Biofuels for the marine shipping sector

Front cover information panel

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Biofuels for the marine shipping sector

An overview and analysis of sector infrastructure, fuel technologies and regulations

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List of Abbreviations

ASTM .... American Society for Testing and Materials
BTL .... Biomass to Liquid
CNG .... compressed natural gas
CO_2 .... carbon dioxide
DME .... dimethyl ether
DWT .... dead weight tonnage
ECA .... Emission Control Area
EEDI .... Energy Efficiency Design Index
EEOI .... Energy Efficiency Operational Indicator
FAME .... Fatty Acid Methyl Ester
GHG .... greenhouse gases
GT .... gross tonnage
GTL .... Gas to Liquid
HEFA .... hydrotreated esters and fatty acids
HFO .... heavy fuel oil
HVO .... hydrotreated vegetable oil
IFO .... intermediate fuel oil
IMO .... International Maritime Organization
ISO .... International Organization for Standardization
LNG .... liquefied natural gas
LPG .... liquefied petroleum gas
LSHFO .... low sulphur heavy fuel oil (<1.5%)
MDO .... marine diesel oil
MEPC .... Maritime Environmental Protection Committee
MGO .... marine gas oil
NOx .... nitrogen oxides (NO and NO_2)
PM .... particulate matter
RED .... Renewable Energy Directive
SECNAV .... [United States] Secretary of the Navy
SEEMP .... Ship Energy Efficiency Management Plan
SOx .... sulphur oxide
TEU .... twenty-foot equivalent units
UCO .... used cooking oil
ULSFO .... Ultra Low Sulphur Fuel Oil (<0.1%)
VLSFO .... Very Low Sulphur Fuel Oil (0.1-0.5%)
WiDE .... water-in-diesel emulsion

Summary

The merchant shipping sector is one of the mayor players in world trade. More than 80% of all goods are transported via international shipping routes. The sector consumes more than 330 Mt of fuel a year and accounts for 2-3% of the global CO_2, 4-9% of SOx, and 10-15% of NOx emissions. This report is written for the biofuel provider and biofuel developer with the aim of providing an overview of the shipping sector, the technologies, fuels and regulations associated with its supply and consumption of fuels. The different biofuel technologies and their supply potentials are presented and discussed.

The shipping sector includes more than 85,000 registered vessels divided into small, medium, large and very large oceangoing ships. The two latter accounts for 20% of the vessels, but 80% of the gross tonnage. The majority of the shipping routes are connected by a relatively small number of ports in North America, Europe and Asia. Therefore a major part of the fuel supply and its infrastructure are concentrated at only a few locations.

Compared to road transport and aviation, the shipping sector uses much less refined or processed fuel types. Heavy fuel oil (HFO) is the main fuel used by oceangoing deep sea vessels, a fuel which is characterized by a very high viscosity and high sulphur level. More refined fuels are marine diesel oil (MDO) and Marine gas Oil (MGO), which has lower levels of viscosity and sulphur content. The latter mainly find applications in coastal waters and/or in smaller vessels operating in ports and inland waterways.

The main engines onboard the large and very large ships are 2-stroke diesel engines. These engines have a constant revolution as well as very high thermal efficiency (~60%) and often include state-of-the-art engine technologies. Associated with the engine is a fuel processing unit, heating the fuel and removing impurities prior to injection into the engine. Marine diesel engines can work with a wide range of fuels and are highly versatile.

Being international in its operation and organization, the maritime sector is regulated by the International Maritime Organization (IMO) under the UN. IMO handles issues regarding safety, security and pollution associated with international shipping. A major issue of pollution from shipping are the particles emitted due to the high levels of sulphur in the fuels. The IMO has put forward strict regulation of the fuel sulphur levels. Emission Control Areas (ECAs) have been set up in coastal waters in Europe, North America, and Asia. Within these areas only 0.1% low-sulphur fuels are allowed, and from 2020 ships sailing in non-ECA areas will need to use less than 0.5% sulphur in their fuel. If low sulphur fuels are not used, scrubbers needs to be installed in order to remove the SOx emissions.
These regulations means that an estimated 70% of the fuels currently used by the sector needs to be modified or changed. Greenhouse gas emissions, i.e. CO_2 are currently not regulated, but expectations are that regulation of CO_2 emissions will be implemented in the short to medium term.

The sector is currently looking at solving the issue of reducing sulphur levels by using more refined fuels, an operation done at the oil refinery. This will not only add an extra cost, but it will also increase the CO_2 emissions associated with the fuel as more refining will be required. The low sulphur fuels currently introduced are labelled Very low Sulphur Fuel Oil (VLSFO) having between 0.1 to 0.5% sulphur and Ultralow Sulphur Fuel Oil (ULSFO) having below 0.1% sulphur content. Another solution to reduced sulphur emissions is to use liquefied natural gas (LNG) as fuel, but this requires a refitting of the engines, just as pressurized fuel storage needs to be installed onboard. Other fuels such as methanol are used to a smaller degree with the latest generation of diesel engine technology, but are still at a supply infrastructure premature state.

Biofuels have very low sulphur levels and low CO_2 emissions, as such they are a technically viable solution to low-sulphur fuels meeting either the VLSFO or ULSFO requirements. The immediate

challenge is that the shipping sector has little knowledge on handling and applying biofuels as part of their fuel supply. Another challenge is that the volumes of biofuels required to supply the shipping sector are large. A single very large ship may consume the annual production from a single medium sized biofuel facility e.g. 100 mio. liters. The market entry for biofuels in the marine sector is therefore most favorable onboard smaller vessels for coastal waters or for use as auxiliary ultra-low sulphur fuel in ports. Of the current biofuels commercially available, only plant biodiesel derived from plant oil or pulping residues and bioethanol are produced at a level where they can supply significant volumes of fuel. The current renewable diesel type fuels are mainly produced from plant based oils or products thereof e.g. used cooking oil (UCO), and the potential supply of sustainable renewable diesel with the current technology is an estimated 10-20 Mt. Another issue is that the plant oil based fuels are the main fuel type currently used at a significant scale for bio jet fuels, leading to competition for feedstocks between the shipping and aviation sectors.

Bioethanol can be sustainably produced from waste and lignocellulosic feedstocks, with much higher supply potential, capable of replacing all fossil fuels in the shipping sector, but bioethanol is not compatible with current marine diesels, and cannot be used as a drop-in fuel. However, the development in engine technology has seen the introduction of multifuel engines. These engines can use oil, gas, as well as alcohols (e.g. methanol or ethanol) in a diesel cycle. Therefore, the use of ethanol may grow significantly in the medium to long term as ships with new engines are introduced.

The cost of biofuels is higher than the cost of fossil fuels and is expected to remain so in the short to medium term. Specific mandates on biofuels or carbon taxes will make biofuels economically more competitive. Alternatively low-carbon transport may be introduced as a business model, putting a value on lower CO_2 emissions.

In conclusion a combination of factors that include:

- New IMO regulations requiring reduced levels of sulphur in marine fuels
- Increased focus on reducing emissions of GHG from the marine sector from governments and customers of transportation services.
- A desire to be able to hedge the cost of fuels in local currency and away from fossil crude pricing
- The ability to “drop in” to existing fuel refining, blending and in some cases even the distribution infrastructure
- Potential regulations on CO_2 emissions from the merchant shipping sector

Together these factors create a potentially large market for biofuels in the shipping sector. From a biofuel producer point of view, the wide technical fuel specifications are attractive, as they can lower production costs. However, both technical and logistic issues needs to be resolved before biofuels can be introduced at a larger scale in the shipping sector, and a closer collaboration between biofuel producers, engine developers and ship owners is recommended as a path forward.

