEPC 75[46]. The IMRB was unable to progress during the MEPC 75 and is expected to be further discussed at MEPC 76.

A market-based measure such as a carbon tax between $US 30-225/ton CO_2 has been discussed among industry leaders at the Global Maritime Forum. A survey of ship owners showed that 75% agreed that carbon pricing is needed, where most were willing to pay $US 50/ton CO_2[48]. However, this may still take 10 years before carbon taxation in the maritime sector would come into force, which could be too late to have the required impact on carbon emissions[40].

2.3.6 National and supranational GHG regulations

The crucial role of policies is to set the regulatory framework to encourage the implementation of maritime biofuels. Since biofuel technologies are diverse and the biomass type and availability differ greatly between nations, biofuel implementations rely on multiple stakeholders and supply chains. This makes establishment of national and supranational level policies particularly important, as these can more specifically support the local supply chains adapted to the technological maturity and biomass availability.

China

There are many unknowns about the scope of China's climate plans, but recently it was announced that China will stop releasing CO_2 before 2060 while peaking in GHG emissions before 2030[49]. However, these goals have not yet been translated into specific national targets for the marine sector.

United States

The US Renewable Fuel Standard (RFS) provided a more predictable framework for biofuel producers to operate, and helped the US to become one of the leading producers of biofuels. This standard set increasing targets for volumes of biofuels to be produced, and set different targets for conventional and advanced biofuels, with a focus primarily on cellulosic biofuel[50]. While this legislation provided a framework for biofuel producers to increase production, US congressional action and legal processes against the legislation ended in creating market uncertainty with regards to future market rules. The current energy directive, should provide a more stable roadmap for the industry. The new target of 3.5% for advanced biofuels of total fuel consumption by 2030, is considered both realistic and ambitious. However, this goal is vastly less than what is necessary to decarbonize the overall transport sector in the United States[51].

EU Strategy

Regulations from the EU could have an important role for biofuel deployment in shipping for its member countries and could potentially put pressure on IMO to increase their GHG emission targets. The GHG emissions in the European transport sector has declined only by 3.8% since 2008, despite a +18% decrease in all other sectors[52]. Shipping emissions represent roughly 13% of the overall GHG emissions from the transport sector in EU. Even though the European Commission recognizes the most effective approach to reduce maritime GHG emissions is through the IMO, they also find the IMO approach relatively slow which has triggered EU to act[53].

EU is currently supporting the IMO SO_x regulations with the EU Sulphur directive expanding the sulphur ECAs. The Non-road Mobile Machinery emission regulations (NRMM) is another EU initiative affecting the inland shipping and port operation sectors which outside IMO jurisdictions. Although the EU support the IMO legislation, there are no maritime GHG emission targets at EU level. However, the European Commission recognizes the shipping sector can reduce GHG emissions and is currently considering to incorporate shipping emissions into the EU GHG targets[54].

On December 11th 2019, the European Green Deal was presented by the European Commission with a set of policy initiatives and revisions to responsibly reduce the greenhouse gas emissions by at least 49% at 2030 compared to 1990, and make Europe climate neutral in 2050[55]. This target was adjusted to 55% through an agreement on European level in December 2020[56]. The goals extend to many different sectors such as food, biodiversity, construction, energy, and transportation – including shipping. An example of relevant action for maritime biofuels is an expected revision of the Energy Taxation Directive covering fossil and renewable fuel subsidies and tax exemptions. Another example is the aim to regulate the access of the most polluting ships to European ports and forcing docked ships to utilize shore-side electricity to reduce air-pollution around cities. On December 9th 2020, a new EU transport strategy was published putting emphasis on the urgent need for actions to reduce emissions from navigation and aviation[57].

The European Commission wants these transportation modes to have priority access to renewable and low-carbon gaseous and liquid fuels due to the short-term lack of suitable alternative powertrains. Furthermore, the Commission considers establishing a Renewable and Low-Carbon Fuels Value Chain Alliance, which would boost supply and deployment of promising alternative fuels through cooperation between publish authorities, industry and civil society. As part of bringing the sector in line with the EU's ambition of climate-neutrality, the Commission proposed The FuelEU Maritime initiative planned for adoption by mid-2021[58]. The initiative aims to increase adoption of sustainable alternative fuels by lowering market barriers through tax exemptions and to include shipping in the European Emission Trading System (ETS). It is expected to greatly encourage and accelerate the adoption of low-carbon shipping in Europe.

With the goal of climate neutrality in 2050, EU show much higher GHG reduction ambitions compared to the 50% reduction target of the IMO. International competitiveness of member countries could be negatively impacted, but it also puts pressure to strengthen international GHG reduction targets due to the large share of European IMO members. One of the initiatives being assessed under the European Green Deal is the Renewable Energy Directive 2018/2001/EU (RED II) which is the main regulatory framework for EUs renewable energy. The overall EU target is 32% renewable energy in 2030.

The differences in countries starting point and potential are considered and reflected in their national targets such as Malta with a low 10% and Sweden with a high 49%. Fuel suppliers for road and rail are required to supply a minimum of 14% renewables on an energy basis by 2030[59]. RED II also defines a range of sustainability and GHG emission criteria which renewable (liquid, solid and gaseous) (bio-)fuels need to meet to count towards the 14%. The RED II poses a limit on food and feed crops of 2020 level + 1% with a maximum of 7%. There is also a limit of 1.7%

for biofuels produced from Annex IX-B feedstocks (used cooking oil and animal fats). The RED II includes a sub-target for advanced biofuels produced of 3.5% in 2030 from Annex IX-A feedstocks (waste materials and residues). Biofuels produced from Annex IX feedstocks may be counted twice for the 14% target. The 1.2 factor is not applicable to biofuels from feed and feed crops. Not only biofuels can count towards the 14% RED II target but also renewable electricity, renewable hydrogen and synthetic fuels produced from renewable electricity are eligible to count towards the target as well. Aviation and maritime fuel are not included in the 14% but is stated as an opt-in and will count 1.2 times their energy content. It should be noted that RED II most likely will be revised in the course of 2021.

The Dutch opt-in model

As an example of national legislation, and the impact on the marine shipping, the Dutch opt-in model is presented here. In the RED II framework, renewable energy supplied to the maritime and aviation sectors are eligible for counting towards the 14% renewable energy in transport target for road transport (by a factor 1.2). So far, the Netherlands is the only EU Member State that has already implemented a voluntary contribution of these sectors to the annual obligation scheme ("Jaarverplichting"). This scheme aims to realize the 14% renewable target in transport from the RED II as well as the target for CO_2 emission reduction in road transport from the Dutch Climate Agreement (2019), i.e. 2 Mtons CO_2 emission reduction in 2030 additional to the forecast made in the National Energy Exploration ("Nationale Energy Verkenning") from 2017. This is to be achieved through a maximum of 60 PJ of renewable fuels in road transport.

The "opt-in" possibility for maritime and aviation (in the legislation referred to as: allowance/permission to register) aims to provide an extra incentive for the application of renewable energy in both sectors, where substantial CO_2 emission reduction is still very necessary. For maritime, this has been very successful so far, since the volume of biofuels used in maritime has increased substantially since 2019.

In practice, the opt-in possibility means that companies that supply renewable energy to maritime or aviation can register these volumes and receive tradable units (HBE's, 1 HBE = 1 GJ of renewable energy) for them, without having to comply with the annual obligation. These HBE's can, just like the HBE's originating from renewable energy in road transport, be used by companies with an obligation to demonstrate compliance with the annual obligation for road transport (generate and buy sufficient HBE's).

When implementing such an opt-in possibility into an obligation scheme for road transport, it should be noted that especially volumes of renewable energy realized in maritime may lead to lower volumes applied in road transport, since biofuels used in (deep) sea vessels can be of lower quality and therefore be cheaper than road transport biofuels. It should be taken into account that these volumes realized in maritime do not contribute to (national) CO_2 emission reduction targets (since it is an international sector) and not to (national) CO_2 reduction targets specifically for road transport. Although the lower costs of biofuels in maritime may lead to lower overall costs for realizing the annual obligation and the RED II 14% target in the Netherlands, it should be noted that with an opt-in possibility the costs of supply of renewable energy to maritime and aviation will be borne by the end-users in road transport. In the draft legislation for adjusting the annual obligation scheme (2022-2030), which is now in consultation, it is proposed to extend the opt-in possibility until 2025 and then stop it and limit the opt-in to biofuels produced from Annex IX-A feedstocks (waste materials and residues) and synthetic fuels produced from renewable electricity (electrofuels). Inland navigation used to have an opt-in possibility under the legislation until 2020, but will be placed under the annual obligation scheme as of January 2022.

This standard set increasing targets for volumes of biofuels to be produced, and set different targets for conventional and advanced biofuels, with a focus primarily on cellulosic biofuel[60]. While this legislation provided a framework for biofuel producers to increase production, US congressional action and legal processes against the legislation ended in creating market uncertainty with regards to future market rules[51].

3. Marine propulsion technologies

Engine manufacturers have a crucial role in the energy transition of the shipping sector. Meeting the specific requirements of MARPOL Annex VI urges engine manufacturers to produce engines with high fuel efficiency, optimized combustion for low NO_x emissions and establish compatibility with low sulphur fuels or an exhaust gas cleaning system.

The engine type defines the ships fuel compatibility, and thus fuel availability during the lifetime of the engine (up to 40 years) is the key concern when deciding which engine type to install.

Modern marine propulsion is characterized by a mechanical system consisting of an engine or electric motor powering a propeller. There are few cases of specialized vessels using other propulsion technologies. The primary propulsion used in LNG tankers is steam turbines powered by steam generated by boilers burning LNG or oil as fuel. Because of the low efficiency of steam turbines, new LNG tankers are typically equipped with a two-stroke diesel engine or diesel-electric engine driven by boil-off gas. Gasoline engines are also available but are typically used in smaller vessels. However, because of high thermal efficiency and low-price fuel, two- or four-stroke diesel engines dominate the merchant fleet.

Table 3.1 Common types of marine engines and their fossil fuel compatibility. HFO: Heavy Fuel Oil. MDO: Marine Diesel oil. LSFO: Low Sulphur Fuel Oil. LNG: Liquid Natural Gas.

Engine	HFO	MDO	LSFO	LNG	Gasoline
Compression ignition (diesel)					
2-stroke slow speed	■	■	■		
4-stroke medium speed	■	■	■		
Diesel electric	■	■	■		
Dual fuel (diesel+other)	■	■	■	■	
Spark-ignition					
Gasoline engine					■
Gas engine				■	
Non-reciprocating systems					
Steam turbines	■	■	■	■	■
Gas turbines	■	■	■	■	■

3.1 DIESEL ENGINES

Diesel engines are compression-ignition engines, where the fuel ignition in the engine's combustion chamber is initiated by the high temperature a gas achieves when it is highly compressed. The high compression ratio (1:20) increases engine efficiency, and therefore diesel engines are known to have the highest thermal efficiency of any internal or external combustion engine. The reliability of the engine is also high, as no built-in ignition, such as a spark plug, system is necessary. The power of a diesel engine can range between 0.25 MW for small high-speed engines to 100 MW for large low-speed marine diesel engines. Diesel engines are manufactured in 2-stroke and 4-stroke versions. Compared to marine 4-stroke diesel engines, large 2-stroke diesel engines are capable of burning fuels with larger range of ignition, combustion performance and cetane numbers[61].

A 2-stroke diesel engine coupled to one propeller with recovery of the waste heat, is the most common setup for merchant shipping vessels. Two-stroke engines, are larger in size and of considerable height compared to 4-stroke engines, and are better suited to large and very large ships. Smaller ships tend to have medium- to high-speed engines that are mostly incompatible with HFO due to the high viscosity of this fuel. These ships use MGO with lower sulphur and viscosity[1]. Larger ships have heating chambers as part of the fuel injection to be able to handle high viscosity fuels. The advantage of using large and heavy diesel engines is the very high thermal efficiency in a wide range of power outputs. Their operation at low RPM allows direct shaft connection to the propeller to minimize transmission losses, and is thus commonly installed in large, slow speed vessels. As deep-sea shipping is gaining popularity, new shipping vessels become bigger and heavier, requiring a high power-to-weight ratio. Marine diesel engines have higher fuel flexibility than road vehicle and jet engines, as they are designed to operate with fuels with a large range of cetane numbers, oxygen content, aromaticity and viscosities. This affords marine diesel engines a theoretical advantage for the introduction of marine biofuels, as the fuel quality, in terms of specific physical and chemical properties, can have a wider range than for terrestrial or aviation fuels. Marine diesel engines are therefore relatively insensitive to fuel quality, as they operate well with both light and heavy fuel fractions[1].

The lifespan of a diesel engine can range from 10 years (high speed) to over 20 years (low speed). If maintained properly, diesel engines can stay operational for up to 50 years, for as long as the shipping vessel remains operational, and as long as appropriate fuels are available on the marked. Marine diesel engines are customized for their intended propulsion speed. The optimal operational speed is dependent on ship size, engine fuel, machinery, and technology combinations.

Slow speed diesel engines are commonly installed in deep-sea merchant vessels (tankers, bulk carriers, and container ships) as the ship's main propulsion engine. They are fitted onto ships designed to travel with uniform speed and load. These engines have very high fuel-efficiency but produce higher amounts of NO_x emissions in comparison to medium- and high-speed diesel engines. The average speed of a merchant cargo ship is about 28 km per hour (15 knots), equivalent to about 670 km per day. Modern ships are able to sail 45-55 km per hour, or 25-30 knots. The average speed of deep-sea shipping is about 24-32 km per hour (13-17 knots). Medium-speed diesel engines can also be used as propulsion engines but are also used as auxiliary applications on board smaller cargo ships and ferries. High-speed engines are generally fitted in small vessels operating at varying speed and load, for example in tug-boats. Engine manufacturers also distinguish between an engine's designed speed and operational speed. The latter is constantly updated as the fuel price, market conditions, and technical specification vary, while the former is based upon hull, engine and propeller design.

3.2 GASOLINE AND GAS ENGINES

Spark plug ignition engines, that are compatible with gasoline, ethanol, methanol, and/or gaseous fuels, are largely found in smaller ships. Spark plug ignition engines rely on the spark plug to ignite an air-fuel mixture, which starts the combustion process[1]. These engines can operate at higher speeds than diesel engines since gasoline combusts faster than diesel, and since they have lighter pistons, connecting rods, and crankshaft. The lower compression ratio of gasoline engines (1:11), however, gives these engines a lower thermal efficiency than diesel engines. The combustion of LNG does not lead to sulphur and particulate matter emissions and it generates lower CO_2 emissions than HFO. Therefore, it has gained interest as a possible pathway to meet IMO regulations. Dedicated small- to medium-sized gas engines exist and are produced by for example Kongsberg (Norway) whose gas engines are certified to power LNG tankers, passenger ferries, short-sea shipping vessels, tugs, and offshore supply vessels running on LNG[1,62]. The only large two-stroke engines supporting LNG use HFO and LNG in a dual-fuel combustion process. The two main injection concepts are found in the low-pressure X-DF gas injection dual-fuel engine developed by WinGD and in the high-pressure ME-GI gas injection dual fuel engine developed by MAN.

3.3 MULTI-FUEL ENGINES

Marine diesel engines include some of the most advanced engine technologies including multi-fuel engines. These engines have a fuel injection system, which allows fuel injection at very high pressure/heat facilitating low-cetane fuel combustion. MAN Diesel & Turbo has developed a two-stroke dual liquid gas injection (MAN B&W ME-LGI) marine engine, capable of operating on both conventional diesel fuels as well as low flash point fuels (i.e. alcohols, liquid petroleum gas, LPG, or dimethyl ether, DME). The engines can within a single stroke switch from one fuel type to the other, providing complete fuel flexibility[63]. These MAN B&W ME-LGI engines were tested in seven oil tankers in 2016, with the aim of providing clean-burning ocean-going merchant vessels compliant with stricter environmental emissions regulations. The multi-fuel engines are the latest type of advanced diesel engines, which allow easier compliance with emission-controlled areas, and provide operators with the option to select fuel type according to cost and availability without compromising performance. It also provides opportunities for low-flash alternative fuels such as renewable liquid natural gas, biomethanol, or bioethanol. Fuel flexibility can thus reduce investment risks during the market adaption for sustainable fuel technologies.

3.4 ELECTRIC ENGINES

With the development of battery technology, ships have started to run on electric power. In ports power from the grid is used for various ship operations to lower local emissions, and power generated by on-board diesel generators can be used for propulsion in hybrid systems. A change to electric power can contribute towards improved energy management and fuel efficiency. The development of direct current (DC) grids on board vessels with electric propulsion has enabled the electric generators to operate at variable speeds without compromising fuel consumption[1]. Battery technology in ships will most likely be implemented based on continuing feedback from the development in the automotive industry, where battery-powered cars are now commercially available. Full electrification of ships is, however, unlikely given that batteries/fuel cells are costly and less energy efficient than diesel engines, especially for large ocean going carriers. Some electric passenger ferries are in use and a few showpieces have been rolled out, primarily in the Nordic countries, however these are primarily viable for extremely short ferry routes, and are unlikely to gain market share of the shipping sector. Hybrid ships (diesel-electric), however, are expected to become more common in the future, as energy storage technology will improve. For large deep-sea vessels, for example, the hybrid technology can be utilized for maneuvering and port operations to reduce local emissions in populated areas, and switch to diesel fuel once in open sea. The major disadvantage of electrification is that batteries take up more cargo space and volume than diesel engines. Additionally, the fixed placement of batteries on-board compared to liquid fuels decreases the area available for freight, thus restricting their acceptance in the merchant shipping sector.

4. Traditional marine fuels

4.1 FOSSIL FUELS

Fossil fuels can be divided into coal, gas and oil, where the latter is basis for the vast majority of marine fuels. Crude oil is pumped out of the ground from fossil reserves and transported to oil refineries. The oil is fractionated into a large variety of petrochemical outputs, such as natural gas, kerosene, gasoline, distillate fuels, residual fuels and asphalt. The yield of the distillation depends both on the distillation process and the chemical composition of the crude oil, with density and sulphur being the most important fuel quality attributes.

An oil is heavy or light and sweet or sour depending on the density and sulphur levels of the oil, respectively. When the sulphur content is higher than 0.5% it is typically called sour. Lighter fuels have a viscosity between 2 and 12 cSt at 40ºC and are able to be pumped without provided heating[64]. The higher viscosity of heavy fuels (up to 700 cSt at 50ºC[64]) makes heating necessary for storage and pumping.

Engines in the road and aviation sector is only compatible with light and sweet fuels, where the aviation sector has the highest requirements to fuel quality. The fuel system of large vessels is unique by being able to run efficiently on heavy and sour oil fractions. The shipping industry is thus an exclusive costumer to 350 million tons per year of the cheapest and dirtiest fuel on the market – HFO.

<u>**Marine fossil fuels**</u>

Heavy fuel oil (HFO)
Also called Marine fuel oil (MFO) or residual oil. High viscosity fuel based on the residual fraction from oil distillation.

Marine gas oil (MGO)
A low viscosity fuel oil blend consisting only of distillates. Typically with a sulphur content of 0.1%.

Marine diesel oil (MDO)
A fuel blend of distillate and residual oil with low viscosity.

Intermediate Fuel Oil (IFO 180/380)
A fuel blend of distillate and residual oil with high viscosity (180 or 380 mm^2/s)

High Sulphur Fuel Oil (HSFO)
Heavy fuel oils with maximum sulphur content of 3.5%. Requires scrubber for compliance in or outside SECAs.

Low Sulphur Fuel Oil (LSFO)
Heavy fuel oils with maximum sulphur content of 1% - typically desulphurized IFO 180/380.

Very Low Sulphur Fuel Oil (VLSFO)
Desulphurized Fuel oils with maximum sulphur content of 0.5%, complying with sulphur restrictions outside SECAs.

Ultra-Low Sulphur Fuel Oil (ULSFO)
Fuel oils with maximum sulphur content of 0.1%, complying with sulphur restrictions outside SECAs.

Liquid Natural Gas (LNG)
Natural gas rendered liquid by cooling. Used in specialized dual-fuel engines. Compliant fuel inside SECAs due to low sulphur content.

*Table 4.1 Oil, gas and jet fuel spot prices as from February 2021[65,66,67]. *Only 0.14% of the global fleet can use gaseous fuels.*

	$US/mmBTU	$US/ton
IFO 380	9.4	390
ULSFO	13.1	550
Natural gas*	18	750
Methane	24.6	1030
Crude oil	12.2	510
Jet fuel	14.4	600

The oil prices are well-known for their fluctuation affecting the long-term commitment from investors and thus the economic viability of alternative fuels. An example is the price of IFO 380 that in the last 7 years has been fluctuating between $US 200 and $US 500 per ton as shown in Figure 4.1. The general low prices for marine fuels is also a major barrier for alternative fuels to reach commercial level. This is especially challenging for the marine sector compared to the aviation sector. When comparing the prices of HFO and jet fuel in February 2021 listed in table 4.1, HFO cost around $US 400/ton where 1 ton of jet fuel cost around $US 600, making jet fuel 50% more expensive than HFO[66,67].

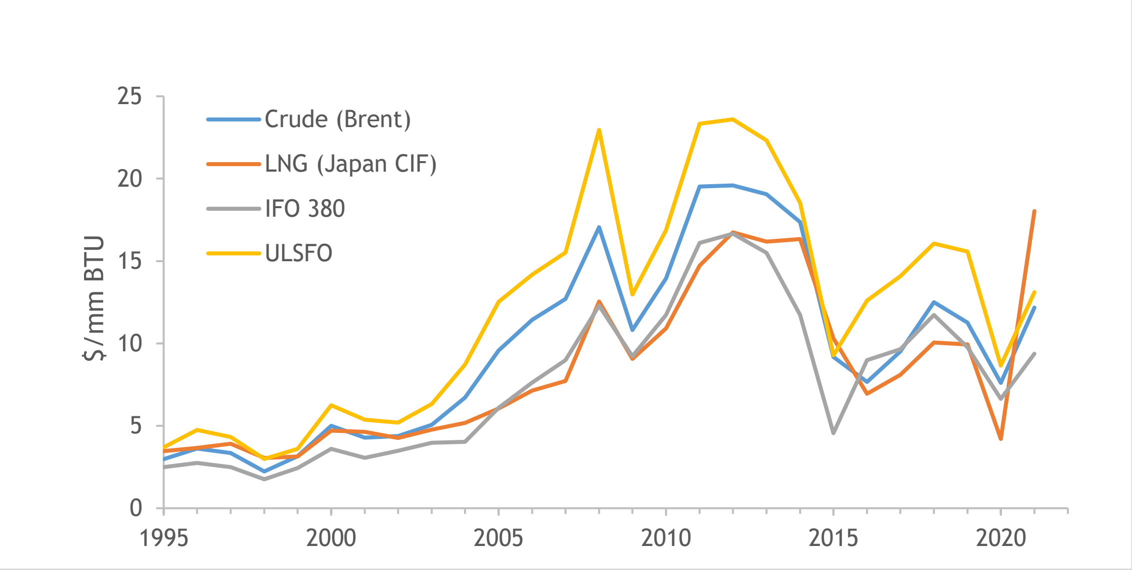

Figure 4.1 Global price development of crude oil (Brent), liquid natural gas, Intermediate fuel oil 380 and ultra-low fuel oil in $US per million BTU from 1995 to 2021. CIF: Costs, Insurance and Freight[7, 65]

Despite the higher associated pollution, the low cost of HFO have provided the shipping industry with an economic advantage compared to aviation and road transportation. Global prices for transporting goods by sea are generally very low and price optimization and market forces have made fuel cost take up to 50% of the operational cost for the ship-owner.

Local opportunities for biofuels could be promoted by the higher oil prices found away from large oil hubs. As an example, in February 2021 ULSFO was $US 640 per ton in Melbourne (considered to be with a considerable distance from large oil hub) compared to a global average of $US 550[65,66]. In the textbox, a calculation for bunkering in Melbourne, Australia is presented, including a hedge fee and a carbon price (approximately 3 ton of CO_2 is emitted when 1 ton of fuel is combusted). The resulting cost of bunkering in Melbourne is then 840 US$, exemplifying that a local biorefinery in many local settings, for example in Melbourne, Australia, could have considerable opportunities to compete with the fossil alternatives, as e.g. hedging costs and carbon pricing would be omitted.

Melbourne, an example of elevated local pricing of marine fuels.

Ultra Low Sulphur Fuel Oils costs in Melbourne, Australia (June 2021):

Bunker Price ULSFO	US$ 640
Carbon tax (3 tons CO_2 at $50 per ton)	US$ 150
Fuel Hedging ($50 a ton)	US$ 50
Total	**US$ 840**

4.1.1 Heavy and light marine oil

HFO is considered the lowest quality fuel oil and is either used by itself or in a blend with distillate fuel. When the blend primarily consists of heavy fuel, the fuel is called Intermediate Fuel Oil (IFO) where the standard fuels are IFO 180 and 380 representing two different degrees of viscosities. IFOs are primarily used in large container ships, tankers as well as in cruise liners but only in a smaller degree in fishing and service vessels. HFO contains solid impurities and water that are removed by on-board centrifuges and stored in sludge tanks emptied in ports. Waste sludge can be sold to sludge treatment companies in ports who reclaims the oil fraction, thus minimizing the additional costs associated with sludge storage and separation.

HFOs are found in a range of grades, defined by the ISO-8217 Petroleum products - Fuel (class F)[64]. The HFO grades are found in grade A to K and is associated with the number of maximum viscosity at 50°C. Lower grade heavy fuel oils have higher viscosity, density, more ash and typically contains more aromatics. The highest HFO grade (RMA 10) has a density of 920 kg/m^3, max ash content of 0.04% and a viscosity of 10 cSt, where the worse grade (RMK 700) has a density of 1010 kg/m^3, maximum ash of 0.15% and has a viscosity of 700 cSt.

Distillate fuels typically called marine gas oil (MGO) are similar to diesel, besides increased density. MGO contains components of the crude which evaporates during fractional distillation and appear transparent or light-colored. In contrast to HFO, MGO has lower viscosity and does not require sludge separation or onboard heating. MGO is commonly used in medium to large speed engines typically found in ferries, fishing or tugboats or other short-sea vessels. Large deep-sea vessels can also switch from HFO to MGO use when they enter ECAs to meet emission restrictions. MGO and HFO also exist in blends called marine diesel oil (MDO). MDO has lower viscosity than HFO enabling wider engine compatibility and is widely used in medium to high-speed marine diesel engines.

Different fuel quality grades of MGOs are DMX, DMA, DMZ and DMB according to ISO-8217[64]. DMB is the lowest quality with the highest viscosity and highest max sulphur content of 1.5%. DMB can contain a small fraction of heavy fuel oil, and is thus not a pure distillate fuel. Low sulphur distillate fuels are low-sulphur marine gas oil (LSMGO) or Ultra-low-sulphur gas oil (ULSMGO) with <0.1% and <0.0015% sulphur, respectively.

4.1.2 Low sulphur fuels

The heavy and/or sour crude oils require more refining to increase their quality. The molecular size of hydrocarbons in the heavy fractions can be reduced by exposing the oil to heat (300-400°C), high pressure (30-130 atm) and typically a catalyst in a cracking unit. After separating the catalyst from the oil, the stream is sent back for re-distillation. Sulphur can be removed catalytically through hydrodesulphurization where hydrogen reacts with sulphur bearing compounds and produces H_2S. This process is limited to large refineries as the capital and operating costs are too high for smaller refineries. After the implementation of the 0.5 % sulphur gap the dynamics of the marine fuel market has changed.

The bunker fuel market was previously a sink for heavy and high sulphur oil fractions and not currently designed to meet the larger demand for sweeter fuels. The hydrodesulphurization capacity is insufficient to cover the transition from HFO to low sulphur fuel oil (LSFO), and it does not seem that the demand has raised the prices of LSFO high enough for more oil refineries to expand their capacity. The short-term solution to this has been a switch to MGO, investment in a scrubber installation or a retrofit to dual fuel engines capable of burning LNG. Figure 4.2 show the share of ships that can utilize alternative fuels.

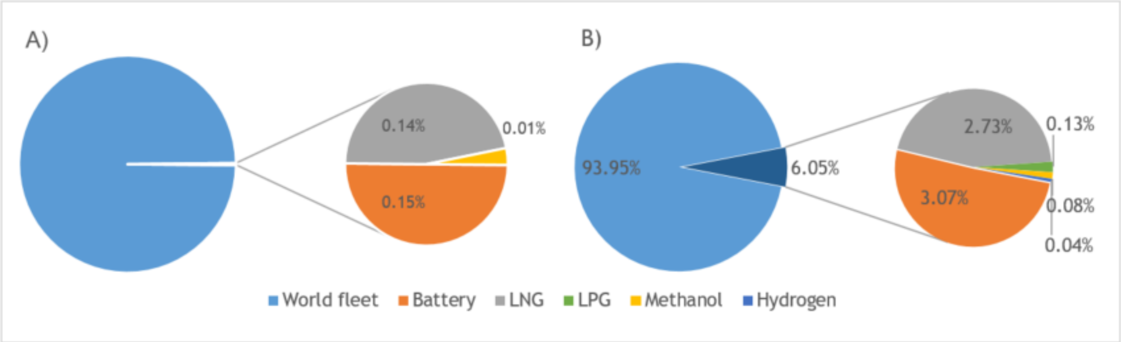

Figure 4.2 Alternative fuel uptake (percentage of ships). A) Ships in operation. B) Ships on order. Data from primo 2019[68]

4.1.3 Liquefied natural gas

LNG is a fossil gas containing at least 90% methane that through refining gets water, CO_2, H_2O and mercury removed and brought into liquid phase at -162°C to facilitate storage and transportation. The LNG is then transported to coastal regasification plants which distribute the gas to industrial and residential heat and electric power generation – the primary use of LNG. Only 3% of LNG is being used in the transportation sector[69].

The combustion of LNG is regarded as the 'cleanest' fossil fuel due to having zero sulphur and particulate matter emissions and 8-20% lower CO_2 emissions compared to HFO, and makes shipowners able to comply with SECA 2015 and Tier III NO_x[70]. Besides the lower emissions, the established LNG market and the availability of large dual fuel engines (available since 2013[63]) reduces the overall risk involved with LNG compared to other bio-based alternatives. However, LNG does not make ship owners meet IMO GHG targets. The cryogenic storage, transportation and bunkering facilities requires higher demands for safety, requires high capital costs and is associated with methane slip. Methane is estimated to have 25x carbon dioxide GHG equivalence[71].

Figure 4.3 shows the increase in LNG vessels and projections towards 2022. In the near term, it is anticipated that alternative fuels such as methanol or biofuel will only occupy a minor share in the market[21]. Biofuels can also offer reductions of multiple types of air pollutants and GHG emissions. Unlike LNG, where only a 10-20% reduction in GHG emissions can be achieved (depending on methane leakage). Biofuels can offer much greater reductions in GHG emissions as compared to LNG.

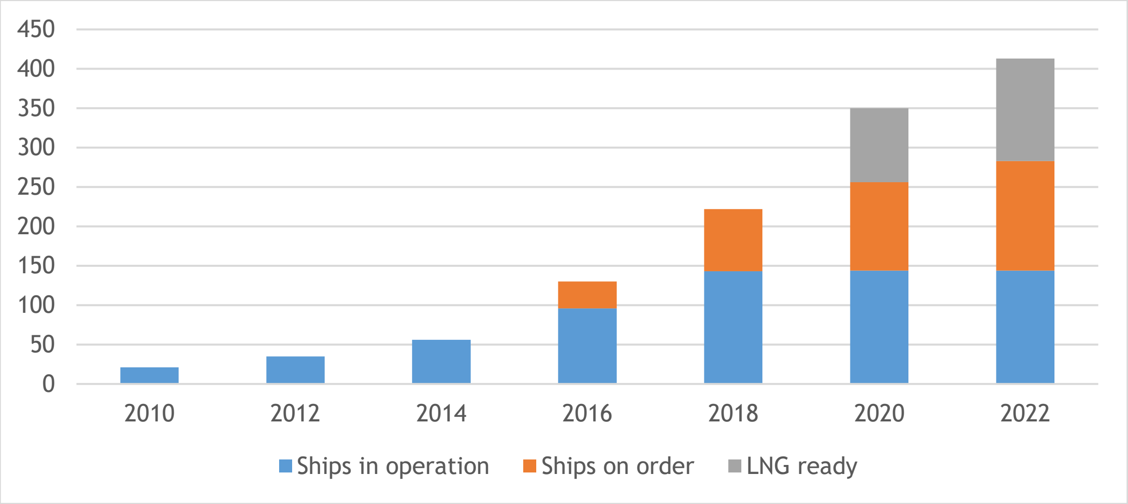

Figure 4.3. Annual development of marine fleet indicating the increase in vessels using LNG[21].

In 2018, 0.14% of the global fleet was running on LNG, compared to the 2.73% of ships on order the same year (see figure 4.3)[68].

Figure 4.4 shows the cumulative increase in the number of vessels with scrubbers installed or on order.