MERCHANT SHIPPING IN NUMBERS

Approx 80% of international trade, with >85,000 registered vessels

The industry consumes 330 Mt of marine fuel a year, of which 77% is heavy fuel

Accounts for 2-3% of global CO_2, 4-9% of SOx, and 10-15% of NOx emissions

Ocean-going merchant vessels

- Two-stroke diesel engines used for propulsion
- Storage capacity of 10-14 kilotonnes of fuel
- Consumes 200-250 tons of fuel per day
- Lower GHG emissions than road and aviation
- High SOx and NOx emissions

Fuel properties and costs (December 2016)

Properties	HFO Heavy Fuel Oil	MDO Marine Diesel Oil	LNG Liquefied Natural gas	FAME Fatty Acid Methyl Ester	HVO Hydrotreated Vegetable Oil	Ethanol	Methanol
Heating value(MJ/kg)	39	43	48	38	43	27	20
Sulphur (% m/m)	<3.5	2.0	0	0	0	0	0
Price (USD/Mt)	290	482	270	1040	542	503	464

Sulphur content of fuel permitted after 2020

Inside SOx ECAs: **0.10%**
Outside SOx ECAs: **0.50%**

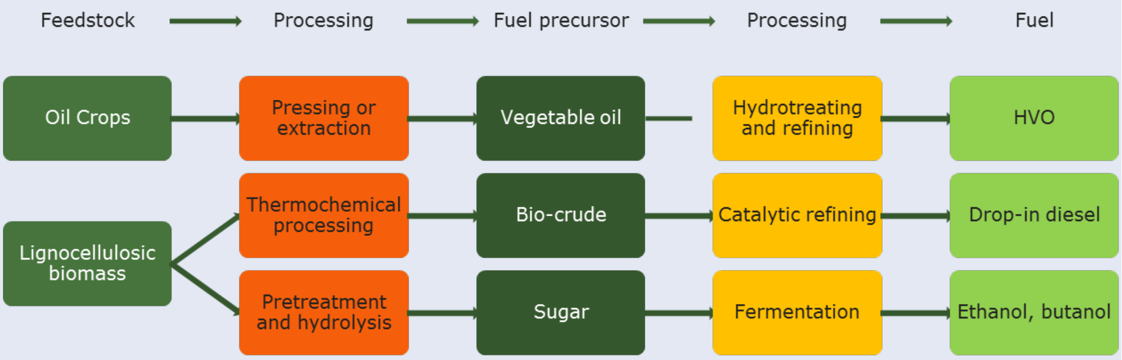
Regulations to reduce CO_2 emissions

No regulations yet. CO_2 monitoring for ships entering the EU to start 2018. Monitoring done on individual ship basis

Goals for reducing CO_2 emission

IMO and EU goal: 50% reduced CO_2 emissions by 2050. International agreement needed

Marine biofuel production technologies



Benefits of biofuels

-Feedstocks contain very little sulphur

-2nd generation lignocellulosic feedstocks potentially available in large quantities

-Drop-in fuels compatible with existing infrastructure

-Compliant with environmental emission regulations

-Potential synergy between multifuel engines and bioethanol

Future developments

-Develop feedstocks and technologies for commercial biofuel production

-Achieve sufficient biofuel production volumes for deep sea shipping

-Obtain long-term test data on diesel engines running on biofuels

-Update international fuel standards to take biofuels into account

1. Introduction and overview

The objective of this report is to provide an introduction and overview of the current maritime shipping sector and describe how biofuel developers can introduce alternative fuels, in light of the sector infrastructure and how it is regulated. To describe and analyze the potential of biofuels for the maritime sector, a technical assessment of biofuels for marine engines, taking into account the entire supply chain from field to ship, is performed.

This report is written from a biofuel developer or manufacturer point of view. The approach can be formulated as “If you were a biofuel developer and would like to develop marine biofuels, what fuel properties would be needed and how would they compete with current fuels given fuel prices and emission regulations?”

The report includes an overview of the current status of the shipping sector; the classes of ships built and in operation, the different marine propulsion technologies, and the fuels available on the market for ship propulsion. Of particular interest are current and near future regulations on the use of marine fuels in the newly created emission control areas (ECAs)[1], introducing mandates on fuel sulphur levels, as well as the fuel specifications needed in order to comply with these. These regulations, motivated by a need to reduce harmful particle emissions from marine diesels, are also an avenue by which biofuels can enter the market as low-carbon, low-sulphur fuels.

Shipping is not only about the transportation of goods and world trade, it also has an important role in the military and fishing industries. This report will focus on the merchant shipping sector, and only little attention will be paid to fishing and military vessels. As in other sectors, the low oil prices since 2014 has halted the demand for biofuels. However, the potential biofuel market and demand is expected to increase in the near future as regulations on sulphur, nitrogen oxides and particulate matter become stricter[2], as well as demands from brand owners intensify as they seek to differentiate their products. Greenhouse gas (GHG) emissions are not directly regulated, but higher energy efficiency and thus reduced emissions are part of the current regulatory scheme[2].

Marine fuels and engine technologies of the future will need to be low in sulphur, low in particle and NOx emissions from the combustion process, and to a large degree compatible with current fuel and engine infrastructures. For biofuels, a main parameter will be the sustainability of the feedstock, including issues on land use and preservation of the natural biodiversity. The cost of biofuels will be an important parameter in their use and introduction in the maritime sector, however, a number of regulatory issues and mandates may over-rule costs as the single most important parameter.

The current state of commercial production for marine biofuels is limited to almost only various forms of biodiesel or hydro treated vegetable oils (HVO). However, other biofuel production technologies from biomass are up-and-coming, with the potential of new biofuels compatible with marine propulsion engines.

Fuels for the shipping sector have different specifications than those for aviation and road transport sectors, and encompass a totally different supply chain[3]. In order to meet the demand and comply with the scale of marine fuel consumption, an expanded use of marine biofuels requires the production to be based on fuels from lignocellulosic feedstocks (2^{nd} generation) rather than e.g. oil crops. Given the concerns for lack of sustainability for oil crops, as well as their limited production potential, only fuels derived from lignocellulose feedstocks can provide a significant long term supply to fulfill current and future demands for shipping fuels. Other biofuel technologies e.g. algae-based are not at a technological level enabling long term projections of their supply potential.

Several companies and research institutes are working on both the production of marine biofuels, and testing of their compatibility with current infrastructure, of which the US Navy has been a major player[4]. As an initiative of the US Federal government, the US Navy developed a scheme to establish the Great Green Fleet in 2009[5]. The program was created to provide the Navy half of its fuel and power from clean, fossil-alternative sources by 2020, with biofuels having a significant portion of the alternative fuel mix in addition to solar, wind, and nuclear energy.

The production technologies for marine biofuels have been commercialized for feedstocks from plant oils, and animal fats. With minor retrofitting, the infrastructure required for refining these lipid feedstocks are already in place, and the production facilities are technically simple compared with other feedstock types.

At the time of writing, full-scale testing of lignocellulosic derived biofuels in marine diesel engines for deep sea vessels have not yet been conducted, in part because the production volumes required to run these engines have not been achieved. However, with tightening emissions regulations and a push towards using more sustainable feedstocks for fuel production, lignocellulosic-derived fuels can prove to be a solid business case for biofuel producers entering the marine biofuel market.

2. The shipping sector

Shipping is an essential part of our economy. By definition, it is part of the maritime industry encompassing watercraft carrying passengers or freight and it deals with the processes of transporting commodities, merchandise goods, and cargo by sea. Merchant shipping is responsible for 80% of international trade[6], with a carrying capacity of approximately 1200 million tonnes of freight worth approximately $7 trillion, and is therefore also known as the 'lifeblood of the world economy'. As a transport service the merchant shipping sector consumes more than 330 million tons of oil products every year.

The shipping sector has seen a general long-term trend of increase in total trade volume due to increasing industrialization and the liberalization of national economies over time. Since the late 19th century, new methods of propulsion and new ship designs have created a boom in ship building[7], along with increased efficiency in terms of speed and cargo volume.

Over the past decades, merchant shipping has risen along with the growth in world population, and thus the demand for traded goods. Additionally, global emerging economies will continue to increase their requirements for raw, intermediate, and finished goods as their standard of living increases, and these goods are commonly transported by sea. Shipping is the largest carrier of freight today and throughout human history, surpassing that of transport by land and air. Shipping is not only reliable, but is also the cheapest and most fuel efficient method of transport on a per tonne basis, and this is why the shipping sector is naturally expected to expand in the future.