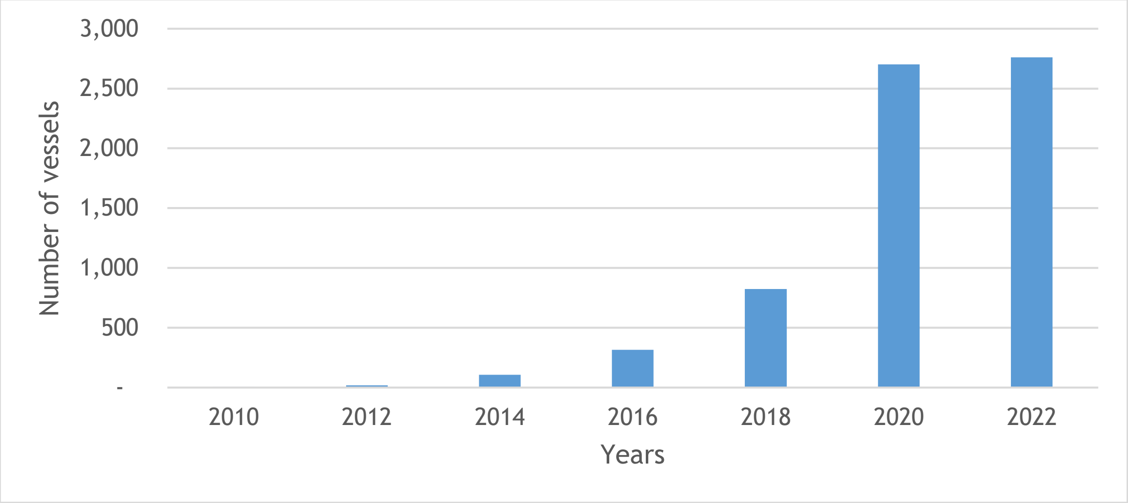

Figure 4.4 Cumulative number of vessels with scrubbers installed or ordered. Data from primo 2019[68]

LNG engines are fully compatible with renewable natural gas (RNG) based on renewable electricity or biomass, and can therefore be part of a solution for a more sustainable marine sector if methane slip is eliminated[38].

5. Sustainable marine fuels

Nuclear propulsion

Globally only around 140 vessels use nuclear power as the primary source of propulsion. This include warships, submarines and icebreakers. Nuclear energy can provide high-speed propulsion while eliminating emissions, but the technology has very little political acceptance, and only few ports allow docking of nuclear powered vessels.

Most fuels used to date in the marine sector are the same as those used in other transport sectors e.g. HVO however due to its demand and its limited availability it has a high price relative to traditional Heavy Fuel Oils. However given the great versatility of two stroke diesel engines and their ability to burn fuels with lower calorific several alternative marine fuel technologies have emerged the past 10 years with varying degrees of emission reductions, supply and blending potential. Examples of emerging biofuel technologies are used cooking oil (UCO), biodiesel, pyrolysis oils, hydrothermal liquefaction (HTL) biocrude, and alcohols. Other alternatives are RNG, hydrogen, ammonia, and Fischer-Tropsch diesel. Apart from their technical challenges, they all suffer uncertainty related to their long-term availability and price, thus making investment on alternative technologies a complex and risky decision for engine manufacturers and vessel owners.

The large amount of vessel types and the diversity of the global fleet will result in multiple pathways to reduce GHG, NO_x, SO_x and particle emissions and meet the IMO targets of 2030 and 2050. With an increased global interest in sustainable shipping, research and development of alternative fuels have accelerated and have led to several biofuel trials especially in the short-sea shipping sector. The characteristics of different marine fuels can be seen in Table 5.1 and Figure 5.1.

Table 5.1 List of fuel characteristics. Fuel names are colored based on their primary energy source[1]*. Fossil: Black. Biomass: Green. Electricity: Blue. *Ammonia, Methanol and hydrogen are currently primarily produced from fossil energy sources, but are listed as ~0 in carbon intensity due to the potential of being produced by renewable electricity. **For 1st and 2nd generation bioethanol. NA: not available.*

Fuel type	**Volumetric energy density**	**Gravimetric energy density**	**Carbon intensity**	**SO_x Emissions**
	[MJ/L]	**[MJ/kg]**	**[TCO_2e/TJ]**	
HFO	38	39	77-87	High
MGO	37	43	87	High
LNG (liquid)	21	49	63	None- Low
RNG (liquid)	21	49	~10 [72]	None- Low
Methane (gas)	0.034	50	< ~10 [72]	None
Ethanol	16	20	24, 34**	None
DME	21	27	NA	None
Biodiesel	19	29	60 (oil crops)[72]	None
Biocrude	35	38	NA	None-Low
Pyrolysis Oils	16	17-20	NA	NA
HVO	25	33	8-25	None
Methanol*	16	20	~0, ~10 (wood)[72]	None
H_2* (liquid)	8.5	120	~0	None
Ammonia* (liquid)	13	19	~0	None
Batteries**	1.3	0.7	~0	None

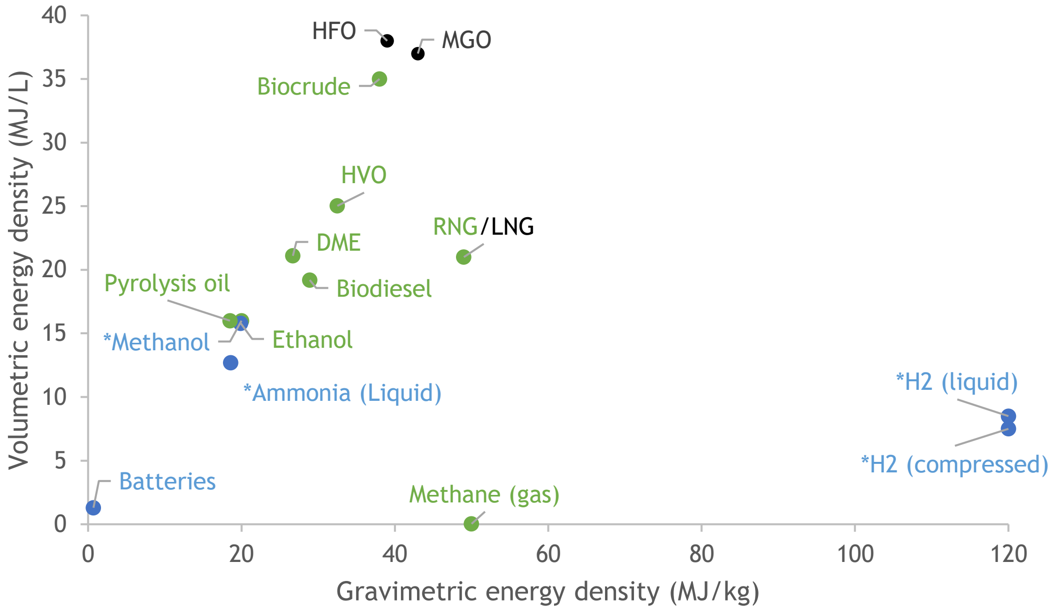

*Figure 5.1 Gravimetric and volumetric energy density of fossil and renewable fuels. Color indicate primary energy source. Black: Fossil. Blue: Electricity. Green: Biomass.*Ammonia, Methanol and hydrogen are currently primarily produced from fossil energy sources* [73-75].

5.1 BIOFUELS

Biofuels consist of many promising candidates as sustainable transportation fuels, and are closer to commercialization than other alternative fuels such as ammonia, hydrogen or batteries, making biofuels a promising short- to medium-term solution to reduce the carbon footprint of marine vessels[1,68,76,77]. There are a wide variety of biofuels, generally defined as fuels derived from material with a recent biological origin, and different biofuels can be used to replace different fuel types. Some of these fuels, such as bioethanol, biodiesel, and biomethane are already available at commercial scale, and are currently being used as stand-alone or blended fuels within the terrestrial transport sector, and tests with them for use in the marine transport sector have begun.

While some biofuels are already produced and available commercially, their suitability as sustainable and scalable fuel replacements for fossil fuels relies heavily on the source and availability of the feedstocks used to produce them. Biofuel feedstocks include among others, food and energy crops, forest and agricultural residues, waste fats or municipal waste. Each of the feedstocks with its own economic and technical challenges as well as social and environmental impacts. Feedstocks which require large amounts of land or fossil inputs to grow, and compete directly or indirectly with food sources are in general not considered sustainable biofuels. Similarly, as land resources which can be allocated to fuel production have limits, and therefore, the total amount of fuels which could be produced is also limited. Examples of these concerns are seen in the production of biodiesel from palm oil, which in some regions has led to an increased clearing of tropical rainforests and peat marshes, and resulted in biodiesels produced from these feedstocks having a significant GHG footprint, and the subsequent decertification on the EU level of palm oil biodiesel as a sustainable fuel (EU Commission supplementing Renewable energy directive 13.3.2019). Similarly, the sustainability of sugar based bioethanol from crops such as corn or sugar cane is disputed and can vary widely depending on location and growth conditions. It is thus widely accepted that for biofuels to be undeniably sustainable, the feedstocks used to produce these fuels, regardless of the final product or conversion technology used, preferably should come from lignocellulosic sources, consist of residual materials from the agro-industrial sectors, come from catch- or cover crops, or be produced on marginal lands. Requirements for sustainable sources of feedstock are being included in most legislation regarding biofuels. It should however be underlined, that techno-economic assessments coupled to LCAs have found that biofuels could be a cost-effective means of reducing GHG, sulfur oxide, and particulate matter emissions from the maritime shipping industry, and that the cost of CO_2 abatement is more favorable for purely biobased pathways than for pathways cofeeding with fossil fuels[78].

Global, regional, and local availability of biomass, can naturally be limited. Previous reports have covered these aspects in depth with focus on biofuels production in general (not only for the marine sector), and have in general found that there are vast amounts of biomass available[79,80]. A study specifically looking at the U.S. domestic feedstock availability for marine biofuels, concludes, that a sufficient biofuel capacity can be achieved to obtain a critical mass for alternative marine fuels[81]. Results from this study also highlight the need to reduce the feedstock cost, a key cost contributor to biofuel production, and found that it can be lowered through the utilization of waste and low-quality feedstocks, adoption of integrated landscape management strategies, and feedstock logistic enhancements[81]. Other proposed strategies to achieve lower biofuel prices include co-processing biomass with fossil feedstock, developing atom-efficient biorefineries, intensifying process designs, utilizing existing infrastructure, and developing high-value coproducts[81].

Biofuels can be produced using a variety of thermochemical and biochemical methods and cover a wide range of fuel products as illustrated below in figure 5.2. These usually involve breaking down biomass into its constituent components, and then converting these components to fuels and chemicals. Many pathways for these conversion processes exist, and depend primarily on the feedstock used and the types of fuels which are to be produced. In the following sections, descriptions of the different types of biofuels currently available or being researched, are described by fuel type and conversion process. While the same end-product can be produced in some cases via different production pathways, the most promising processes have been described.

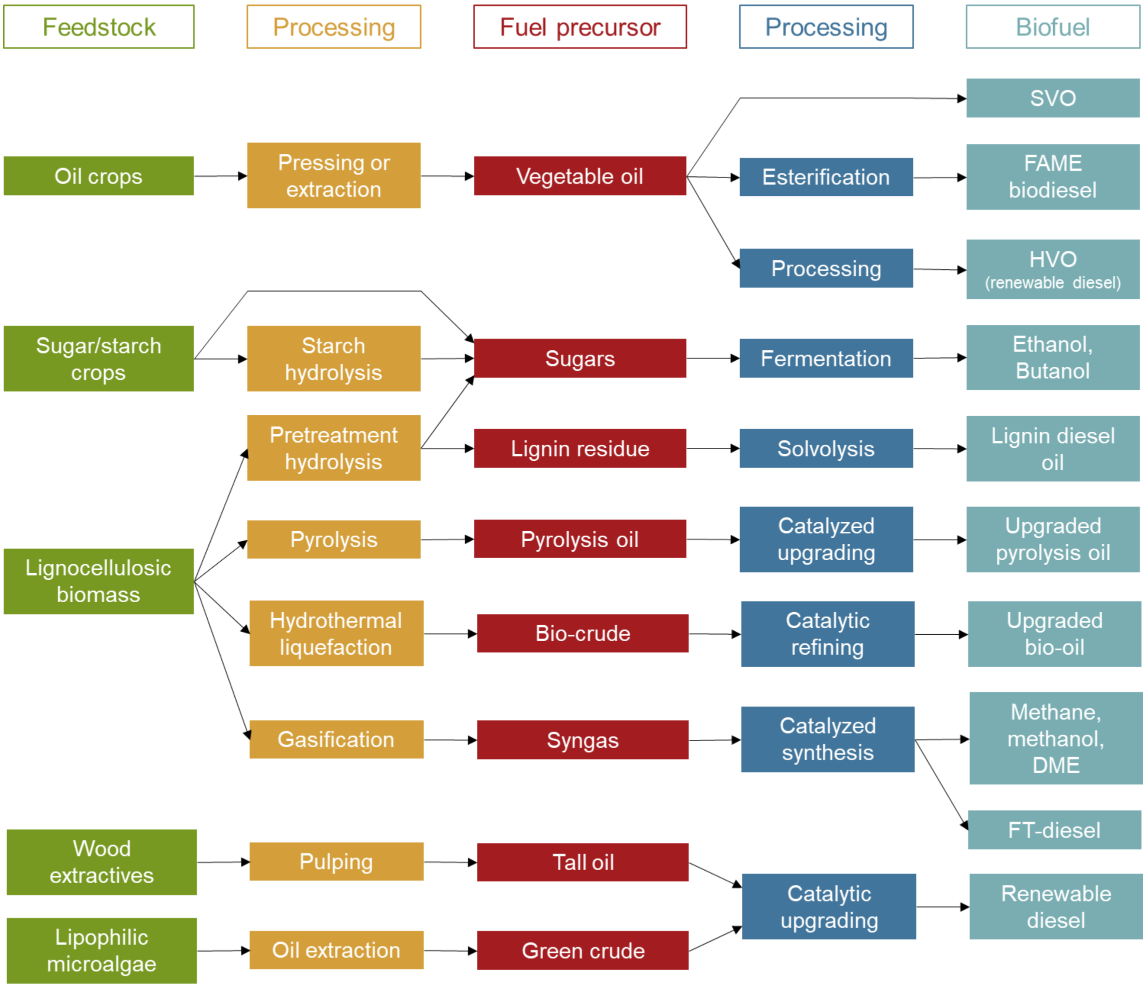

Figure 5.2. Feedstock conversion routes to marine biofuels including both conventional and advanced biofuels. Adapted from the 2017 IEA Task 39 Marine Biofuels report[1].

5.1.1 Oleo-chemical derived diesel fuels

Diesel replacement fuels from biomass sources are currently available commercially in a variety of forms. Straight vegetable oils (SVO) are oils derived from plants, which can be used as diesel replacements either on their own directly in diesel engines, or as blends with fossil diesel fuels. While the minimum amount of processing of these fuels makes them attractive. Long term use of oxygenated fuels in fuel systems designed for HFO can cause excessive engine wear, and SVO may be unstable over long storage times, although the addition of antioxidants can improve long term storage performance[82].

More commonly, SVO is trans-esterified into Fatty Acid Methyl Esters (FAME), more commonly referred to as biodiesel. Additional to SVO’s, FAME can also be produced from used cooking oils and animal fats, and due to the double counting scheme in the RED/RED these are the most used feedstocks in EU Member states like the Netherlands. Transesterification results in a fuel which has lower viscosity and good lubrication properties. This biodiesel is more suitable for use in marine engines, and can be used to replace MDO or MGO. The biodegradability of biodiesel makes it beneficial in the case of spills. While theoretically it is possible to run marine diesel engines on 100% biodiesel, this requires some engine adjustments and certification by the engine manufacturer. More commonly it is found sold as a blend with fossil diesel, with labels such as B5 and B20. Without engine modifications, biodiesel blends has demonstrated lower particulate matter and CO emissions in a 2 stroke engines[83].

While FAME biodiesel represents a technically feasible replacement for MDO and MGO, the availability of plant oil feedstocks and their inherent sustainability issues make biodiesel unlikely to meet a majority of shipping fuel needs. Oil based crops such as rapeseed, soy, and sunflower are not productive enough to produce enough oil to replace fossil diesel, and biodiesel needs face competition from food uses, and as diesel replacement in other transport sectors with higher value fuels such as aviation.

Total potential biodiesel production worldwide, has been estimated as 45Mt/year without increasing cultivated land and taking into consideration food needs, while marine shipping uses 330 Mt oil equivalents per year, and aviation uses 220 Mt/year[84]. Thus, biodiesel from plant oils can only replace a small amount of fossil diesel in the transport sector. While microalgae has been shown to be a promising source of plant-based oils with high productivities, the technology to produce commercial scale algal oil at competitive prices is not yet available. Thus, it is unlikely that FAME biodiesel will replace a significant amount of marine fuel, beyond in blends and boutique applications.

> *"The fact that fat oils from vegetable sources can be used may seem insignificant today, but such oils may perhaps become in course of time of the same importance as some natural mineral oils and the tar products are now."* In 1912, **Rudolf Diesel**, the inventor of the diesel engine[85]

Another diesel fuel alternative made from oil crops is Hydrotreated Vegetable Oil (HVO), where vegetable or animal oils are hydrotreated with hydrogen, and usually in the presence of a catalyst, and then cracked to produce a diesel like fuel. This fuel is often referred to as green diesel or renewable diesel. HVO can be used as a direct replacement for diesel as a drop in fuel, and is more stable then FAME biodiesel, due to low oxygen content. It is already being produced commercially by companies like Neste, and has been tested in marine diesel engines.

> *“Oil crops could have a smaller permanent role of being a pilot fuel for alcohol based fuels.”* **Maria Strandesen**, Head of Future Fuels at Maersk A/S

While HVO is technically a viable biofuel for marine applications, the dependence on plant oils as feedstock makes its application as a wide spread fuel available in large enough quantities to be used by a large portion of the shipping sector challenging, due to limited supply of feedstock. Dependence on hydrogen, often produced from fossil fuels, also reduces the sustainability of this fuel. Therefore, besides near term and niche uses of this fuel, like using it as a pilot fuel to achieve stable ignition of alternative fuels, it is unlikely that HVO will substitute a large amount of fossil fuels for the shipping sector.

5.1.2 Ethanol, Methanol, and Butanol

Alcohol fuels consist primarily of ethanol, methanol, and butanol fuels. Bioethanol is the most widespread biofuel in production currently and is industrially produced via a biochemical fermentation process from starch and sucrose sugars. Total world ethanol production is on the order of 87 Mtons/year[86] and is already blended into automotive gasoline in the US, EU, and Brazil in blends up to 85% (w/w). Ethanol can also be produced via the fermentation of sugars derived from lignocellulose, a much more sustainable and available feedstock, and demonstration projects across the world have shown that it can be produced at an industrial scale from a wide variety of lignocellulosic materials[87]. Ethanol can be burned in most gasoline engines up to blends of 20% with gasoline, and pure ethanol can be used as a fuel with minimal engine tuning and upgrades. In Brazil, the use of ethanol powered vehicles is widespread, and in the US there has been a proliferation in flex-fuel vehicles which are certified to run on blends of up to 85% ethanol with gasoline. Butanol can also be produced from lignocellulosic or sugar-based feedstocks via a fermentation process, however the high toxicity of butanol (1.5-2 g/L) to fermenting organisms makes its application and industrial scale-up economically challenging.

Methanol is a widely used industrial chemical for the production of a variety of other chemicals in including formaldehyde and MTBE. Current methanol production capacity worldwide is 98 million tons (2016). It has historically been produced from wood via pyrolysis, but is currently produced via the catalytic hydrogenation of syngas from fossil fuels. However, syngas can also be produced from lignocellulosic biomass, thus making methanol a promising biofuel candidate. More recently, methanol has been proposed as a possible electrofuel product, with hydrogen being produced from excess renewable electricity, and carbon dioxide being sourced from for example ethanol fermentation processes, making an electro-syngas. Methanol can also by produced from the catalytic conversion of biomethane, another route to methanol from biomass. Thus, while not always a fuel of biological origin, its potential application as a biofuel for marine shipping is somewhat similar to that of ethanol. Methanol has the added advantage of having no carbon-carbon bonds, so produces almost no soot during combustion, and can produce significantly less NO_x emissions than fossil fuels.

Another advantage of methanol and ethanol is that distribution and storage systems already exist and are present at many ports, where they could easily be connected to bunkering infrastructure. Retrofitting of fuel storage bunkers is also straightforward, and thus these fuels would fit well into existing infrastructure.

While methanol and ethanol can both be produced from renewable sources (including lignocellulosic biomass), and can be scaled up to produce large amounts of fuel given current technology, there are a few key barriers to their wide use as marine biofuels[88]. While alcohol blends could be added to current gasoline powered engines given minimal engine modifications, due to the physical properties of ethanol and methanol, they are not suitable for use in compression ignition (diesel) engines. Using these fuels for deep sea shipping container ships would require the installation of multi fuel engines, or engines tailored for running solely on methanol[89]. Currently, two companies (MAN diesel and Wärtsilä) have developed multi fuel engines, with the Wärtsilä engine a retrofit of four stroke engines, which are capable of running on fuels such as methanol and ethanol. Research is ongoing to improve methanol engine performance and combustion methods.

A second technical challenge of using methanol and ethanol fuels is their low flash points of 12°C and 14°C, as compared to marine fuel oil of 60°C. Low flashpoints fuels (with flash point below 50°C) are potential fire hazards and are thus not compatible with the Safety of Life at Sea (SOLAS) regulation without a double barrier design[90]. Thus, fuel tanks would require modification for methanol and ethanol to be used as a primary fuel. Thirdly, both ethanol and especially methanol have much lower energy densities than either diesel or gasoline (Table 5.1), and therefore would require more frequent refueling, or larger onboard storage tanks[91].

Fossil methanol

Annual worldwide production of 98 million tons, based on coal and natural gas (2019). Methanol is mainly used for producing other chemicals, but approximately 30% is used as a fuel (2019): 14% in a blend with petrol, 11% as MTBE; 3% as a feedstock for biodiesel (FAME) and 3% as DME

Methanol production doubled the last decade, mainly due to growth in China.

Renewable methanol

There are currently a few production facilities, with an annual production <0.2 million ton, mainly bio-methanol. Among others there is one commercial biomethanol plant in the Netherlands (from biomethane) and one plant producing biomethanol from MSW in Canada.

Production of green e-methanol is limited to one plant in Iceland, producing methanol based on renewable electricity and CO_2 from a geothermal electricity plant.

Source: Irena and Methanol Institute[88]

5.1.3 Biocrude from hydrothermal liquefaction

Hydrothermal liquefaction is a thermochemical process which heats wet biomass to elevated temperatures and pressure in the presence of catalysts (250-550 C, 5-25 MPa), producing a crude bio oil. This oil has an energy content significantly higher than that of pyrolysis oils 32-36 MJ/kg vs 17-20 MJ/kg, and has an oxygen content between 5-20% (normally 12-14%). HTL biocrudes have the potential to be used without hydrotreating due to their higher energy content e.g. by distillation, however upgrading by for example fractional distillation can be applied due to low HHV and[92].

Recent work has shown that distillation combined with esterification can produce a diesel like fuel with similar performance in a diesel blend of up to 20%[93]. While promising, research is behind that of HVO, and more work needs to be done to assess engine compatibility and process scale-up. While promising, research is behind that of HVO, and more work needs to be done to assess engine compatibility and process scale-up.

5.1.4 Drop in biofuels (pyrolysis- and synthetic biofuels)

Drop in biofuels are defined as '*liquid bio-hydrocarbons that are functionally equivalent to petroleum fuels, and are fully compatible with existing petroleum infrastructure*'. These types of fuels are more of a technological concept than a specific type of fuel, and their promise and challenges are covered extensively by two IEA reports[94,95]. Drop in biofuels are conceptualized as a fuel which can either be used directly in internal combustion engines without requiring engine modifications, or as a bio-crude substance which can be blended into petrochemical refineries. Drop in biofuels should have a high H/C ratio, and low oxygen content, similar to that of petroleum based fuels. These processes often rely on large amounts of hydrogen, and involve some type of hydrotreating of the biomass fuels. There are a few main pathways to produce these types of fuels. The primary method is by hydrotreating oleochemical or lipid feedstocks, creating fuels such as hydrotreated vegetable oils (HVO – as described in section 5.1.1) or green diesel. The second approach is the thermochemical deconstruction of biomass into either a pyrolysis oil or syngas via biomass gasification, followed by catalytic upgrading and hydrotreating these streams into hydrocarbon fuels. The final proposed process involves the biological conversion of lignocellulosic or starch biomass to long chain alcohols or hydrocarbons.

While all of these methods are attractive, as they would allow for a smooth insertion of biofuels into existing engines and infrastructure, there are significant barriers to their widespread application. Chief among these being the large amounts of hydrogen needed for such hydrotreating processes. Hydrogen is currently produced primarily from fossil methane sources via steam reforming and the water gas shift reaction, and using hydrogen from fossil sources will not result in a sustainable fuel. Competition for hydrogen supply from the petrochemical industry and as a fuel in itself will also make access to large amounts of hydrogen difficult, even with increased hydrogen production from excess electricity from solar and wind. Similarly to the limitations for biodiesel, oleochemical and lipid based drop in biofuels will also suffer from a lack of supply of plant and animal oils, and therefore large scale production is unlikely. Hydrotreated pyrolysis oils have been investigated as a refinery drop in fuel, however significant technical challenges remain to their integration into petrochemical refineries.

Bio-based syngas must first be upgraded with extra hydrogen and cleaned of impurities before it can be used with conventional methods to produce diesel via Fischer-Tropsch synthesis routes[96]. The most recent IEA report points towards co-processing of drop in biofuels in petrochemical refineries as a possible approach to overcome issues with hydrogen supply, however significant hurdles remain before drop in fuels might result in commercial scale marine fuel production[94,95]. Similarly, such fuels will most likely command a premium price, and therefore be used for terrestrial or aviation fuels before marine fuels.

A recent study comparing emerging marine biofuels through LCA and techno-economic evaluation showed that bio-oil via fast pyrolysis of low-ash woody feedstock offers the most promising marginal CO_2 abatement cost[78]. However, this study compared the pyrolysis oil to only 2 other technologies, 1) renewable diesel via hydroprocessed esters and fatty acids from yellow grease and 2) Fischer−Tropsch diesel from biomass[78].

Pyrolysis is one biofuel technology where cofeeding biomass with the fossil feedstock such as natural gas has been assessed. E.g. when converting the syngas via Fischer-Tropsch synthesis using natural gas has been found to be an effective synergistic approach to improve liquid fuel yields while simultaneously lowering greenhouse gas (GHG) emissions[97]. In these cases, cofeeding biomass with fossil fuels should be seen as a practical approach to smooth a transition to biofuels by reducing alternative fuel costs.

5.1.5 Lignin solvolysis and emulsion fuels

Lignin, a highly cross-linked phenolic complex heteropolymer, makes up between 15-50% by mass of most terrestrial plants, and is more energy dense than cellulose or hemicellulose, making it an attractive starting material for biofuel production. While cellulose and hemicellulose can be enzymatically hydrolyzed and fermented into fuel products using yeasts or bacteria, lignin is non-fermentable, and therefore is most often targeted for conversion to fuel via thermochemical pathways. It is also present in large amounts as a residual from cellulose processing, either in lignocellulosic ethanol production via the biochemical pathway, or from pulp and paper production from the forest industry. These residues can either be insoluble solids (lignin rich hydrolysis residues and kraft lignin) or soluble slurries (black liquor and lignosulfonates), and usually contain a wide size range of lignin molecules. The heterogeneity of lignin, both in its native form and as a residual, means that significant processing and technological innovation is needed to produce valuable fuels and chemicals.

One type of approach is to blend the lignin residues with other biofuels or fossil fuels. This can increase energy density, and can also improve whole biomass utilization. This approach can be taken either by using insoluble lignin particles to produce an emulsion fuel, sometimes including water and using lignin as a surfactant, or via a solvolysis process, solubilizing the lignin in a carrier fuel at moderate temperatures and pressures, either with or without the presence of a catalyst[98].

Another approach is to first remove lignin from a given biomass feedstock via a solvolysis process before further processing cellulose into fuels, chemicals, or materials[99]. Emulsion based fuels with lignin have been shown to improve combustion efficiency, and have been applied to marine engines, however storage stability of these emulsion remains an issue[100]. Solvolysis processes have shown recent promise, and are currently a focus of research for the production of specifically marine fuels[101]. These processes can use alcohol-based biofuels and increase their energy capacity, improving some of the drawbacks of alcohol based fuels and improving bunkering energy capacity.

The primary advantage of using lignin as a feedstock for these mixed fuels targeted at marine fuels is that lignin residues represent an underutilized low-cost feedstock with little competition from other sectors which may require biofuels. Due to the heterogeneity of these fuels, it is less likely that they would become compatible with the road or aviation sector. Marine engines are flexible enough to accommodate the differing combustion properties of these fuels, and with engine modifications, will most likely be able to burn these fuels. Lignin based fuels thus have the potential to become a maritime exclusive biofuel with similarities to the previous and current role of HFO. There is a history of tests of emulsion fuels in the marine sector to improve engine performance and reduce emissions (by adding water to reduce combustion temperatures[102]), making it easier to imagine their adoption by the industry. However, significant work needs to be done on research and development within this field to prove fuel stability, increase lignin content, and to produce fuels with acceptable levels of heterogeneity and combustion properties.

5.1.6 Renewable methane

The increased interest in methane and LNG and shipping fuels is related to the reduced NO_x and near elimination of SO_x emissions, but LNG is a fossil fuel and reduces total GHG emissions only when replacing HFO. The advantage of adopting LNG as marine fuel is that the engine technology will be fully compatible with RNG, that is methane produced from biological sources such as biogas, and e-methane (methane produced from hydrogen produced as electrofuel from excess electricity from solar and wind generation). The established technology and the experience in LNG tankers lowers the risk for shipowners and LNG DF engines could therefore be a long-term investment to combat both SO_x, NO_x and GHG while keeping the risk low for shipowners. Many studies also emphasize the huge potential of RNG[103,104].

Methane produced from biomass is either through thermal gasification that mainly produces hydrogen and CO, or via anaerobic digestion, which produces methane and CO_2. RNG can also be produced through the Sabatier methanation reaction where CO_2 and hydrogen in the presence of a Nickel catalyst produce methane and water[105]. In many countries, methane gas is already an established part of the energy infrastructure, making integration in ports less technologically challenging. REN energy in British Columbia, Canada is at the time of writing, building a 1.2 GJ/yr RNG plant using woody biomass as feedstock[106]. The technology is based on gasification and catalytic methanation with an end product consisting of 96%+ methane.. According to them there are 110 operational plants in the US and Canada and 40 more under construction and 58 additional RNG plants in development. Thus, RNG production is seen as a rising market. RNG production is a feedstock flexible technology that gives local producers with access to the gas grid the ability to integrate in a circular economy by using waste feedstocks from agriculture or even sewage sludge[107].

Despite the current interest, RNG has some technical and sustainability challenges. The largest sustainability issue with RNG is the greenhouse impact of leakage and accidental methane release during its production, storage and combustion. The technical requirements of handling gaseous fuels are high, and small methane leaks during production and transport are common in the industry worldwide. Even small amounts of fugitive methane emissions from production, transport and combustion will have a very large negative impact on the climate, as the global warming potential (GWP) of methane is 25-35 times higher than that of CO_2. Methane release due to the extraction of natural gas by fracking, one of the major sources of fossil methane, is on the order of 10% (±7%), thus giving the use of fossil methane the total GHG emissions similar to that of coal[108].

To minimize methane slip, secondary partial cryogenic barriers for tanks and tubing are implemented in storage solutions and in fuel systems. However, using a low pressure gas engine gas may be injected into the combustion cylinder while the exhaust valve is open leading to methane slip[38]. The 4th GHG emission study by IMO estimates the methane emissions related to LNG vessels have increased from 55kt in 2012 to 140kt in 2018[16]. Since gaseous fuels are kept at cryogenic temperatures (~ -162°C) fuel handling requires more technical solutions than with HFO. Spillage can make metal brittle and break, resulting in increased risk for frostbite to personnel. The storage technology of liquefied gas is limited to above-deck storage tanks that is challenge loading and offloading. Additionally, RNG has less than 50% of the volumetric energy density of HFO, reducing the max distance or increases the fuel storage volume of the vessel.

The large investment for ports and cities related to the required infrastructure to bunker LNG as well as its competition with household electricity and heating should also be taken into account. The technical problems with methane leakage and the technical challenges with storage are the main reasons Maersk is not looking to transition to LNG or RNG (From stakeholder interview with Maersk).

5.2 MARINE FUEL STANDARDS

The ISO Standard 8217-2017, "Specifications of marine fuels", is widely accepted as the technical specification for marine fuels by all industry participants: owners, operators, fuel suppliers and engine OEMs. The ISO standard insures comparison and evaluation of fuel quality, fuel engine compatibility, safety and price, thus facilitating the use, trade and production of fuels. However it should be noted, that although the ISO 8217 standard is commonly accepted and used in the sector, it is not a legal requirement or obligation and companies can deviate from it (rarely seen).