Sea transport is generally regarded as energy efficient and environmentally friendly compared to road and air transport. While oceans cover 75% of the planet, little resources are consumed in transporting goods and fuel by shipping. In other words, it is a relatively low-energy mode of long distance transportation. Therefore, in terms of CO_2 emissions it is considered to be the least environmentally damaging form of commercial transport. However, with stronger global demand for goods and energy, emissions from the shipping sector need to take a center stage to allow for sustainable long term growth.

From an environmental perspective, shipping accounts for 2-3% of global CO_2 emissions, being the lowest emitter of CO_2 per tonne of cargo transported per km in the transportation industry[8]. On the other hand, shipping accounts for up to 4-9% of all sulphur oxide (SOx) and 10-15% of all nitrogen oxide (NOx) emissions. The sectors overall share of emissions is expected to increase significantly, if seaborne trade grows at the current rate without any modifications and maintaining the technical status quo.

As for other industrial trading sectors, shipping is susceptible to economic cycles. With a contraction of trade, demand for merchandise goods and commodities is also reduced. The overall driver of supply and demand within the shipping industry is freight rates. Shipping companies constantly aim to maintain or reduce freight cost levels. Contrary to popular belief, oil price fluctuations do not correlate with the general state of the shipping sector, though it does have an effect on shipping operations. When the price of oil is high, shipping companies tend to prolong transit times and reduce speed to save on fuel. Low oil prices are often beneficial to consumers, since they lead to lower freight rates; however, shipping companies often decrease operations and idle their vessels if revenues start to fall.

Even though merchant shipping is affected by economic cycles, the industry has overall grown exponentially in the last hundred years[9]. It is a dynamic industry, where ship managers and operators need to constantly adjust to changing market trends. Over the years, ships have been able to travel longer distances and increase in size to accommodate heavier loads of cargo. Marine engines have also been constantly redesigned to be more fuel efficient, and they represent in many ways state-of-the-art engine technology.

With globalization, new geographical concentrations of trade have sprung up, and existing ports have been redesigned to accommodate larger and more specialized ships. The shipping industry face competition from the air and road transportation industry, but differentiates itself from other modes of transport by being the most fuel- and cost-efficient form of transport.

Apart from the global market demand and supply for freight transport, the future development of the marine fuel market will also depend on: environmental and regulatory aspects, the availability of specified fuels for marine propulsion, and the costs associated with obtaining those fuels[10]. Current and future legislation will affect the types of fuel available in the market, and influence the types of propulsion systems developed to accommodate these fuels.

Merchant shipping is a global industry, but the industrial activity is concentrated mainly in the Northern hemisphere around a few shipping hotspots, including but not limited to: Western Europe, the Nordics, the North American east and west coast, and East Asia.

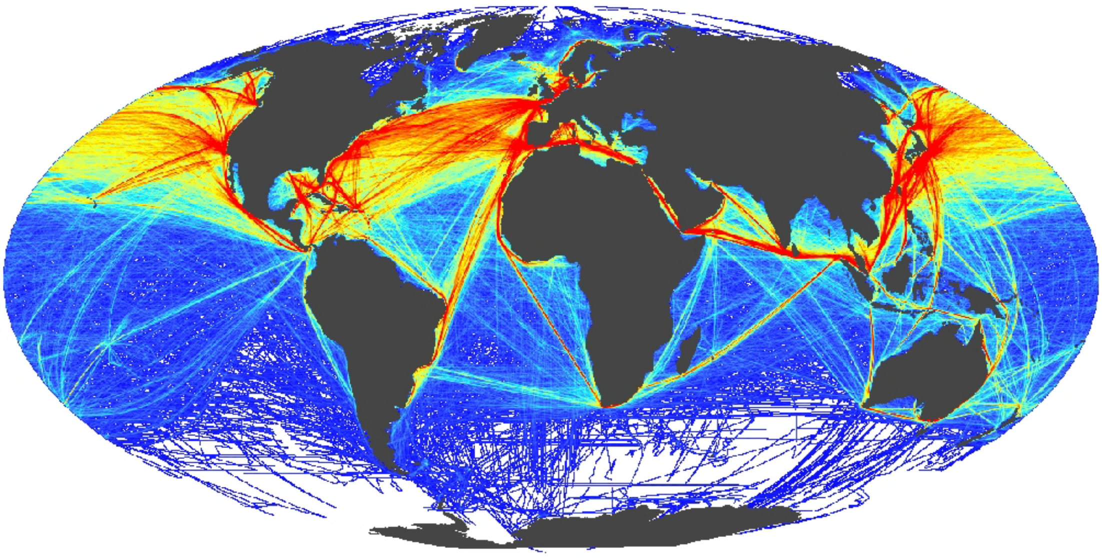


Figure 1. Merchant shipping routes around the world[11].

Since the introduction in the early 1900s of diesel engines on board ships, heavy fuel oil (HFO) also known as bunker fuel have been the fuel of choice in the shipping sector. However, the finite supply of crude oil and environmental regulations on air pollution have pressured the sector to look for alternative fuels, which are more benign to the marine and air environments and more sustainable for the industry in general[12–14]. Furthermore, there is also a strategic interest in decreasing the dependency on only one type of fuel. In this context, biofuels are potential marine fuels as they are produced from renewable feedstocks and are widespread in supply.

The most common commercially produced biofuels, bioethanol and biodiesel[15], have mostly been utilized in the road transportation sector. Contrary to biodiesel, bioethanol is not compatible with conventional marine diesel engines; however, as will be described, developments in marine engine technology may enable the future use of bioethanol in marine diesel engines.

The most convenient way to introduce marine biofuels in today's market is by drop-in biofuels compatible with fossil diesel fuels. There is also the possibility of blending biofuels with conventional marine diesel, though the quantities allowed for blending, as dictated by fuel standards, are at a level of 0.1 volume% for biodiesel in distillate diesel fuels[3]. In other words, for current fuel standards, biofuels are looked upon as a contamination in the fuel supply chain, regardless that the properties of blended diesel fuels are fully compatible with conventional fuels and the propulsion systems that use them. However, regardless of the tight standards for biofuel-diesel blends, these are not being viewed by the industry as a bottleneck for increased use of biofuels.

While electric vehicles have slowly become more prevalent in the road transportation sector, shipping and aviation cannot be electrified to any significant level and are likely to continue to be dependent on liquid or gaseous transportation fuels. Production of biofuels for the maritime sector is cheaper than biofuels for aviation, because the marine engines have more flexible fuel options, and do not require a high quality or a highly refined fuel to operate.

Due to the large volumes of fuel consumed by merchant shipping, and the emissions that diesel engines produce, international regulatory bodies such as the International Maritime Organization (IMO) has introduced regulations to limit the air pollutants produced by bunker-fuels. In 2005, emission control areas (ECA) were implemented in jurisdictions with high marine traffic in order to restrict the amount of sulphur oxides (SOx), nitrogen oxides (NOx), and particulate matter (PM) emitted by ships[16]. These regulations dictated merchant shipping to use cleaner, low sulphur diesel, where the requirements around coastal areas are stricter than in open sea. This had an impact not only on the fuels used by ship operators, but the efficiency of the ship engines as well. By 2020, these regulations will become even stricter amid concerns for cleaner air and building a more sustainable, environmentally-conscious future.

As the trade volume of merchant shipping is expected to increase in the following decades, so will CO_2 emissions if no action is taken to reduce carbon emissions now[10,17]. The shipping industry uses the term 'low carbon shipping' to describe more sustainable shipping practices to decrease carbon emissions by e.g. using low-carbon emission fuels and implementing energy efficient ship design and operation. Low carbon shipping entails all players in global shipping (port operations and logistics, ship owners and operators, ship architects and builders, policy makers) to assess the status quo of the shipping sector and explore the future possibility of achieving a cost-effective reduction of carbon emissions, as the merchant shipping sector is expected to increase its CO_2 emissions from 3% in 2007 to 18% in 2050 if no action is taken. Low carbon shipping is also part of the 'Sustainable Shipping' business model, where environmental concerns are taken into account in order to reap the long term benefits of decreasing emissions. Likewise the expression 'slow-steaming' covers the use of reduced speed in order to reduce fuel consumption.

The main driver for the introduction of marine biofuels in the first decades of the 21st century in the shipping sector will largely be regulatory. Stricter shipping fuel emission limits on sulphur oxides, nitrogen oxides, and probably greenhouse gases will make biomass an attractive feedstock for fuel production. Biomass contains little or no sulphur, and contributes with less CO_2 emissions compared to fossil fuels, as plants take up CO_2 during their growth offsetting the CO_2 produced when the biofuel is combusted. In the medium- to long-term, the use of marine biofuels also helps improve the environmental credentials of the merchant shipping industry, as more end-users are becoming environmentally conscious and places a commercial value on the origin of their products and how they are transported.

In response to the increasing regulation on emissions, fuel alternatives-mainly refined diesel oils and liquefied natural gas (LNG)[18]-have entered the market, but being fossil based they are only a partial solution to the emission challenges facing the maritime sector. Biofuels with their very low sulphur content and low CO_2 emissions are of increasing interest and relevance to the maritime sector.

2.1. SHIPPING VESSELS

With the increase in global trade, many technical, infrastructural, and operational changes have taken place in the shipping sector. Until a few decades ago, ships were commonly used as a transporter of people. With the rise of intercontinental air travel, however, sea travel has now been limited to shorter trips (ferry services) and recreational cruises. With merchant shipping dominating the shipping sector, oil tankers and bulk cargo ships outnumber other vessels in the merchant fleet. These vessels also transport the largest proportion of goods in terms of carrying capacity in dead weight tonnage (dwt).

The average size of ships has also increased substantially over the past decades. Larger vessels reduce shipping costs per load unit as well as operational costs and maintenance for the crew. They are also able to sail longer distances and transport larger volumes of cargo and fuel. Large vessels have also become more specialized, constructed or customized for different types of freight. Examples of specialized vessels include reefers (refrigerated cargo ships), roll-on/roll-off (ro-ro) ships designed to carry wheeled cargo (also known as vehicle carriers), and gas carriers designed to transport liquefied bulk chemical gases, especially LNG and LPG[19].

2.2. CLASSIFICATION OF SHIPPING VESSELS

Modern merchant ships can be placed in one of the following categories:

Table 1. Merchant shipping vessel classifications[20]

Vessel	Carrying capacity	% of merchant fleet		Purpose
		By tonnage	By number	
Dry bulk carriers	10,000 – 400,000 DWT	35	15	Transport unpacked bulk cargo (grains, coal, ore, etc.)
General cargo ships	20,000 – 550,000 DWT	6	21	Multi-purpose vessels transporting non-bulk cargo
Work and service vessels	Varies	4	19	Tug boats, offshore support vessels, harbour work craft
Tankers	10,000 – 550,000 DWT	20	14	Transport of fluids (crude oil, petroleum), also known as liquid bulk carriers
Container ships	3,000 – 19,000 TEU (approx. 50,000 – 160,000 DWT)	18	10	Transport non-bulk cargo in containers
Chemical tankers	3,000 – 42,000 DWT	6	10	Transport of bulk liquid and dry chemicals
Passenger ships	2,000 – 225,000 GT (approx. 1,000 – 25,000 DWT)	6	8	Ferries, cruise ships, roll-on/roll-off passenger ships
LNG tankers	500 – 300,000 DWT	5	3	Transport of LNG, also known as gas carriers

A vessel's carrying capacity is commonly measured in deadweight tonnage (DWT), defined as the mass a ship can safely carry, including cargo, fuel, provisions, passengers, and crew, but excluding the weight of the ship. The standard carrying capacity for container ships is measured by twenty-foot equivalent units (TEU). As an approximation, a container ship with a capacity of

50,000 TEU can carry around 3,000 40-foot containers. Passenger ships are conventionally measured by gross tonnage (GT) as an indicator of their size, which is a dimensionless figure calculated from the total enclosed volume of the vessel.

Small and medium sized ships make up the largest percentage of merchant fleet by number. Different ship sizes not only have different fuel consumption, but are also fitted with different engines, hence they use marine fuel with different specifications.

Table 2. Classification of merchant vessels by size[20]

Vessel	Size (GT)	% of world fleet	
		By total number	By gross tonnage
Small	100-499	37	1
Medium	500-24,999	44	19
Large	25,000-59,999	13	35
Very large	≥60,000	6	45

General cargo ships, oil and chemical tankers, as well as bulk carriers are the most common ship types by number, making up about 80% of the world's shipping fleet. Most of these are small and medium sized ships, used for short shipping distances. Large and very large ships are dominated by bulk carriers, tankers, and container ships, which are used to ship more than 85% of goods, fuel, and commodities. These are mostly utilized in intercontinental or deep sea shipping, and represent about 80% of the merchant fleet in terms of tonnage, accounting for 70% of the shipping industry's fuel demand.

Large vessels can also be divided in commercial vessels, pleasure craft, and military vessels, each with different fuel requirements and specifications. Pleasure crafts such as ferry cruises have higher energy demand for passengers on board than for propulsion, often demanding three times more fuel for day-to-day operations. Military vessels often operate with irregular fuel supply and demand, as fuel is provided under long-term voyages or short-term contracts. This report focus mainly on the fuel needs of commercial vessels, where marine fuel is used mainly for propulsion.

2.3. SHORT VS. DEEP SEA SHIPPING

Commercial vessels transporting cargo vary in size with the distance and places travelled. Cargo can be transported by either short sea shipping or deep sea shipping. Short sea shipping, which is also historically referred to as coastal shipping, involves the movement of cargo and passengers along a coast or on inland waterways. The short distance fleet consists of vessels small enough to travel on narrow waterways such as rivers and lakes, mainly carrying dry and wet bulk cargo. Cargo capacity ranges from 1,000 to 15,000 DWT, and accounts for roughly 40% of all freight moved in Europe, with fixed routes which could lend itself to consistent biofuel supply in the near-term. Mini-bulkers have a capacity of less than 10,000 DWT, but typically have an even lower range of 500-2500 DWT designed for river transport. Feeders, or small container ships, used for short sea shipping can carry up to 3,000 TEU, though most have an average capacity of 300 – 500 TEU. These operate by collecting shipping containers from ports, where they are subsequently loaded to larger container ships.

Ships used for deep sea shipping, on the other hand, have a much higher DWT capacity. Deep sea shipping is the maritime traffic crossing oceans. The industry is highly concentrated, where a small number of companies, mostly private, account for 95% of the industry revenue. Large companies have access to a large fleet size and specific port access, and most ships used for deep sea shipping are large or ultra large sized, carrying up to 70 days' worth of fuel in their storage tanks. Container ships, dry bulk carriers, and tankers dominate this segment. Tankers, for example, can travel 31-46,000 km without refueling (17-25,000 nautical miles; 1 nautical mile = 1.852 km). Large bunker ships have enough space to carry 10-14 kilotonnes of fuel.

2.4. SHIPPING ROUTES

For both short sea and deep sea shipping vessels, there are different shipping route services: liner, charter, and tanker service. Liner service refers to regular, scheduled stops along a fixed route. Liner routes are dominated by container ships transporting manufactured goods. The fuel supply for liners is available at fixed locations, where shipping companies have set contracts with marine fuel suppliers. Charter, or tramp, service has no fixed route, travelling wherever suitable cargo is available and needed. This segment is dominated by bulk carriers and passenger ships. Ship operators in this case have irregular fueling schedules at different ports, and have to deal with fuel supply and price uncertainty. Tanker service refers to the transport of crude oil, petroleum, and other liquid chemical products. This service is mainly managed, owned, and operated by major oil companies, who decide where, when, and how often tankers sail.