The standard is written around oil and marine industry experience with fuels made from fossil petroleum crude oil, for both distillate and residual fuels. The latest update (2017) to the ISO standard includes FAME biodiesel blends up to 7.0% v/v in distillate marine fuels, which is the first time fuels without crude oil origin have been included.

Hydrocarbons from HVO, gas-to-liquid, biomass-to-liquid fuels (Gasification followed by Fischer Tropsch synthesis) and co-processed renewable feedstocks are also accepted because the hydrocarbons produced via these routes are chemically identical to the types of hydrocarbons already found in fuels produced from petroleum crude oil, and the resulting blends will usually conform easily to the specifications in the standard. However, there are European standards EN 15940 and EN 14214 for paraffinic diesels (like HVO and FT diesel) FAME, respectively.

FAME is currently the only biofuels included in marine fuel standards, and is chemically similar to marine distillate fuel besides its higher oxygen content. It is permitted only up to 7.0% v/v in the Distillate Fuel ("DF" or MGO) grades. Its inclusion is based on its implementation in diesel engines in the road sector as well as several marine trials with MGO and MFO blends.

The complexity of biofuels associated with the wide range of feedstocks and production processes makes it challenging to include it in the current ISO 8217-2027, and is thus a barrier for its further commercialization.

5.2.1 Standards for alcohol based biofuels

For single component fuels such as alcohol-based fuels do usually not comply with the ISO 8217/2017 specification on important characteristics such as:

- Density
- Flash Point

- Viscosity
- Combustion quality
- Calorimetric value

A preliminary qualification of their suitability can be made on the basis of known properties, and compared to the requirements of ISO 8217-2017 by direct laboratory measurement for the fuels and their blends with conventional petroleum marine fuels. However, the majority of the standard methods developed to test ISO-8217 fuel characteristics are exclusively designed to analyze petroleum-based or petroleum-like fuels.

An example of method incompatibility is *ISO3733:1999 'Determination of water of petroleum products and bituminous materials'* which is the standard method to measure water content in marine fuels. The method description includes: '*Volatile water-soluble material, if present, is measured as water*'. As alcohols such as methanol, ethanol and butanol are volatile water-soluble material, these would be perceived as 100% water according to the standard measurement. The ISO-8217 standards therefore requires a revisit to insure suitable methods to analyze alternative fuels. Although such standards are presently not established, it should be noted that in November 2020, the IMO Maritime Safety Committee approved methanol and ethanol as a marine fuels. These guidelines include provisions for the arrangement, installation, control and monitoring of machinery, equipment and systems using methanol and ethanol as fuel. Furthermore, it is expected that ISO will develop standards for methanol and ethanol as marine fuels in the course of 2021, which according to stakeholders will enable more shipping companies and vessel owners to convert vessels to use alcohol fuels and consider methanol and ethanol when planning newbuilding projects.

5.2.2 Standards for upgraded pyrolysis oil, synthetic biofuels and biocrudes

Drop-in fuels, such as HVO, is composed of long uniform alkanes and are thereby chemically very similar to diesel oil, thus the current marine fuel standards can be applied. However, it becomes more complex with pyrolysis oil and biocrudes.

When biomass is processed by either HTL or pyrolysis, the resultant liquid fuel, is a mixture of a vast number of different chemical compounds. In addition, the liquid will have a low calorific value and contain a significant level of oxygen before it is upgraded by hydrogenation. The resultant fuels are chemically different to petroleum-based fuels and may not conform to the present specifications of ISO 8217-2017. This does, however, not mean that the fuel is unsuitable in marine service, but rather that the traditional specifications may not reflect the performance of the fuel in actual use. An example is HTL oils have high total acid number due to the high amount of resin acids or aromatic hydroxyls, however these are not corrosive

The following elements in the current fossil standard ISO 8217-2017 need to be amended to reflect the differences in bio based feedstocks:

- Density: Fuel density may exceed 1000 kg/m^3, requiring a different approach to water removal to the usual methods of tank settling and centrifugation
- Acid number: Oxygenated compounds e.g. resin acids or aromatic hydroxyls will report as a high acid number, which may have not be a real indicator of corrosivity, if these are predominantly very weak acids.

- Combustion quality: The Calculated Carbon Aromaticity Index (CCAI) depends on the correlation of combustion quality with density for traditional hydrocarbons. Oxygenated fuels will have an artificially elevated density, so another means of assessing combustion quality will be required.

5.2.3 Qualifying alternative fuels for use as marine fuel

Qualifying any alternative fuels will require an R&D program to:

- Ascertain their suitability for marine use
- Demonstrate which of their unusual characteristics are not a threat to marine use
- Develop alternative approaches to fuel management
- Develop alternative specifications to better measure and manage required characteristics

Once a preliminary (positive) assessment is made, it will be necessary to de-risk these novel fuels by more detailed analyses and engine testing by marine engine OEMs. Finally, pilot scale trials in commercial marine vessels will be required to create confidence in their use by the marine industry. If trials are successful and the biofuel‘s characteristics can be accommodated within the scope of ISO 8217-2017, then the ISO standard will need to be modified to incorporate the novel fuel and its characteristics. Alternatively, a separate new standard could be developed.

The process of modifying a standard, or the creation of a new standard, is a long one and may take several years. In this situation, it may be beneficial to accelerate deployment of the fuel by the issuance of other guidance documents by the ISO, such as a Technical Report, Publicly Available Specification or a Technical Specification.

The global trade and utilization of marine fuels are highly dependent on the ISO 8217 fuel standards as it is used to verify and compare fuel qualities, ensure fuel engine compatibility and on-board safety. The complexity of biofuels makes it incompatible with the current state of the ISO 8217/2017 is a barrier for the further commercialization of biofuels.

5.3 BIOFUEL SUSTAINABILITY

The increased use of biofuels is in itself not a goal, but is merely a tool to transition society to one which is environmentally sustainable, and where societies’ collective actions do not result in catastrophic climate change and mass environmental degradation. Thus for biofuels to be beneficial to society, they must be ecologically sustainable, and function as a net carbon neutral fuel source. This carbon balance must encompass both the growth of the biomass itself, its conversion to biofuels, transportation to point of use, and finally emissions from use. The overall sustainability of biofuels and chemicals have been studied extensively, and there is shown to be large differences in the sustainability of different biofuels[109-111].

The sustainability of a given biofuel depends primarily on the type of biomass used, the fossil inputs needed to produce them, and the amount of land use change which results from growing the biofuels. Land use change (LUC) is particularly important, as the conversion of land from natural and carbon sequestering ecosystems to agricultural land can result in massive carbon emissions due to land clearing and soil degradation. This can either take place through direct clearing of land for growing feedstock for biofuels, or via indirect land use change (ILUC), where market forces brought on by increased demand for a given feedstock (usually a food crop) lead to the risk of increased clearing of natural ecosystems for cropland[112,113]. The production of these crops for biofuels in general has caused the deforestation and dewatering of peatland. The fear is that an increase in demand for fuels will worsen this. Especially the case of palm oil, increased demand have induced planting of new palm oil plantations leading to large scale clearing of tropical rainforests, which are massive biogenic carbon sinks. Large use of these crops for biofuel production would increase this practice and result in a significant increase in GHG emissions, thus many organizations to question the sustainability of palm oil based biofuels[114].

Also, biofuels produced from starch sugars or food grade oils such as corn starch or rape seed oil (feedstocks for ethanol and FAME biodiesel/HVO, respectively), require a large amount of fossil inputs (fuel and fertilizers) to produce, thus reducing the sustainability of these fuels. Variations in these factors result large differences in the overall carbon emissions from different biofuels, and this must be taken into consideration when deciding which biofuels will be produced on industrial scales.

While the sustainability of biofuels is an ongoing debate in society and within the research community, there is beginning to be a consensus some general traits for the production of sustainable biofuels. Biofuels should be produced when possible from residual sources, meaning feedstocks that are not grown for their own sake, but are residual from agricultural and forestry sectors. This can be feedstocks like corn stover, wheat straw, and rice straw, or agro-industrial residues like saw mill waste, sugarcane bagasse, corn cobs, or pulping liquors. This has the benefit of not using fossil inputs directly for the production of biofuels, but also by making sure feedstock demand does not result in land use change. Another important factor for biofuel sustainability is that the primary product from which the residual is produced must be grown using sustainable agricultural principles, and with a minimum of fossil fuel and chemical inputs. Industrial agriculture is responsible for roughly 50% of global GHG emissions, and thus even though biofuels may not be the primary product, it is important that biofuel production support the transition to sustainable agricultural practices[115]. This could be a crop that has a function in a circular agriculture system, like catch- and cover crops, or biomass from crops used in rotation systems as soil improver or fauna strips. If plants are to be grown for biofuel production alone, it is necessary that they do not use land which would otherwise be used for agriculture or convert natural ecosystems, and should be grown primarily on marginal or degraded land, and ideally include ecosystem and soil carbon development in their growth and harvest methods. By not competing with agricultural or forestry land or by adding quality to the soil or ecosystems in a circular agriculture system, it is possible to reduce the impact of direct and indirect land use change on the sustainability of a given biofuel.

While most of the sustainability of a given biofuel is dependent on the type and method of feedstock production, there are some important considerations within biofuel production processes which can have a significant impact on overall biofuel sustainability. Two prime examples are raw biomass transport distances and hydro-treating conversion processes. Most biomass is bulky and is dispersed over a wide area, requiring transport to a central biorefining facility. This transport is usually carried out by trucks, which currently run on fossil fuels. If the distance from field to biorefinery is too large, then more fossil fuels are used in transport than can be offset from the production of biofuels. This has an impact for biorefinery size and also placement, and may also limit the economies of scale for some conversion processes. Thus, biorefineries must be placed as close as possible to biomass sources, and at a scale which does not require large transport distances for feedstock collection.

Hydro-treating combined with other thermochemical conversion processes has been shown to be a promising method for the production of drop in fuels, however the current reliance on fossil fuels for the production of hydrogen for the process results in the production of biofuels with a significantly larger GHG emissions footprint[116]. For this to be avoided, hydrogen can be produced from biogenic sources, such a biomass gasification or from anaerobic fermentation biogas. Nevertheless they reduce significant amounts of GHG because systems like the RED demand stiff reductions compared to the use of fossil fuels when used to comply with the obligation. Biofuels produced at a plant that started their production after 2020 are only eligible if they reduce more than 65% GHG (well to wheel) when compared to fossil use.

As a part of the development of biofuels for the shipping sector, it is thus important to include considerations of a given biofuel's sustainability and total GHG reductions over the fossil and other alternatives. This can be done by implementing life cycle assessments (LCA's) for the different biofuels, and use this data to make decisions which will prioritize sustainability and reduced GHG emissions. Some attempts within the marine sector have been made to include these considerations in their comparison of different fuels[117], however more work should be done to incorporate such LCA's when evaluating biofuels for marine transport. As well, international standards and certifications are needed for the evaluation of biofuels and their sustainability, so that there can be agreement between producers, consumers, and regulators on the sustainability of a given fuel, and that collectively recognized standards can allow for accurate decision making. While there have been some attempts at the national and regional level for this, more work must be done for international and inter-sector collaboration on these standards.

5.4 ELECTROFUELS

Electrofuels are a category of fuels which are produced using electricity as the primary energy source, converting electrical energy into chemical energy which can then be transported or used as a fuel. This technology is also commonly referred to as 'power-to-x' technology and has been the focus of much recent research and technology development. Electrofuels are an alternative to storing energy in batteries, with the idea that liquid or gaseous fuels could be easily stored, transported, and burned in either internal combustion engines or used in fuel cells. It is theorized that these fuels can be produced using renewable sources of electricity, such as photovoltaic and wind, and produced intermittently when there is excess electricity in the power grid.

The primary electrofuels under development start with the production of hydrogen, produced from the electrolysis of water. The long-term renewable solutions and the envision of zero-carbon shipping typically involves hydrogen produced from renewable electricity (fx. solar or wind)[37,38,118]. Hydrogen itself can be used as a fuel in fuel cells, or it can be further upgraded and combined with other molecules such as CO_2 or nitrogen to produce methane, and ammonia, respectively. This is done primarily by catalytic processes, but also production via biological process for methane is being demonstrated by electrochaea[119]. While ammonia can be produced from hydrogen via the traditional Haber-Bosch process, new methods to electrochemically produce ammonia have been demonstrated, making it a promising electrofuel[120]. Ammonia is much easier to liquefy and transport as compared to hydrogen, and it can be used as a source for hydrogen for fuel cells, or used as a fuel itself in internal combustion engines[121]. This includes recent tests by Wärtsilä of ammonia as a fuel for marine four stroke engine[122]. Methanol can also be produced via electrochemical processes from CO_2, and therefore can be included as an electrofuel[123].

Hydrogen as a fuel in itself has the benefits of having no GHG emissions during the combustion/fuel cell process, and also produces no/or very low SO_x, soot, or NO_x emissions. It produces only water as a byproduct, and has high energy conversion efficiency when used in fuel cells to generate electricity. However, hydrogen has significant drawbacks in terms of energy capacity, and difficulties with storage and transport. While hydrogen has a very high gravimetric energy density of 120.9 MJ/kg. It only has a volumetric energy density of 8.5MJ/L (see figure 5.1) as a liquid at 700 bar, roughly 7 times lower than that of HFO. Fuel storage volume affects cargo volume, refueling rate and travel distance of a vessel. Decreasing hydrogen storage volume is therefore a central barrier to make hydrogen viable for shipping and is a field of active research.

Hydrogen is the smallest and lightest, molecule and can therefore leak more easily than methane due to its smaller size (289 vs 380 pm kinetic diameters, respectively). Handling hydrogen in the fuel system, storage and in transport thus requires specialized equipment and leakage may be difficult to avoid. Hydrogen is in itself a greenhouse gas with GWP of 5, and has also been shown to negatively impact polar ozone layer[124,125]. Similarly, hydrogen is difficult to store in gaseous form, and liquefies at very low temperatures, making liquid storage energetically costly. The fuel cell technology at large scale needed to fit deep-sea vessels does not yet exist and no initiatives from IMO exist on hydrogen.

The deep-sea sector is still especially interested in the longer term perspectives of hydrogen. In the business model of deep-sea shipping the capital investment required to retrofit is less important than the long-term costs of fuel. The potential of hydrogen and hydrogen-based marine fuels is large but challenged by production cost, infrastructure, cleaner production methods and on a much larger capacity of renewable electricity production[37,126].

Today, two percent of global energy demand is currently used to produce hydrogen, primarily from fossil methane and coal, where the main hydrogen utilization is the production of ammonia and methanol. The current hydrogen production has a carbon intensity between 10 and 19 tCO_2/tH_2 for fossil methane and coal, respectively[126].

Hydrogen from electrolysis could however instead of being used as a fuel in itself, be instead used to produce drop in biofuels where hydrogen is needed for upgrading of biomass intermediates. It can also be used as an intermediate to produce methane, methanol, or ammonia fuels, thus providing an important intermediate in the production other electrofuels which are easier to store and transport.

Electrofuels beyond hydrogen, especially ammonia, methane, and methanol, are promising sustainable fuels as they can take advantage of current infrastructure for shipping and storage which already exist for these chemicals. Similarly, as the global economy transitions away from fossil fuels, production of methanol and ammonia for other uses will transition to electrochemical processes, and thus marine fuel production could benefit from this scale-up and increased capacity. However, economic factors will impact marine fuels as the prices of other chemicals produced from hydrogen such as fertilizers will compete with marine electrofuel prices unless it is regulated through policies like a renewable fuel mandate. As well, engine modifications is required and engine capacity will need to be developed, similar to other sustainable fuels. Electrofuels will also require a significant increase in renewable electricity production, such that excess electricity is present in the grid at various times, enabling these conversion processes to take advantage of cheap electricity.

While solar and wind energy has reached price parity with fossil fuels for electricity production, there is still a large amount of fossil fuel energy infrastructure which needs to be phased out and replaced with renewables, and this will most likely be prioritized over the production of electricity for electrofuels in the near future. According to BP Energy Outlook, the share of wind and solar energy should reach between 40% and 70% of the total global power production at 2050[127]. However, hydrogen as an energy carrier is not expected to play a large role before closer to 2050, where the hydrogen production is expected to be a mix of electrolysis using renewable power and from natural gas combined with carbon capture. According to the IEA, electrofuels will become the dominant fuel-type in the 2040s with hydrogen-based fuels such as ammonia and synthetic fuels providing more than 60% of the total fuel consumption in 2050[128].

The transition away from fossil fuels leads room for an important role for bioenergy with up to 10% of the global energy mix according to BP[127]. Heavy-duty and long-distance transportation are harder to electrify which makes bioenergy a crucial short-term sustainable solution for the shipping industry.