A small, yet important, segment of commercial shipping consists of support vessels. These are generally not used to carry any commercial cargo or passengers, but assist in port and ship operations. For example, harbour work crafts e.g. tug boats maneuver other vessels such as barges across rivers and lakes by pushing or towing them. Other vessels in this category include small carriers and specialized ships for training, research, fire-fighting, and patrol. With the exception of offshore support vessels, which are mainly associated with deep sea oil drilling, most support vessels operate in shallow coastal waters or around port areas, and are mainly small ships.

2.5. LIFE CYCLE OF SHIPPING VESSELS

A shipping vessel's life cycle starts at the drawing board, where the decision to build a ship is made by ship owners, operators, designers, and the designated shipyard. Depending on the ship size and specifications, construction of a ship can last between a few months to more than a decade. Large container ships, for example, are ordered three to four years in advance before they can begin operation. Ships also undergo constant maintenance, repair, and remodeling throughout their lifespan. In the current market, most commercial small and medium-sized ships are older than 25 years old, and can remain operational for even longer given proper maintenance. The current large and very large ships, however, are generally less than 5 years old, as the new technologies applied to build them are also quite recent, just as the demand for larger ships has increased only during the past decade. Very large bulk carriers, container ships, and tankers fall into this category.

The life cycle of a large deep-sea container ship requires an investment of at least 15 years, but can still be operational after 20-25 years, and in some cases for up to 40 years. Thus, given the long life span of a shipping vessel, shipping companies have to select marine engines that can run with a fuel that is compatible and easily accessible to their ships for a long period of time. Therefore, engine manufacturers play an important role in the introduction of new marine fuels to the market, as they provide the guarantee that their engines will run on fuels with specific properties. With the development of new technologies, ship owners can sometimes choose to retrofit their existing fleet to improve energy efficiency. Later, at the end of a ship's operational cycle, vessels gets scrapped or recycled for parts. Scrapping is common for ships more than 40 years old. Current IMO[21] and EU[22] environmental regulations require ships to be designed in such a way, that once it nears its end-of-term, it can be disassembled or disposed of easily thereby reducing the waste to a minimum.

3. Marine propulsion technology

Modern ships are propelled by mechanical systems consisting of an electric motor or engine turning a propeller. The first mechanical engines used in marine propulsion were steam engines i.e. external combustion engines powered by steam, derived from heating sources such as wood or coal. At the beginning of the 20th century, the use of steam engines began to decline in favor of using steam turbines, as they raised the power-to-weight ratio. At the same time, the British Royal Navy introduced diesel engines and the commercial ship operators soon followed and started to utilize fuel oil instead of coal. By the mid-20th century, new ships were almost only built with diesel engines. The only ships built with steam turbines today are military vessels or specialized vessels such as LNG carriers, in which the cargo can serve a second purpose as fuel.

Modern merchant ships, regardless of size, are propelled by two-stroke or four-stroke diesel engines. Petrol or gas-fired engines are also available, but are more commonly used to propel smaller vessels. LNG fueled engines are slowly gaining more use for their lower CO_2 and sulphur emissions, but are still a small segment of the merchant fleet (see table 1).

Table 3. Common types of marine engines and their fuel compatibility. HFO: Heavy fuel oil, MDO: Marine diesel oil, LSHFO: Low Sulphur Heavy Fuel Oil, LNG: Liquefied Natural Gas

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

With tightening emissions regulations and rising fuel prices, engine manufacturer MAN Diesel & Turbo unveiled a 2-stroke dual fuel gas injection (GI) marine engine capable of operating on either HFO or natural gas in 2011. This engine gives ship operators the advantage of using either fuel depending on price and availability without compromising performance. Additionally, in 2013 MAN Diesel & Turbo started to develop a 2-stroke dual fuel liquid gas injection (LGI) marine engine capable of operating on methanol, ethanol, LPG, and DME (low flashpoint liquid fuels) together with heavy fuel oil, marine diesel oil, or marine gas oil (see paragraph 4.2). These flexible dual fuel LGI engines were launched in seven oil tankers in 2016, with the aim of providing clean-burning, ocean-going merchant vessels compliant with stricter environmental emissions regulations[23].

The type of engine used on the ship determines which type of fuel that is compatible. Thus, the guaranteed availability of a marine fuel for the lifetime of the engine (up to 40 years) is the determinant factor in deciding which type of engine will be installed on a ship. Over the years, marine engines have been continually improved to be more fuel efficient, consuming less fuel for propulsion, and diesel engines remain the engine technology of choice for the majority of shipping vessels.

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 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 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 two-stroke and four-stroke versions. The 2-stroke diesel engine and 1 propeller with waste heat recovery is the most common setup for merchant shipping vessels. Two-stroke engines, however, are larger in size and of considerable height compared to 4-stroke engines, and are better suited to large and very large sized ships. Smaller ships tend to have low-medium speed engines operating on MDO/MGO fuel, as HFO would be too viscous for this type of engine.

The advantage of using large and heavy diesel engines, is that they offer a wide range of powers and operate with very high thermal efficiency. 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. An additional waste heat recovery system further increases the energy efficiency of the vessel.

Larger ships have heating chambers as part of the fuel injection and can tolerate high viscosity fuels. As long distance deep sea shipping is gaining popularity, shipping vessels are built 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 a wide range of fuel viscosities. This possesses a significant advantage for marine fuels, as the fuel quality, in terms of uniform or specific physical and chemical properties, need not be high. In other words, marine diesel engines are relatively insensitive to fuel quality, as they can operate with both light and heavy fuel fractions. This also means, however, that diesel engines produce exhaust with a high amount of pollutants given that they mainly operate on high-sulphur residual fractions from oil refineries, to keep the ship operating costs low. This practice has thus led the international organizations regulating the maritime sector to create stricter environmental regulations concerning the type of fuel that is permitted for shipping. This will be covered in the 'Marine fuel regulations' section of this report.

Marine Engine Technology. Wärtsilä (Finland) is a publicly traded marine engine and power equipment manufacturer founded in 1834. The company produces marine propulsion systems, power plant energy generators, and engineering/maintenance services supporting these areas. Of the marine market, Wärtsilä produces a range of low- and medium-speed diesel, gas, and dual fuel engines as well as scrubbers. Their dual fuel engine systems allow very high fuel flexibility, as they are able to run on natural gas, marine diesel oil, heavy fuel oil, and biofuels. The company also offers retrofitting services for its customers. The company currently only produces 4-stroke marine diesel engines, and has developed LNG fuel propulsion systems.

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. 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.

Table 4. Types of diesel engines according to speed

Speed	RPM	Engine
Slow	Up to 300	Two-stroke
Medium	300-900	Four-stroke
High	Above 900	Four-stroke

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 are the most fuel efficient on the market, but produce higher amounts of NOx 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, or 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 which operate at varying speed and load, for example 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 with time, while the former is based upon hull, engine and propeller design

Marine Engine Technology. MAN Diesel & Turbo SE is a German multinational diesel engine and turbine producer for marine and stationary applications. MAN Diesel & Turbo is a subsidiary of the German MAN SE corporation, founded in 1758. Their marine propulsion systems include 2-stroke and 4-stroke engines, auxiliary engines, gas turbines, steam turbines, and propellers.

MAN Diesel & Turbo is a leading designer and manufacturer of low and medium speed diesel engines, and have also run tests on new liquid-gas-injection engines for installation on methanol carriers. Their range of marine engines can be used to propel all types of merchant shipping vessels, from container ships to cruise liners and specialized vessels such as tugs and dredgers.

Recent developments within fuel technology in merchant shipping include the new Mitsui OSK Lines, fitted with MAN marine engines, which can switch over to methanol from HFO from 50% to 75% before switching back to HFO, thus being able to operate on low-flashpoint fuels (methanol and LPG)[24].

CASE STUDY: Transit times from the EU to US takes on average 10-12 days, covering 6,400 km travelling at 24 to 32 km per hour. Large ships use about 140-150 tons of fuel a day, while ultra large vessels can consume between 200-250 tons a day. The world's largest container ships consume approx. 16 tons of fuel per hour (380 tons per day). Due to periods of high crude oil prices over the past decade, shipping companies have adopted the practice of slow steaming, where they operate container ships at lower speed in order to save on fuel. This is mostly applied to long distance transoceanic routes, adding an additional week's sailing time between Asia and Europe or trans-Pacific voyages. Most container ships are designed to travel at 24 knots, where normal, optimal cruising speed is between 20-25 knots, or 37-46 km/h. Slow steaming engines run at 18-20 knots, or 33-37 km/h. Extra slow steaming is between 15-18 knots, or 28-33 km/h.

Slow steaming was first adopted by Mærsk Line in 2009 to reduce fuel consumption on their container ships, though it also meant that goods would take longer to arrive at port. By 2010, nearly all global shipping lines were using slow steaming to save on fuel costs. By reducing the speed from 27 to 18 knots, fuel consumption can be reduced by as much as 59% reducing both costs and emissions simultaneously. As a result, shipping companies such as Mærsk have commissioned a line of container ships (Triple E class) where the ship engine and propeller have been designed to operate optimally at lower RPM with less powerful engines than its predecessors.

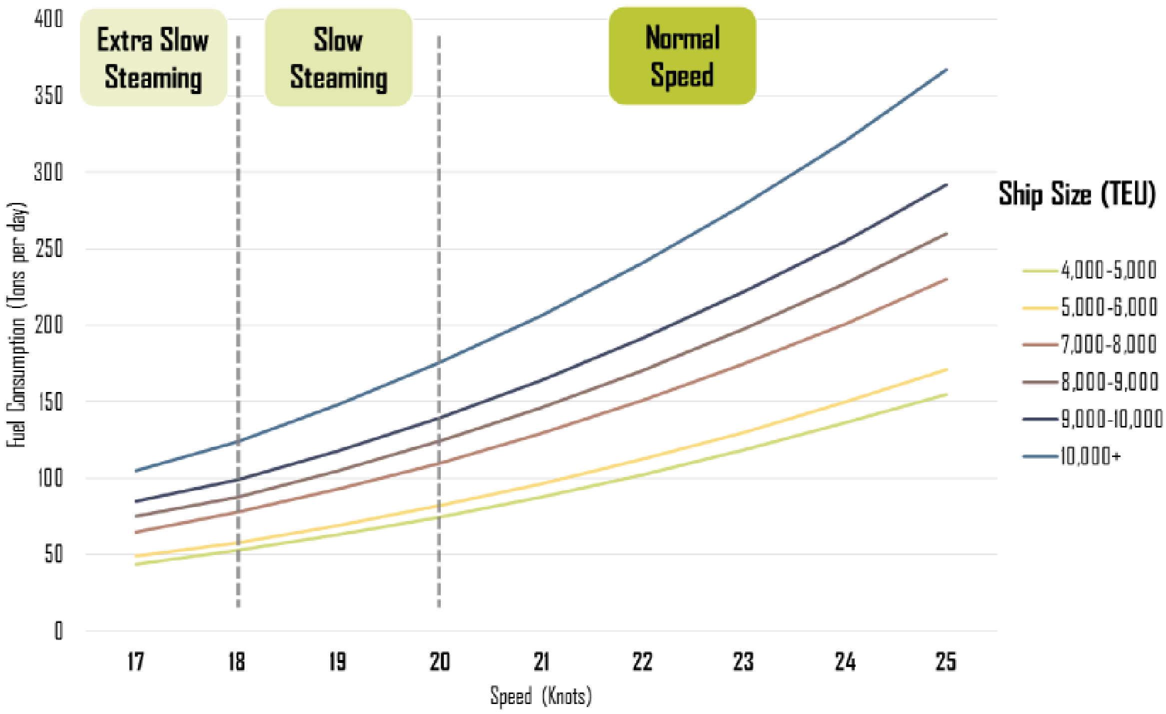


Figure 2. Container ship fuel consumption as a function of speed[25]

3.2. MULTIFUEL ENGINES

Marine diesel engines include some of the most advanced engine technologies, with very high compression ratios and advanced control systems. The latest generation engines includes multifuel engines. These engines have a fuel injection system, which allows to inject the fuel at very high pressure/heat. Thereby fuels with low cetane numbers e.g. below 10 can be used in a diesel engine cycle. This allows for both gaseous fuels like LNG and liquid fuels such as methanol and ethanol to be used in a marine diesel engine.

One example of such engines are the MAN B&W ME-LGI series, which can run on both conventional diesel fuels as well as the volatile low cetane fuels methanol and ethanol. The engines can within a single stroke switch from one fuel type to the other thereby giving full flexibility for the choice of fuel[26].

A practical issue when using methanol and ethanol fuels is their low flash points of 12 and 14 deg. C, as compared to diesel MFO of 52 deg. C. These low flashpoints are not compatible with the Safety of Life at Sea (SOLAS) regulation without a double barrier design for all components associated with the methanol and ethanol. For the MAN B&W ME-LGI engines this double barrier is furthermore ventilated. Compared to handling and of a fuels such as LNG which needs pressurized storage, methanol and ethanol are easier to handle and store in the fuel tanks onboard the ship.

The multifuel engines are the latest type of advanced diesel engines. Both the existing vessels and a major part of the vessels to be built in the short to medium term, will not be using these engine types. Some of the engines may be refitted, but in many cases this will most likely not be economically attractive. Thus, regardless that the engine technology is available, it will not allow for e.g. methanol and ethanol to become a significant part of the fuel supply in the short term, but it can provide opportunities for expanding the use of especially bioethanol.

3.3. PETROL, GAS AND ELECTRIC ENGINES

Petrol engines are mainly found in smaller ships, and are compatible with gasoline, ethanol, methanol, and gaseous fuels. Spark plug ignition engines rely on the spark plug to ignite an air-fuel mixture, which then starts the combustion process. Petrol engines can operate at higher speeds than diesel engines, partially due to lighter pistons, connecting rods, and crankshaft, as well as the fact that petrol combusts faster than diesel. The lower compression ratio of petrol engines (1:11), however, gives these engines a lower thermal efficiency than diesel engines.

LNG engines are typically dual LNG/diesel engines and are mainly used onboard LNG tankers. Dedicated gas engines are produced by e.g. Rolls-Royce (UK) in partnership with Bergen Marine (Norway) and they deliver gas engines certified to power passenger ferries, short sea shipment vessels, tugs, and offshore supply vessels running on LNG[27].

Bulk carriers and container ships are generally powered by diesel engines fueled by the cheapest fuel oil to ship goods and merchandise at the lowest cost. The most fuel efficient engines require less fuel storage and thus save cargo space.

With the advancement of battery technology, ships have also started to run on electric power from the grid for ship operations in ports[14] as well as for propulsion generated by on-board diesel generators. 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.

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. 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 onboard compared to liquid fuels decreases the area available for freight, thus restricting their acceptance in the merchant shipping sector.

3.4. THE FUEL OIL SYSTEM

The increasing market demand for distillate fuels (gasoline, diesel) and changes in refinery processes to fulfill this demand has led to a deterioration of heavy fuel quality. Oil reserves have become heavier and sourer, while light and sweet (low-sulphur) products are in higher demand, mainly from the aviation industry.

Many large shipping vessels have been redesigned to have fuel treatment facilities on board (see figure 3). Fuel circulation from the onboard storage tank to the engine involves many steps before it can be introduced in the main engine. A two-stroke diesel engine is usually designed to operate continuously on heavy fuel. The fuel is stored in tanks, from which it is pumped to a settling tank and heated. The fuel is centrifuged to filter out particulate matter, after which the cleaned heated oil is pumped to a daily service tank. The centrifuges are also known as purifiers. From the daily service tank, the oil flows through a 3-way valve to a mixing tank. Booster pumps are used to pump oil through heaters and fuel pumps. The fuel pumps will discharge high pressure fuel to their respective injectors. Before injection, a viscosity regulator will control the fuel oil temperature to provide the correct viscosity for combustion. A pressure regulating valve ensures a steady pressure supply to the engine-driven pumps, and a pre-heating bypass is used to heat up the fuel before starting the engine.