6. Recent advances and the state of the industry for marine biofuels

Since the publication of the previous IEA report on biofuels for the marine sector in 2017[1], there have been significant advances in both the technology for producing marine biofuels, and in the commercialization of marine biofuels. Similarly, there have been a number of trials of biofuels in marine engines, as well as the development of new marine engines capable of running on biofuels. The past 5 years have seen an increase in both worldwide production capacity and use of biofuels for marine applications, both in short sea routes and for long distance sea shipping. However, while increasing, the share of shipping fuels from biofuels or other alternative fuels remains low.

6.1 INDUSTRY RESPONSE TO SULPHUR EMISSIONS REQUIREMENTS

By far, the largest change in the past 5 years is the implementation of low sulphur fuel and emissions standards in 2020. The way in which the shipping industry has responded these new emissions requirements may give some indication of how it will respond to GHG emissions mandates in the future.

Three main options have been explored by industry: the installation of scrubbers to remove sulphur emissions from the exhaust, switching to low sulphur fuels, and switching to fossil gas as a fuel. By far the most straight forward option is to switch to low sulphur fuel, and has been adopted by the majority of ships, and especially older ships. Depending on the motor configuration, this option may require some engine modifications due to differences in viscosity and lubricity of low sulphur fuels, which can otherwise lead to fuel leakage and engine wear. Scrubber installation has primarily been implemented on newer ships with a longer future lifespan, such that they can continue to run on HSFO, and some ship owners hope to take advantage of future lower fuel prices for HSFO. While demand for scrubbers has increased recently, there are only 3,800 scrubber systems installed on ships worldwide, accounting for only 3% of the shipping fleet[129]. More scrubbers are currently being installed, and ship owners will continue to try to save money by using HSFO as long as it remains cheaper than low sulphur alternatives, and may account for up to 20% of all marine fuels by the end of 2021.

The third option being explored is to retrofit ships to use fossil methane gas as a fuel. This is primarily being driven by low prices on fossil gas, and the ability to market it as a 'clean burning' fossil fuel or as a 'transition fuel'. While these two claims (at least with regards to GHG emissions) are dependent on a variety of assumptions which were discussed earlier, LNG does reduce sulphur and NO_x emissions, and thus represents a significant option for future fuel use for shipping. A majority of the current LNG tankers run on fossil gas, but only around 175 ships which are not LNG tankers are running on LNG. However, these ships tend to be for larger deep sea ships, and therefore represent larger fuel use. Currently around 10-20% of ships ordered are to be outfitted with LNG compatible motors, and therefore this is a growing response to dealing with sulphur emissions[130]

Seen in light of GHG emissions reductions standards, this shows that given strong regulations, ships can transition to low carbon fuels including biofuels, and that the market will adapt to future regulations. Current carbon capture technology is not advanced enough to allow for retrofitting of ships with carbon capture equipment similar to sulphur scrubbers, so ships will have to be retrofitted to run on alternative fuels. One takeaway from this is that ship owners will run whatever fuels are cheapest, and are willing to make significant ship upgrades to allow them to run on cheaper fuels.

6.2 BIOFUEL PRODUCTION AND COMMERCIAL CAPACITY

Globally, biofuels production has continued to increase over the last decade, from over 37 Mtoe produced in 2007 to over 84 Mtoe in 2017[79]. The majority of the global capacity is from starch and sugar-based ethanol (54 Mtoe), followed by FAME biodiesel (9 Mtoe). A thorough description of the current world production of biofuels can be seen the IEA Bioenergy report "*Implementation Agendas: 2018-2019 Update Compare and Contrast Transport Biofuels Policies*" [79].

Despite the biofuels capacity still is being heavily dominated by conventional biofuels, the past 5 years have seen an increase in the number of advanced biofuel producing facilities worldwide. The majority is located in North America and Europe, as documented by the IEA Biofuels task 39 and presented in Table 6.1. Currently operating commercial facilities of advanced biofuels focus primarily on HVO production from oil crops, pyrolysis oil from forest residues, and cellulosic ethanol from agricultural residues. Together these have capacity to produce 5.1 Mtons/y biofuels, thus only capable of covering approximately 1.5% of global shipping fuel needs (based on annual consumption of 350 M tons fuel). These advanced biofuels are produced currently for all transport sectors, and thus most likely actually represent a much lower share of shipping fuels. Biofuels continue to represent only a small fraction of fuels used in marine shipping, which has not changed significantly since 2016. Table 6.1, lists commercial scale biofuel production facilities in operation, while Table 6.2 lists biofuel production facilities in under construction.

Currently there are a number of new biofuel production facilities under construction set to be completed in the next 2 years. These new facilities are set to produce a wider variety of fuels, with the main focus on cellulosic ethanol, pyrolysis oil, and Fisher-Tropsch liquids. The one exception is a large palm oil to HVO facility under construction in Singapore by Neste, which represents much of the capacity under construction. The primary feedstocks are forest residues, followed by MSW and agricultural residues. Total capacity in production is 1.6 M tons/year, and while this represents a significant increase in the total amount of biofuel production capacity in the world, will do little to reduce fossil fuel consumption in the marine shipping sector.

Table 6.2 Known commercial scale advanced biofuel production facilities in operation (Not including FAME biodiesel and sugar/starch based ethanol, February 2021)[131].

Project owner	Project name	Location	Technology	Feedstock	Products	Capacity (tons/y)
Ensyn	Cote Nord Project	Canada	Fast pyrolysis	Forest residues	Pyrolysis-oil	36,000
Biomcn commercial		Netherlands	Other	Glycerine/ biomethane	Methanol	65,000
Granbio	Bioflex 1	Brazil	Fermentation	Sugarcane Baggase	Ethanol	62,000
Henan Tianguan Group	Henan 2	China	Fermentation	Wheat straw, Corn stover	Ethanol	30,000
Longlive Bio technology Co.	Longlive	China	Fermentation	Corn Cob	Ethanol	60,000
Raizen Energia		Brazil	Fermentation	Sugarcane Baggase	Ethanol	31,000
POET-DSM	Project Liberty	USA	Fermentation	Agricultural residues	Ethanol, FT liquids, biogas	75,000
Enerkem Alberta Biofuels LP	Edmonton Waste-to-Biofuels Project	Canada	Thermo-chemical gasification/ FT	MSW	Ethanol	30,000
Daimond gree diesel	Daimond greed diesel	USA	Hydrotreat.	Animal residues	HVO	412,000
ENI	HVO	Italy	Hydrotreat.	Oil crops (soybean)	HVO	500,000
Neste	Porvoo 2	Finland	Hydrotreat.	Oils and fats	HVO	190,000
Neste	Rotterdam	Netherlands	Hydrotreat.	Oils and fats	HVO	800,000
Neste	Singapore	Singapore	Hydrotreat.	Palm oil	HVO	800,000
Neste	Porvoo 1	Finland	Hydrotreat.	Palm oil, rapeseed, animal fat	HVO	190,000
Preem	Preem HVO2015	Sweden	Hydrotreat.	Tall oil	HVO	800,000
REG Geismar	Geismar Project	USA, Louisiana	Hydrotreat.	Animal fats	HVO	225,000
Sunpine	Sunpine HVO 100 mio litres	Sweden	Hydrotreat.	Tall oil	HVO	77,000
Total	La Mede	France	Hydrotreat.	Rapeseed oil	HVO	500,000
UPM Biofuels	UPM Lappeenranta biorefinery	Finland	Hydrotreat.	Tall oil	HVO	130,000
BTG bioliquid (BTG-BTL) CA	GREEN FUEL NORDIC OY	Finland	Pyrolysis	Forest residues	Pyrolysis oil	2,000
BTG-BTL	EMPYRO	Netherlands	Pyrolysis	Wood pellet waste	Pyrolysis oil	26,100
Ensyn	Ensyn	Canada	Fluidized bed reactor	Forest residues	Pyrolysis oil	14,790
Fortum		Finland	Fluidized bed reactor	Forest residues	Pyrolysis oil	54,810
Twence	Hengelo	Netherlands	Fast pyrolysis	Forest residues	Pyrolysis oil	24,000

Table 6.2 Known commercial scale advanced biofuel production facilities in under construction (Not including FAME biodiesel and sugar/starch based ethanol, February 2021)[131]

Project owner	Project name	Location	Technology	Feedstock	Products	Capacity (tons/y)
Austrocel Hallein	Biorefinery	Austria	Biochemical, Borregaard	Sulfite spent liquor	Ethanol	
Clariant	Clariant Romania	Romania	Fermentation	Cereal straw	Ethanol	50,000
Fiberight LLC		USA	Fermentation	MSW	Ethanol	18,000
Fulcrum (Sierra Biofuels)	Sierra	USA	Gasification	MSW	FT liquids	30,000
Red Rock Biofuels		USA	Gasification FT	Forest residues	FT liquids	44,000
Neste	Singapore expansion	Singapore	Hydro-treatment	Palm oil	HVO	1,300,000
Advanced Biofuels Solutions Ltd	Swindon Advanced Biofuels Plant	UK		MSW and wood	Methane and hydrogen	2,000
Ensyn, Suzano S.A	ARACRUZ PROJECT	Brazil	Circulating fluid bed	Forest residues	Pyrolysis oil	100,000
Green Fuel Nordic	Lieksa	Finland	Fast pyrolysis	Forest residues	Pyrolysis oil	24,000
Pyrocell (JV of Setra and Preem)	Pyrolysis oil upgrading	Sweden	Fast pyrolysis	Saw dust	Pyrolysis oil	24,000

6.3 ENGINE TECHNOLOGY AND SHIP MANUFACTURING

Along with production and delivery of biofuels, having engines that can burn biofuels and other advanced biofuels is critical to their adoption in the marine sector. The last 5 years have seen improvements in this sector, with major engine manufacturers approving some biofuels for use in their engines, and the introduction of multi fuel and flex fuel engines into the market.

Goodfuels, a Dutch fuel producer, introduced in 2018 biofuels which they claim are compatible with all diesel marine engines, consisting of HVO but also with BTL technology, and have proven compatibility with existing engine systems. While drop in capabilities is most desirable for biofuels, there is a high likelihood that advanced biofuels, especially those with particulate suspensions or alternative combustion properties, will require some amount of engine modification.

Some of the large engine manufacturers have begun to produce flex fuel engines, which are capable of burning both diesel and fossil gas. MAN Energy Solutions for example currently sells dual fuel engines which can run both HFO and other diesel like fuels as well as fossil gas, which could also include biodiesels and biogas if available. MAN also offers two stroke engines which can be retrofitted to run on Methanol, LNG, LPG, or ethane. However, MAN does not as yet certify its 4 stroke diesel engines with biofuels besides dilute blends such as B7 and other road grade diesels, and thus future biofuels will most likely still require some engine modification and work with engine manufacturers to approve their use.

While MAN Energy Solutions does acknowledge biofuels and viable future marine fuels, it also focuses on other alternate fuels, such as ammonia and other electrofuels, and also has set goals to introduce an ammonia 2 stroke engine by 2024. Similarly, Wärtsillä has begun testing engines running on ammonia, and is working towards their own ammonia engine production[132]. Wärtsillä also offers dual fuel engines which can run on either diesel fuel, 'liquid bio fuels', or LNG. It is thus apparent that engine manufacturers are working to build fuel flexibility into their engines, and that this does and can in the future include different types of biofuels, including the lighter biofuels such as ethanol, methanol, and biogas. However, this also means that ships which have flex fuel engines installed will most likely run on the cheapest fuel available, which in the current market is LNG. Thus, engine compatibility will not on its own lead to the adoption of biofuels, but is a necessary step which is currently being undertaken by leading engine manufacturers.

6.4 MARINE BIOFUEL TRIALS

While uptake of biofuels has been slow on a volumetric basis, there have been several recent biofuels engine and ships trials in the marine sector, with the goal to run proof of concept use of these fuels, and to increase demand through marketing and feasibility tests. GoodFuels has tested its bio distillate and bio residual fuel oils in a number of different ships, including deep sea vessels. The residual fuel is produced from organic waste streams (including used vegetable oil) and aims to be a sulphur-free and sustainable substitution of heavy fuel oil.

GoodFuels has been involved in several biofuel trials between 2015 and 2020. In March 2020, they partnered with the short-sea shipowner UECC as well as BMW Group to test a biofuel based on used cooking on UECC's ro-ro M/V Autosky able to carry 2080 vehicles. The biofuel trialled was a drop-in BFO named MR1-100 made from used cooking oil, which is fully compatible with marine engines. The trial ran between March and July 2020, and BMW claimed that shipment had and 80% to 90% CO_2 reduction.

The first wood-based biofuel trial in the maritime sector was done in a collaboration between the global dredging and marine expert Boskalis, GoodFuels, and the Finnish UPM Biofuels that provided the UPM BioVerno biodiesel produced from tall oil. The 1696 dwt cutter suction dredger 'EDAX' was working on the Dutch Marker Wadden nature restoration project in the Markermeer lake and was successfully running on up to 50% bio/fossil blends in the first 6 months of 2016.

In collaboration with the Global mining company BHP and GoodFuels, The Japanese shipping giant NYK trialed a 30% UCO-based drop-in marine gasoil blend in their 180,000 dwt dry bulk carrier 'Frontier Sky' in January 2019, in the port of Rotterdam, Netherlands. BHP and GoodFuels also collaborate on a biofuel trial using fuel based on cooking oil, crude tall oil and sewage sludge on the 81,000 dwt dry bulk carrier Kira Oldendorff. It was on April 4 2021 refueled in Singapore on its way from Australia to Europe. This was the first time a ship has been refueled with biofuel in Singapore, the world's largest bunkering hub.

The Stena Bulk 49,646 dwt Suezmax tanker 'Stena immortal' successfully trialed GoodFuel's 'bio-residual fuel' in spring 2020. The same drop-in fuel was also trialled in collaboration with the Belgian dredging company Jan De Nul Group, where the trailing suction hopper dredger 'Alexander von Humboldt' since November 2019 has been carrying out maintenance dredging works in the maritime access routes, on the North Sea and in Flemish seaports.

As a follow-up on a 100% biodiesel trial in 2020, the Canada Steam Ship Lines (CSL) will be trialing a second generation biodiesel on half of its fleet

Examples of biofuel trials on deep-sea vessels are scarce. The largest deep sea pilot of biofuels was carried out between March and June 2019 by one of Maersk's Triple-E container ships. The ship journeyed from Rotterdam to Shanghai and back using a blend of 20% ISCC certified used cooking oil (UCOME), thereby saving 1500 tons of CO_2 and 20 tons of sulphur emission with no reported issues. The biofuel trial was a collaboration with Maersk and the Dutch Sustainable Growth Coalition with members including FrieslandCampina, Heineken, Philips, DSM, Shell and Unilever.

These biofuel trials are important integrated collaborations between biofuel producers, ship owners, engine manufacturers, shipping customers, encompassing some of the key stakeholders in adopting biofuels in the shipping sector. They represent a stepping stone on the way to increased biofuel uptake, and eventual commercial production and use. Proving this integrated fuel usage is important for market development, and should be watched closely in the future. However, it remains to be seen if these represent primarily marketing activities, or will lead to increased usage of marine biofuels. In the following section, the opinions of stakeholder across the value chain is presented.

7 Stakeholder analysis

A low or zero carbon maritime sector is an ambitious goal that requires more than technically mature fuel technologies to become reality. International shipping affects most aspects of the global economy and includes many interdepending small and big stakeholders ranging from cargo owners to policy makers. To better understand the barriers for the commercialization of marine biofuels, interviews were conducted with 7 key stakeholders involved with the marine freight transportation sector (Table 7.1). The interviews were based on questions found in Appendix A.

Table 7.1. Overview of interviewed stakeholders

Company (abbreviation used in figures)	**Name**	**Interviewee Title**	**Stakeholder category**	**Description**
Blended Fuel Solutions NZ (BFS)	Simon Arnold	CEO	Alternative fuel producer	Producer of renewable fuels and fuel emulsions from New Zealand.
GoodFuels (GF)	Johannes Schürmann	Innovation Manager	Alternative fuel producer	Dutch biofuel producer and distributor with large influence in several marine biofuel trial
Maersk A/S (M)	Maria Strandesen	Head of Future Fuels	Shipping company	Danish shipping company and world's largest overseas cargo carrier
NYK Line (NYK)	Wataru Nishio	Manager of Marine Engineering Team	Shipping company	Large Japanese shipping company
BMW (BMW)	Stephan Reinhold	Sustainability Manager for Transport and Logistics	Cargo owner	German car manufacturer
Port of Vancouver (PoV)	Ronan Chester	Manager, Strategic Environmental Initiatives	Port	Largest port in Canada
Wärtsilä (W)	Sebastiaan Bleuanus	General Manager Research Coordination & Funding, Future Fuels & Decarbonisation, R&D and Engineering, Marine Power Supply	Engine manufacturer	Finnish company that manufactures and services marine propulsion equipment. Is involved in both in marine and energy markets, including biofuel power plants

The aim of the interviews was to understand the barriers of biofuel commercialization from the perspective of the industry and not necessarily from policy makers, advocacy groups or academia. The result of this analysis demonstrates the great complexity of transitioning to alternative marine fuels and shows the main barriers towards biofuel investment are related to lack of economic incentive, uncertain cost development, uncertain sustainability criteria as well as regulatory uncertainty (Figure 7.1-8.1). These findings are in line with previous studies on the barriers for the commercialization of advanced biofuels in the transport sector.