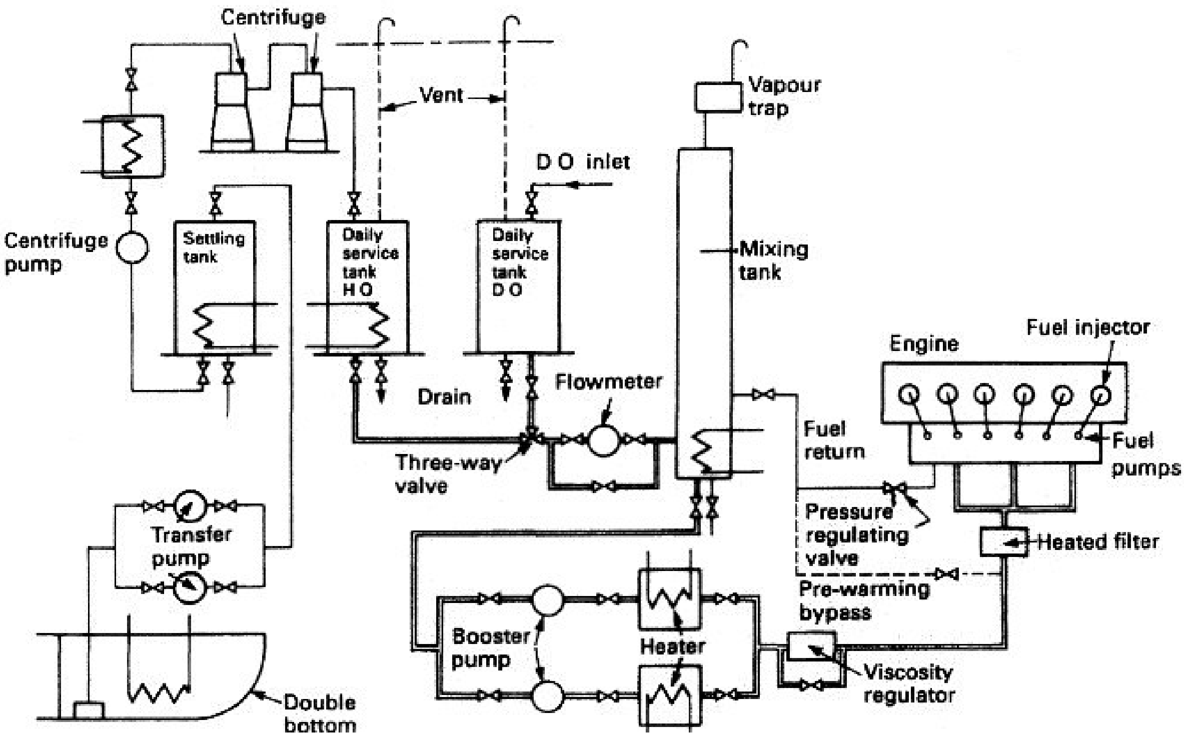


Figure 3. Fuel oil system for a two-stroke marine diesel engine[28].

4. Current marine fuels

The most common marine fuels are heavy fuel oil (HFO) and marine diesel oil (MDO) produced from crude oil at refineries. As described, these fuels usually have lower quality, and thus lower cost, compared to other transportation fuels for road and air. The marine fuels are derived from the heavier distillates of petroleum refineries, containing very long carbon chains and little or no aromatic components.

Other diesel fuels which are used, but only to a small extent includes; SVO (straight vegetable oil), DME (dimethyl ether), GTL (gas-to-liquid), BTL (biomass-to-liquid), biodiesel/FAME (fatty acid methyl ester), and HVO/HEFA (hydrotreated vegetable oils/hydrotreated esters and fatty acids).

4.1. MARINE FUEL STANDARDS AND CLASSIFICATIONS

The International Organization for Standardization (ISO) has implemented standard 8217 in 1987 for refined marine fuels, which was last updated in 2010. ISO 8217 define the requirements of petroleum fuels use in marine diesel engines and boilers, to ensure reliable engine operation with fuel from refining processes. These guidelines are also used by marine engine suppliers and purchasers of marine fuels, and are updated regularly to accommodate changes in engine technology, crude oil refining processes, and environmental regulations. Note that as described below, ISO 8217 has its own nomenclature for the different fuel types.

There are generally two types of marine fuels: (1) distillate and (2) residual fuels. Fuel grades are designated by codes, consisting of a group of letters: the initials ISO, F (for the class of fuel), D or R (distillate or residual), M for marine, and a letter from A to Z that has no particular significance, but is related to the particular properties of certain product specifications, ending with a number corresponding to the maximum kinematic viscosity of the residual fuel. For example, marine residual fuel can be designated ISO-F-RMG 380, or RMG 380 for short.

Petroleum distillate fuels include marine gas oil (MGO) and marine diesel oil (MDO). MGO, classified internationally as DMA, is a light gas oil that contains about 60% aromatics and has low sulphur content (<0.10 to 1.50% m/m – that is, per cent mass of sulphur per mass of fuel). This fuel is used in diesel engines with frequent and widely varying speeds and loads, and most commonly utilized in small and medium sized ships powered by 4-stroke diesel engines. A new grade of MGO was introduced in 2010, DMZ, and is identical to DMA, with a higher minimum viscosity than DMA. A low-sulphur version of MGO, known as LSMGO, contains less than 0.1% sulphur and is to be used in EU community ports and anchorages (emission controlled areas). An ultra-low sulphur MGO is also available in the market, with a maximum sulphur content of 0.0015% (in US) or 0.001% (in EU), which is the limit allowed for EU inland use.

MDO marine diesel oil, or DMB, mainly referred to as diesel, is a specific fractional distillate of petroleum, composed of lighter distillate fractions than residual oil and has low sulphur content (0.3 to 2.0 m/m %). Diesel contains C10-C22 hydrocarbons with a 25% aromatic content. It typically has a lower cetane index than MGO, and has a higher density. It is a blended heavy gasoil with a low viscosity of less than 12 Centistokes. Diesel oil can also act as a lubricant and is less harmful to the oil film on piston rings and cylinder bores, reducing engine maintenance time. MDO and MGO are typically used in smaller vessels with medium and high speed 4-stroke diesel engines. It is typically used in applications with relatively high loads and uniform speeds. An ultra-low sulphur diesel (ULSD) version is available with a maximum of 0.0015%, or 15 ppm sulphur.

Residual fuels are a marine fuel, available with low and high sulphur content and a range of different viscosities. As the name implies, residual fuels are produced from the residue of the refining process. These heavy fuels tend to have high viscosity, requiring heating before use, and are most commonly used in large and very large shipping vessels.

Table 5. ISO distillate marine fuel specifications[3]

Specification	Unit	Limit	DMA	DMZ	DMB
Kinematic viscosity	Centistoke	Max	6.0	6.0	11.0
		Min	2.00	3.00	2.00
Density at 15°C	Kg/m^3	Max	890	890	900
Cetane number		Min	40	40	35
Sulphur	Mass %	Max	1.5	1.5	2.0
Flash point	°C	Min	60	60	60
Acid number	Mg KOH/g	Max	0.5	0.5	0.5
Total sediments	Mass %	Max	-	-	0.10
Oxygen stability	g/m^3	Max	25	25	25
Cloud point	°C	Max	n/a	n/a	n/a
Lubricity	µm	Max	520	520	520
Pour point	°C	Max	-6 to 0	-6 to 0	0 to 6
Water	Volume %	Max	n/a	n/a	0.30
Ash	Mass%	Max	0.10	0.10	0.10

To produce residual fuels to a desired viscosity, the high-viscosity fractions can undergo secondary refining techniques, such as thermal and catalytic cracking. Thermal cracking uses a technique called 'visbreaking' to crack large hydrocarbons in the oil and produce lighter hydrocarbons. This reduces the viscosity of the fuel and increases the energy density and carbon content, but culminates in a lower quality residue and lower ignition quality. Catalytic cracking, which is more popular than thermal cracking, uses catalysts (aluminum silicates being the most common) to refine heavy oil fractions to more valuable oil fractions. The residues from the cracking process, which tends to be highly aromatic and of poor ignition quality, can later be blended with the final residual fuel oil. Due to their low cost, residual fuels power most large merchant vessels, often containing higher amounts of sulphur than regular diesel.