> *"Biofuels are very promising. But it is impossible to say exactly what role biofuels will have … It is not going to be 'one solution fits all' kind of scenario, but a plethora of alternative fuel solutions."* **Ronan Chester**, Manager, Strategic Environmental Initiatives at Port of Vancouver

They reported high customer demand for sustainable shipping solutions but see the supply and price development of biofuels as unable to support a marine fuel market.

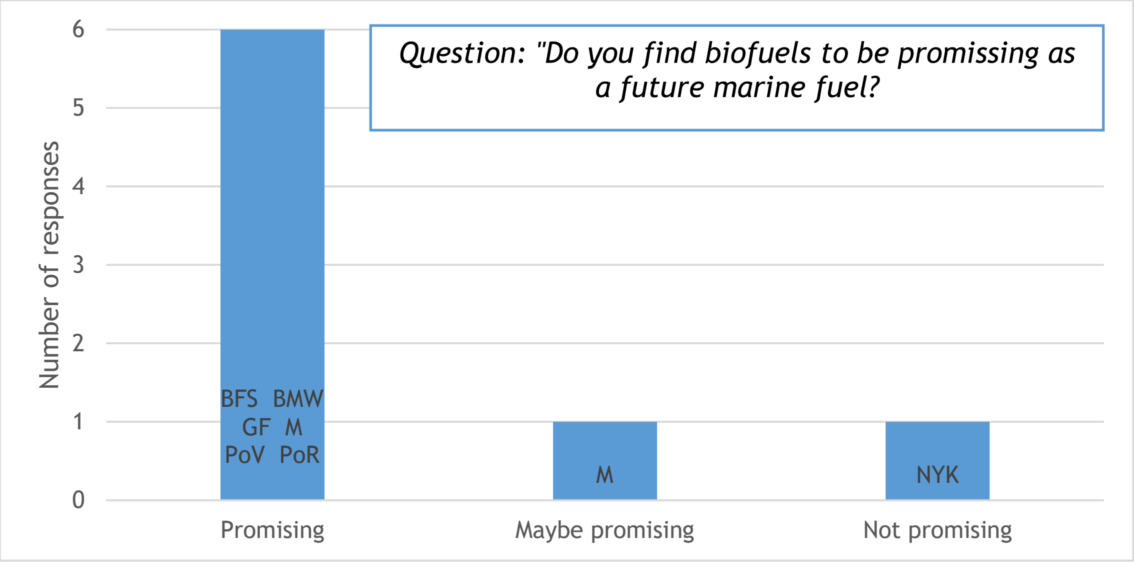

Figure 7.1 Role of biofuel in the marine fuel market according to stakeholders. Abbreviations see Table 7.1.

Other stakeholders like Sebastiaan Bleuanus from Wärtsilä expressed some the skepticism. He does not expect biofuels to ever become more than a 'niche fuel', and he does not expect the marine fuel market to ever exceed a 10% biofuel share. However, he shares the perception with most stakeholders that biofuels have the potential to be the necessary steppingstone towards sustainable shipping.

> *"It could kick-start the business and build up the market with legislation, standards and pave the way for other more abundant sustainable fuels, such as electro fuels."* **Sebastiaan Bleuanus**, Programe manager, R&D at Wärtsilä

When stakeholders were asked to share their expectations towards how much biofuels would cover the future marine fuel market, the answers were very diverse. Blended Fuels Solutions NZ, Nyk Line and Port of Vancouver choose not to answer. Among answers, the expected biofuel share ranged from 2 to 15. This corresponds to an expected biofuel consumption of 7 to 52.5 Mtoe (million ton of oil equivalent) in 2030, presuming continued fuel consumption of 350 million tons/yr. In comparison, the global biofuel production in 2019 was 96 Mtoe.

Table 7.2: Answers from interviewed stakeholder on their expected share of biofuels in 2030 and 2050.

Expected share of biofuels in the global marine fuel market		
	2030	**2050**
BMW	2%	7%
Wärtsilä	>10%	>10%
Maersk	10 - 15%	20 - 25%
GoodFuels	10%	33%

> *"Biofuels are very promising. But it is impossible to say exactly what role biofuels will have … It is not going to be 'one solution fits all' kind of scenario, but a plethora of alternative fuel solutions."* **Ronan Chester**, Manager, Strategic Environmental Initiatives at Port of Vancouver

7.1 MOST PROMISING MARINE BIOFUEL TECHNOLOGIES

Although most stakeholders shared a general enthusiasm towards biofuels, they answered differently to which marine biofuel technology they find most promising. Ronan Chester from Port of Vancouver, Johannes Schürmann from GoodFuels and Simon Arnold from Blended Fuel Solutions NZ put emphasis on the advantages of HFO-compatible drop-in biofuels. They dramatically lower the capital investments associated with the required port infrastructure as well as reduces the need for vessel retrofits. Drop-in fuels based on existing waste streams would also contribute to a circular economy and would not risk competition with food or increase indirect land-use.

Maria Strandesen from Maersk points out that HFO is a cheap low-quality fuel, exclusively sold to the deep-sea shipping market. When entering the global market of renewable fuels, the shipping sector will compete with aviation, road transportation as well as green chemistry producers. With the current international regulations, the shipping industry will not be able to compete on fuel prices, which makes it important to find an abundant source of low-quality biofuel. Maria Strandesen identifies lignin as the most promising fuel feedstock due to abundance, no interference with the food or feed industry, and no obvious competition with the road or aviation sectors.

A majority of the interview stakeholders, suggested HTL- or pyrolysis oil to be the most promising marine biofuel alternative (Figure 7.2), based on prospects of relatively low prices and simple processing of abundant biomass feedstock such as lignocellulose. Sebastiaan Bleuanus from Wärtsilä describes biomass as typically spread across large areas of land and collecting and transporting the biomass in sustainable way is a great challenge for biofuels. He expects an increase use of LNG as a short-term solution to SO_x restrictions and GHG reduction. Sebastiaan Bleuanus highlights that vessels adapting the LNG technology would also be compatible with RNG, which can be produced locally in gasification plants connected to existing gas-pipelines and be widely implemented because of the feedstock flexibility. He also finds RNG the most promising biofuel, attributed to the low energy required to collect and transport as well as fuel compatibility with existing supply chains and engine technology.

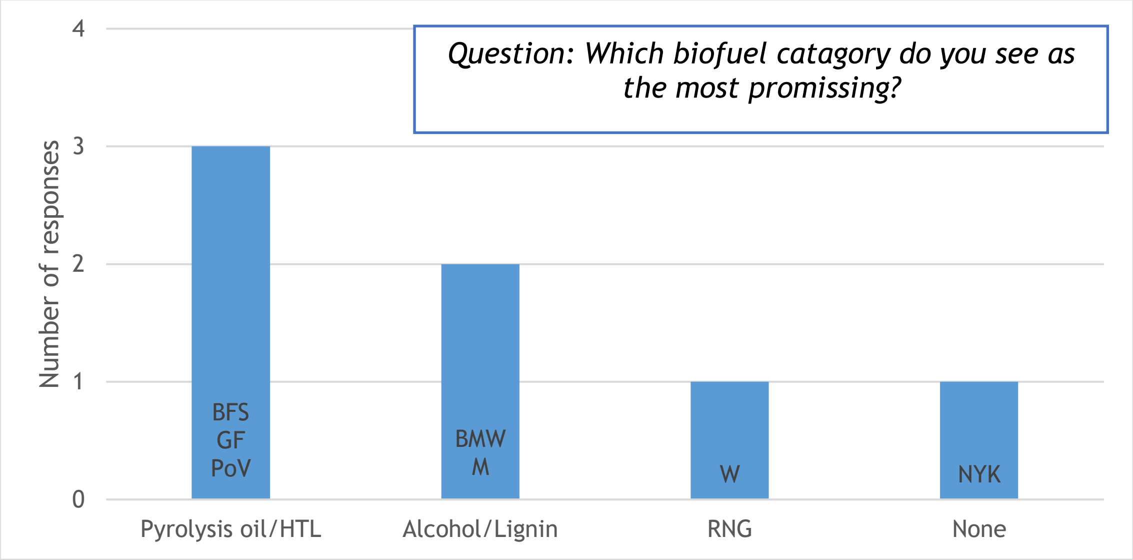

Figure 7.2. Most promising biofuel in the future marine fuel market according to stakeholders. Abbreviations see Table 6.1.

7.2 STAKEHOLDER PERCIEVED BARRIERS

All stakeholders, with no exceptions, mentioned price as one of the largest barriers facing biofuels on the path to commercialization. The elaborate answers on the biofuel price barrier is two-fold – the price gap between HFO and biofuels and the price stability over time. To the first aspect Johannes Schürmann from GoodFuels describes it as a ‘chicken and egg situation’ where the combined effects of economy of scale and fossil carbon price regulations are needed to make biofuels a better business. The fuel price is the single largest cost for carriers and switching to an even marginally more expensive fuel could have a large impact on the economy and competitiveness of the carrier. The elevated fuel cost would translate into a higher freight cost per volume cargo, resulting in a disproportionally increase in the relative freight price between low-value bulk and high value cargo. Since more than 80% of all global goods are affected, it is important to consider the market reactions to such a cost disproportionality. In survey conducted by Lloyd's register in collaboration with UMAS, shipowners agreed they could not absorb more than 10% increase in overall transport price which Maria Strandesen from Maersk recognized[48]. Large shipping companies are therefore hesitant to invest in renewable fuels without a clear global and united effort among stakeholders and legislators. It was mentioned in several of the interviews that the maritime sector needs to "level the playing field" by putting a price on GHG emissions and by increasing the economic incentive towards renewable fuels such as biofuels through regulations. Maria Strandesen from Maersk points to a decrease in the large amount of subsidized fossil energy as an obvious regulatory opportunity to promote more sustainable fuel options. According to the international renewable energy agency global fossil fuels were subsidized by 450 $Bn in 2017 while the subsidies for renewable power generation and liquid biofuels in the same year were 110 and 25 $Bn, respectively[76].

The second aspect of the price barrier relates to the market reaction to an increased demand of feedstocks. According to Maria Strandesen from Maersk, predicting the supply and price development of biofuel feedstocks for the next 15 years is crucial to evaluate the economic viability of a biofuel. The effect on price and supply of a sudden demand of millions of tons of biofuels is very difficult to predict, especially considering the emerging green technologies within other sectors also transitioning towards more sustainable energy sources.

Biofuel sustainability was mentioned as one of the largest barriers by Maersk, Port of Vancouver, Wärtsilä and BMW. Biodiesel produced from palm oil was mentioned as an example of how large upstream emissions, social and environmental impacts of unsustainable nature management could be a consequence of large demands of biofuels without suitable sustainability requirements[133].

> *"There is not a globally recognized certification of sustainability when it comes to biofuels. There is no way to differentiate between similar fuel with different carbon intensities."* **Ronan Chester**, Manager, Strategic Environmental Initiatives at Port of Vancouver

Sustainability certification on biomass exist - an example is the Forest Stewardship Council (FSC) on sustainably harvested trees. FSC focus primarily on forest management and promotes 'environmentally appropriate, socially beneficial, and economically viable management of the world's forests'[134]. FSC could be adopted to biofuels, however, this would only be applicable to a certain group of biofuels and would not guarantee sustainable processing or transportation. The sustainability aspect would, thus, diminish if the fuel were produced using large amounts of fossil energy, or transported long distances by fossil fuels. An international fuel sustainability certification would therefore need to cover the complete life cycle of the fuel. The Roundtable on Sustainable Biomaterials (RSB) aims to cover the complete life cycle of biomaterials, biomass production and biofuels. The RSB standard system covers production and processing of the biomass as well as the production and transportation of biofuels, and could have an important role in supporting a global recognized sustainability certification to marine biofuels[135]. Other regional and worldwide schemes that are specifically focusing on biofuels also exists, such as RSB and ISCC. Many of them are recognised by the European Commission as sufficient proof for demonstrating compliance with the sustainability and GHG requirements in the RED/RED II. ICAO is also recognising such schemes for the ICAO/CORSIA scheme.

> *"The political barriers are much larger than the technical ones"* **Simon Arnold,** CEO Blended Fuel Solutions NZ

It is important to note, that even though a large support of biofuel R&D was mentioned as an important action to achieve biofuel commercialization, most stakeholders did not mention technological challenges as major barriers for biofuel commercialization. However, international regulations such as a carbon tax or a renewable fuel mandate as well as an international recognized sustainability certification system were identified by most stakeholders as central measures to facilitate marine biofuel commercialization.

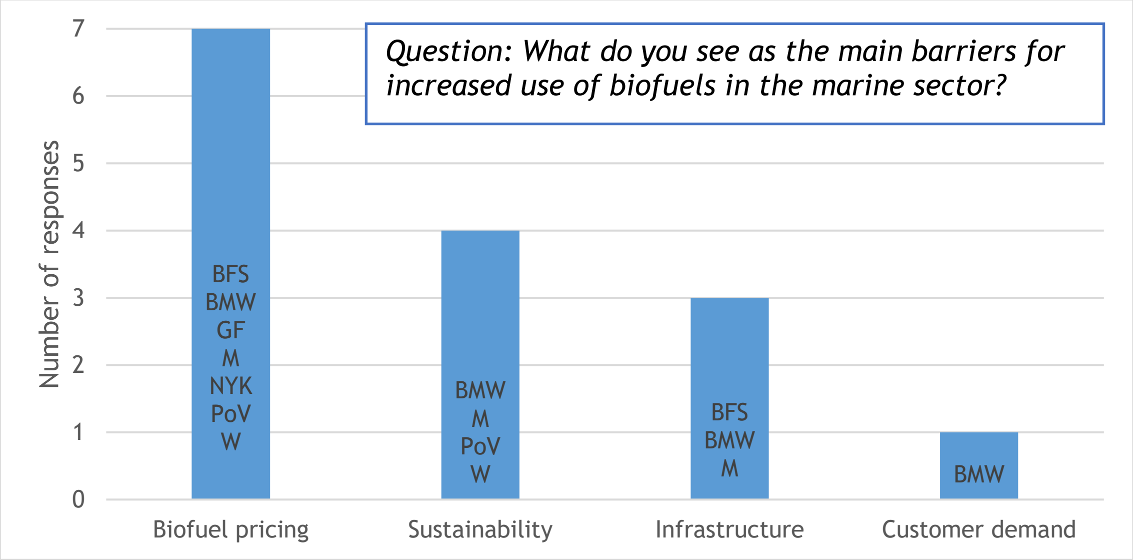

Figure 7.3. The most significant barriers for increases deployment of biofuels in the marine sector according to stakeholders (more than one answer possible). Abbreviations see Table 6.1.

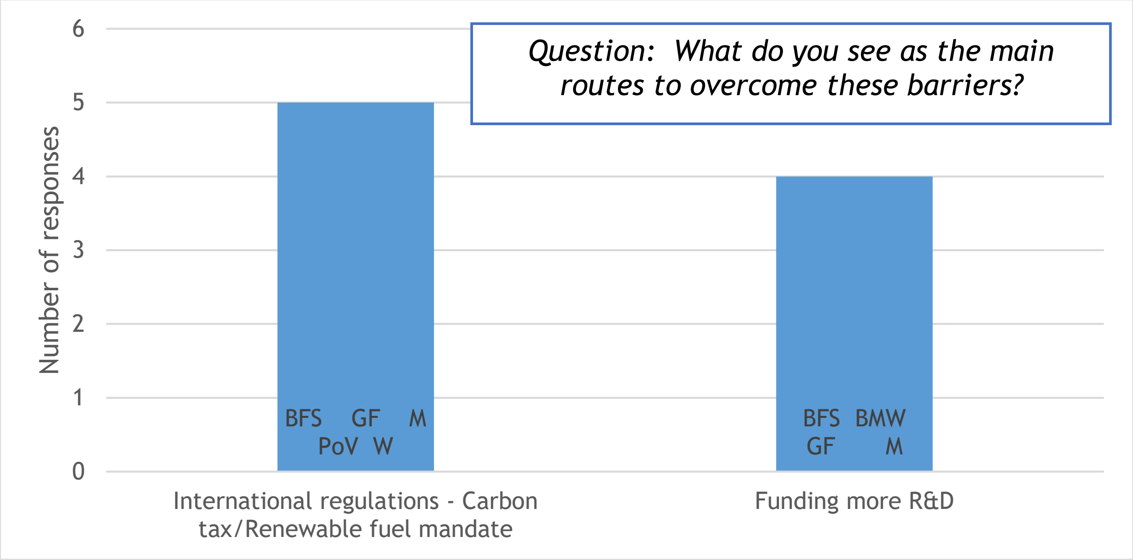

Figure 7.4 (more than one answer possible). NYK Line did not point to a specific action but answered price stability and a supply of sustainable biofuels are needed before they would expect biofuels to be able to penetrate the marine fuel market. Abbreviations see Table 6.1.

The stakeholders showed broad knowledge about the different existing biofuel technologies, and even BMW as cargo owner with no direct involvement with marine fuels mentioned biofuels based on feedstocks with no competition with the food industry such as residual oil or lignin, as especially promising candidate fuels. NYK line and Maersk also mentioned their close attention towards the development of all types of fuels. The interest and importance of biofuels demonstrated by the interviewed stakeholders could be an indication of a general trend in the industry. However, participating stakeholders accepting to be interviewed on their views on biofuels might be positively biased towards biofuels, compared to those stakeholders who did not participate. Even though the views of the interviewed stakeholders do not necessarily reflect the entire maritime sector, initiatives by large stakeholders like Maersk has the potential to pave the way for the rest of the sector. Slow-steaming is a good example of this.

In 2007, Maersk decided to significantly slow down their vessels to save fuel as a reaction to higher fuel prices and an oversupply of ships. Fuel saving derives from reducing the drag which increases quadratically with speed[32]. Sailing at 12 knots (13.8 mph/22.2 kph) instead of the previous 24 knots (27.6 mph/44.4 kph) became the standard at Maersk in 2009. Despite slower cargo deliveries and higher staff related costs, Maersk reduced bunker fuel consumption by 22% which was both environmentally and economically viable[136]. The innovation of slow-steaming was later further adopted through new hull and engine designs optimized for slower sailing speeds as seen on the Maersk large triple-E containerships. Slow steaming was quickly adopted by nearly all global shipping lines and significantly contributed to reduced carbon intensity in the shipping industry. In 2007, the sector was estimated to account for 2.8% of the global man-made CO_2, but in 2012 it was reduced to 2.2%[8]. This shows how, an otherwise rigid industry, can adapt quickly when large players demonstrate how alternative shipping solutions can benefit both the environment and shipping business.

> *"We are in the middle of the biggest change since shippers went from break bulk to intermodal containers, or since ship propulsion went from coal to oil."* **Tim Reeve**, Senior Project Manager at Maersk.

As the economic circumstances in the financial crisis catalyzed the shift towards slow-steaming, implementing a price on carbon or a renewable fuel mandate could together with existing regulations drive economic, scalable and sustainable maritime biofuel innovations.

8 Barriers and opportunities for biofuels in the shipping sector

Based on the information presented in this report the interest and demand for biofuels in the shipping industry is clear. The transition towards alternative marine fuels is visible at the Port of Rotterdam, the world's second largest bunkering hub, where blended fuel sales containing some biofuels increased from 3% (~53.000m^3) in the fourth quarter of 2019 to 11% (~210.000 m^3) in the first quarter of 2020[137].

However, the adoption of biofuels in the shipping industry faces substantial barriers to becoming a large fraction of marine shipping fuels. These barriers are both technological, logistical, and political in nature (illustrated in figure 8.1), and therefore may require different approaches to overcome them. Below is presented the major barriers to biofuel adoption as found by this report, along with notes on how these barriers might be lowered.

As the shipping sector still operates on small profit margins, price drives most economic decisions for bulk commodities like shipping fuels. Currently, biofuels are more expensive than fossil fuels across the board, and as is discussed in section 6, this price difference keeps the majority of actors within the shipping sector from choosing to buy biofuels. Fuel price is a driving factor for change within the marine sector, as can be seen by the number of ships being fitted with scrubber or converted to run on fossil gas, due to low prices for HFO and fossil gas.

While much research and development has been carried out in the last 20 years to reduce biofuel production prices, the vast amount of existing fossil fuel producing infrastructure, giving an advantage as already invested capital costs, and current price of crude oil, means that it is unlikely that biofuels will outcompete fossil fuels on price without political or market intervention. This can be achieved both by eliminating global fossil fuel subsidies, and by implementing a GHG tax on fossil fuels, to drive the price of fossil fuels higher. However, this action needs to come on national and international levels, and current levels of political instability and recalcitrance make this less likely in the next 10 years.

Another price issue for biofuels in the shipping sector is due to competition for biofuels from other sectors, primarily road transportation and aviation. These two sectors are closer to private end consumers of fuel, and these consumers have shown a willingness to pay a premium for sustainable biofuels. Therefore, the majority of biofuel producers are targeting these sectors for biofuel production, as it is easier to charge a premium price and therefore easier to compete with fossil fuels. Similarly, while biofuel supply is limited, the shipping sector will be competing for these sectors for biofuel supply, and therefore the availability of biofuels will be limited. This competition for biofuels could be overcome by relying on other biofuels sources then those currently under production for the road and aviation sectors, and by developing residual biofuel production processes which can be coproduced in a biorefinery already producing fuels for road or air transport.

Do to the vast abundance of lignocellulosic feedstocks, opportunities exists e.g. within pyrolysis HTL. Furthermore, there has been recent promise in the shipping sector targeting biofuels made from residual lignin, and thus not competing for feedstock or supply with processes such as cellulosic ethanol or oleochemical biofuels. This research and development should be continued and promoted, along with the development of biorefinery concepts which include the production of residual biofuels specifically for the marine sector. This is similar to how fossil fuels are produced for the marine sector, as a heavy residual from fossil fuel production to other sections, and thus should be possible to emulate within biorefineries.

Feedstock

- Availability
- Security of supply
- Cost and its variation
- Quality and its variation
- Collection
- Storage and transport logistics
- Sustainability criteria

Conversion technology

- Technological maturity
- Production capacity and scalability
- Widespread applicability
- Price per ton fuel
- Energy efficiency

Local and global regulations and markets

- Sustainability criteria
- Renewable fuel mandate
- Carbon tax
- GHG emission targets
- Sulphur gap
- R&D support

Fuel utilization

- Bunker infrastructure
- Fuel system and engine compatibility
- Fuel tank volume
- Freight price

Society and environment

- Sustainability certification
- Food vs. fuel
- Public opinion

Figure 8.1 Central aspects of marine biofuel commercialization (Based on [51]).

Navigating the diverse landscape of renewable fuels involves risks, especially for the deep-sea ship owners but as the aviation sector has demonstrated these challenges can be addressed. Marine biofuel commercialization depends on the interplay between conversion technologies, sustainability criteria, local and global regulations as well as the fuel compatibility with existing bunker infrastructure, fuel system and engine.

Shipping companies might be reluctant to retrofit and invest in biofuels before other central aspects of marine biofuel commercialization support it.

The marginal business of oceanic freight transportation is highly profit-optimized, making shipping companies reluctant to invest in biofuel solutions before other parts of marine biofuel commercialization process is mature enough to de-risk the investment. Lloyd's register in collaboration with UMAS made an industry viability assessment on how to get zero-emission vessels in 2030[48]. Lloyd's register is part of the 'Getting to Zero Coalition' where more than 70 public and private organizations including Maersk, Shell and Cargill have a shared ambition to make deep-sea zero emission vessels commercially available by 2030. In a survey of shipowners the following was concluded:

- 80% agreed that zero-emission vessels are needed
- 75% agreed that a carbon price is needed with most willing to pay $US 50/ton CO_2
- 85% were concerned about upstream emissions
- Consensus on shipowners cannot absorb more than a 10% increase in overall transport price
- The most important fuel propulsion options are hydrogen, biofuels and batteries
- Technological reliability and scalability are more important factors than capital cost

Transport cost is expected to increase independent of their different future energy scenarios. Among propulsion technologies biofuels were found to be the most profitable option for zero-emission vessels [48].

Given the global diversity of natural environments, seasonality, accessibility to renewable electricity or biomass and the available amount and type of waste streams, truly sustainable solutions are expected to be local and diverse. For the short- to midterm future it is unlikely any 'one-fits-all' biofuel solutions will occur. As alternative fuel technologies mature and global and national policies develop, the maritime sector will have to learn how to navigate in more uncertainty.

> *"The emergence of large diversity of different solutions to reach IMOs GHG targets will already be visible in a few years" ... "The time where a fuel system lasts the life of a vessel is probably over. In the future you should expect to retrofit your vessel more often. What is needed is to prepare yourself by the outmost to be flexible."* (Niels Kjemtrup, Senior Technical Advisor, Research and Development, MAN Energy Solutions. At inaugural virtual ABS Sustainability Summit, 2020, Shaping maritime's future together, ABS).

Fuel flexibility is key strength in the adaption through the unclear transition towards sustainable shipping where the market for sustainable marine fuel technologies is small but has many different technological options.

9 Conclusions and outlook

In the past half-decade, the stringency of national and international emission regulations has pushed the marine sector into a crossway with multiple pathways with potentials to reduce emissions. Liquid and gaseous biofuel pathways contain capable and obvious short- to midterm solutions to bring the marine sector closer towards its target of net zero carbon intensity.

However, there is no “silver bullet”, with a vast number of available biofuel options each with minor or major barriers for their commercialization. To our knowledge, no major stakeholders is yet dedicated to any single future fuel option, and several strategies can be seen in the marked (as described throughout this report). Drop-in-fuels, one favored strategy, require close to no adaptation on engine and fuel systems, but is challenged by low supply and high production cost. Emerging biofuels such as biocrude, alcohols, emulsion fuels, and gaseous fuels are all able to be produced from sustainable sources and with low carbon intensity, however, they are all challenged by the lack of infrastructure and compatibility issues with the main part of the existing engines and fuel systems. A solution for shipowners, is to show more adaptability and flexibility to the changing fuel market by retrofitting their vessels with dual-fuel and multi-fuel engines designed to use a range of different types of fuels including alcohols, RNG and other low-flash fuels as well as traditional MGO.

In combination with changing regulations and emerging technologies, a complex and uncertain landscape is created for marine stakeholders to navigate in. Based on our literature study and the stakeholder interviews, this report has identified several barriers for the commercialization of biofuels for the marine sector. Most importantly are, *sustainability criteria*, *marine fuel standard incompatibility*, and, *economic incentive and the lack of targeted policies*.

Sustainability criteria

Sustainability criteria uncertainty relates to the changing regulatory framework defining fuel sustainability and the lack of an internationally recognized and utilized standards. Europa has especially been experiencing shifting legislations with the implementation of the RED I in 2009, following the ILUC Directive in 2015 which was updated in 2018 (RED II). The fluctuating sustainability criteria creates uncertainty on the development of future markets, thus obstructing the investment potential of sustainable fuel technologies. This tendency is further emphasized by the related change in public perception of what is considered sustainable.

In order to facilitate the big investments needed to be biofuel-ready (on engines, fueling, infrastructure etc.), long-term stability of policies and framework conditions are needed. This is especially true within sustainability criteria due to fluctuating framework conditions impose significant economic risks in a changing marked. Further, international agreements and uniformity within these criteria will help reduce risks and stabilize the development within the sector.

Marine fuel standard incompatibility

The ISO standard ensures comparison and evaluation of fuel quality, fuel engine compatibility, safety and price, thus facilitating the use, trade and production of fuels. The complexity of biofuels associated with the wide range of feedstocks and production processes makes it challenging to include it in the current ISO 8217/2017, and is thus a barrier that needs to be overcome. The recent IMO interim guidelines on using ethanol and methanol as marine fuels shows a path for alternative fuels and makes low-flash alcohol biofuels more attractive for shipowners. As the current production of ethanol and methanol from sustainable electricity is low, their production will likely be dominated by biomass sources until the 2030s-2040s. Biobased methanol or ethanol fuels could therefore be viable options for ship operators to reach the IMO 2030 emission targets. Some major stakeholders have initiated large R&D efforts in different biofuels, but not all players in the marine sector can be expected to follow their examples, and thus a general investment in R&D, trials in engine and fuel systems, and sea-going trials of emerging biofuel technologies are essential.

Economic incentive and the lack of targeted policies

As long as the overall costs ($US/MJ) of fossil energy sources remain cheaper than biobased alternatives, the transition towards a sustainable shipping sector will be slow, and the majority of the interviewed stakeholders identified the lack of more targeted policies such as a renewable fuel mandate, carbon taxation or subsidies directed towards biofuels, as essential to overcome the economical barrier.

However, opportunities do exists. E.g. with the introduction of the new low sulphur requirements there is now significant demand for low sulphur fuels (VLSFO, ULSFO, and MGO), which currently have prices at large oil hubs 25-50% higher than that of HFO, and significantly higher at bunkering facilities distant from the major hubs. This, combined with 1) the additional costs associated with carbon pricing at US$150-US$300 per ton of fossil fuel, and 2) the additional hedging cost savings by providing offtake in local currency at fixed offtake pricing, combines to provide a real opportunity for biofuels to be able to compete with the fossil alternatives.

There is clearly a need for international policies to take into account emissions from fuels burnt in international waters, and how to factor in the costs of these emissions should be established. An increase of freight prices following the current discussions on carbon equalization pricing covering the emissions associated with the transportation, could be an important tool towards achieving this. Lately we have seen many stakeholders across the value chain advocating for international carbon pricing. Policies that favor selection of contractors that use biofuels in their operations is another way to facilitate biofuel adoption.

A barrier for implementing biofuels for shipping industry is if the short-term investment costs needed to establish supply chains and infrastructure are expected to be absorbed by only a few stakeholder categories. The typical marginal business model of shipping companies makes it hard for these companies to absorb more than 10% higher fuel prices. As always, “first movers” will need to look for innovative ways to justify these higher costs. There is a need for legislation that promotes renewable technologies, where the required investment cost is shared among maritime stakeholders. In the same time, this legislation should provide long-term stability to mitigate the high risk of investing in biofuel capacity. Building such legislation on an international scale is bureaucratic and time consuming. Policies on a national and supranational level are easier to implement and are crucial to support local fuel demands. Policies at this level will also be better adapted to the local biomass availability and production capacity.

Finding an economic and sustainable fuel solution to substitute current marine fuel technologies is a complex task on multiple levels. The field is in a positive global movement towards a sustainable maritime sector, with intense research and development and with renewed political attention. This is creating a fast-paced environment with new research breakthroughs and changing policies. This is overall a positive movement, but it also creates a high-risk investment environment for deep-sea shipping companies. In the light of the large investment risks associated with biofuel technologies, technical as well as regulatory actions towards lowering these risks are in great demand to facilitate the ongoing transition towards a sustainable marine sector.

Despite the large potential of electrofuels to provide the maritime sector with low carbon intensive fuels, it is predicted to take at least a decade before the needed technologies are matured, and the capacity of low carbon electricity can cover a substantial part of the maritime fuel demands. A combination of energy efficiency improvements as well as gaseous and liquid biofuel pathways seem to be the quickest and most mature solutions to meet the IMO 2030 40% emission reduction targets. These pathways will also be an important part of the solution to reach the 70% emission reduction by 2050. The expansion of current biofuel technologies will initiate the required changes in supply chains, infrastructure and local solutions supported by international and local policies to push towards a marine sector with net zero carbon intensity.

Regardless of a widespread desire from various stakeholders in the marine sector to get more targeted and uniform international policies responding to the barriers for utilization of advanced biofuels in the marine sector (as identified in this report), it should be noted that many stakeholders are already showing great ambitions, enthusiasm, and climate-responsibility by being first movers in the field. The role of these initial actions towards transitioning the marine sector should not be underestimated, and many initiative have been seen in recent times.

The next important task is to accelerate the development by lowering the investment risks related to sustainable biofuels for marine propulsion. This will involve de-risking fuel pathways through continued R&D of potential pathways, development of appropriate standards, and enabling suitable policies.

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Appendices

Appendix 1- interview guide used in stakeholder interviews

- *How would you assess the long- and short-term potential of biofuels compared with other type of renewable fuels? (Biofuels defined as fuels based on biomass)?*

- *How many percentages of the global marine fuel market would you expect biofuels to cover in 2030 and 2050?*

- Is there any specific biofuel technology you find more promising than others (in the long/short term)?

- In your opinion, what are the most significant barriers to increase the use of biofuels in the maritime sector?

- Which changes do you think would help bringing biofuels into the market in commercial quantities?

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