There are different types of residual fuels, including light fuel oil (LFO) and heavy fuel oil (HFO). LFO is of lower viscosity and density than HFO. LFO is classified ISO-F-RMA through RMD. HFO, also known as heavy diesel oil (HDO) or marine fuel oil (MFO), is classified ISO-F-RME through RMK, and is the most common marine fuel, taking up about 47-66% of the marine fuel mix. It is derived from heavier distillates of refineries containing very long carbon chains and low or no phenolics. There are different grades (viscosities) of residual fuel, of which 380 and 180 centistoke at 50°C are the most common. HFO with 380 centistoke, which is colloquially referred to as bunker fuel, needs to be heated before fueling and use. HFO is used in combustion equipment on ships, including the main engine, auxiliary engines, and boilers. A low-sulphur version of HFO, LSHFO (low sulphur heavy fuel oil) contains less than 1.5% sulphur, and is also available in low (180 Centistoke) or high (380 Centistoke) viscosity. LSHFO has a common transfer and purification system as HFO, but is stored in separate tanks and has a separate supply pipe in the fuel supply system to the engine/boiler. Ultra low sulphur fuel oil (ULSFO) available in the market contains less than 0.1% sulphur. For both low-sulphur fuel types, the pricing is considerably higher than HFO.

Intermediate fuel oil (IFO) is a blend of both refinery distillate MGO and residual fuel, with less gasoil than MDO. It is a 'middle distillate' petroleum fraction, combining heavy and light crude fractions to a specified viscosity, most commonly available with a maximum of 180 or 380 Centistokes. IFOs have good ignition characteristics due to the high percentage of paraffinic material present, and are commonly used in low speed 2-stroke engines. Residual fuel can also be used to operate gas turbines, but fuel specification requirements before injection are very strict, and subject to thorough fuel pre-cleaning, including removal of alkali metals.

ISO 8217 specifies the following criteria for residual fuels, as shown in Table 6, of which the limits on density, kinematic viscosity at 50°C, and flash point are of most importance for engine compatibility.

Table 6. ISO residual marine fuel specifications[3]

Specification	Unit	Limit	RMA 10	RMG 180	RMG 380
Kinematic viscosity	Centistoke	Max	10	180	380
Density at 15°C	Kg/m^3	Max	920	991	991
Sulphur	Mass %	Max	3.5%, or statutory requirement in SECAs		
Flash point	°C	Min	60	60	60
Acid number	mg KOH/g	Max	2.5	2.5	2.5
Total sediments	Mass %	Max	0.10	0.10	0.10
Pour point	°C	Max	0 to 6	30	30
Water	Volume %	Max	0.30	0.50	0.50
Ash	Mass %	Max	0.040	0.100	0.100
Vanadium	mg/kg	Max	50	350	350
Sodium	mg/kg	Max	50	100	100
Aluminum + silicon	mg/kg	Max	25	60	60

4.2. PROPERTIES OF MARINE FUELS

- The thermal efficiency of a fuel is determined by its **kinematic viscosity**, specific density at 15°C, and flash point. Kinematic viscosity is measured in centistoke, where 1 cSt = 1 mm^2/s, at 40°C for distillate fuels, and at 50°C for residual fuels.
- The **specific density** of a fuel is measured in kg per cubic meter at 15°C. It serves as an indicator of the ignition quality of the fuel, particularly for low-viscosity residual fuels. It is also important for purifier operation.
- The **flash point** is the lowest temperature at which a volatile material can vaporize to form an ignitable mixture in air, and is a measure of a fuel's flammability. Standards indicate it should be at least 60°C for all marine fuels in order to be considered combustible, and not flammable. Ideally, diesel should have a high flash point and low auto-ignition temperature.
- **Cetane index** is only applicable to gasoil and distillate fuels. It is a measure of the ignition quality of the fuel in a diesel engine, and the cetane number is based on the density and the distillation of the fuel. The higher the rpm of the engine, the higher cetane index required.
- **Acid number**: all fuels have an acid number based on the concentration of acidic compounds in the fuel. Fuels with high acid numbers contain acidic compounds which can damage large diesel engines, especially the fuel injection equipment.
- **Total sediments or particulate matter (PM)** can be removed by centrifuging and filtering systems, but fines can affect the engine lubrication and piping systems.
- **Cloud point** is the temperature at which dissolved solids are no longer soluble and precipitate in solution forming a second phase, giving the fluid a cloudy appearance.
- **Pour point** is the highest temperature at which the liquid can become a semi-solid or gel and is unable to flow. This marks the limit at which the fuel can be pumped.

- **Sulphur**: High sulphur content is not damaging to the diesel engine, but the fuels generally need to have low sulphur because high sulphur content (>3%) has a corrosive effect on heating systems, shortening their lifespans and increases polluting effects. Sulphur in the fuel, once it is burned, is converted to sulphur oxides which have damaging consequences for the environment, especially air pollution.
- **Water** in the fuel affects the cloud point, pour point, and fuel storage stability, which in turn may damage engine fuel system components. It is considered a fuel contaminant as it has no energy content, and thus translating to energy loss for the fuel purchaser. Many ships have on-board water removal systems by centrifugation.
- The **ash content** is a measure of metals present in the fuel, which can be inherent to the fuel or a contaminant.
- The most common method of producing marine fuels in refineries is by catalytic cracking. Heterogeneous catalysts used in the refining process can leave fines, leaving traces of **aluminum silicate**[29] in the fuel product which can damage engine, thus they have a maximum limit in mg/kg to avoid abrasive damage in the fuel system. Fuel pre-cleaning onboard can adequately remove about 80% of catalytic fines. However, in order to avoid abrasive wear of fuel pumps, injectors, and cylinder liners, a maximum limit for aluminum + silicon fines has been set.
- The use of **used lubricating oils** (ULO) is not allowed in residual fuels. A fuel is considered to contain ULO if the calcium level exceeds 30 mg/kg and zinc or phosphorus content exceeds 15 mg/kg.

Another important parameter for a marine fuel is its **stability**. As bunker fuels are kept in storage tanks, they need to be stable over a period of minimally 3 months. They also need to be stable at elevated temperatures and/or pressures, as the fuel is re-circulated through an engine's fuel system. Fuel storage degradation involves the formation of small particulate matter which can clog filters. Both diesel engines and gas turbines are susceptible to damage if unstable fuel particles are present past the ship's filtration system, causing fuel injection pumps to stick and injection nozzles to coke and clog. As fuel ages, it can also oxidize over time, leading to higher acid numbers which can damage fuel tanks, or to the formation of gums, particulates, and sediments that clog filters. High storage temperatures can also accelerate fuel degradation. Thus, fuel needs to be stored in a clean, dry, and dark environment.

4.3. LIQUEFIED NATURAL GAS

LNG (liquefied natural gas) logically has different standards and fuel specifications than distillate and residual marine fuels. LNG as a fuel is more commonly used in specialized chemical/product tankers, of which have been built since 2010, and comprises about 31% of their fuel mix. LNG is predominantly methane that has been converted from a gas to liquid form to facilitate storage and transport. It takes up a lower volume than compressed natural gas (CNG), thus increasing its energy density, but on a volume basis it is still 60% that of diesel. Special cryogenic storage vessels have been designed to keep LNG at -162°C. By definition, LNG needs to contain at least 90% methane gas and needs to be treated to remove impurities (water, H_2S, CO_2) before storage at low temperature.

A few small ships have also been recently built with LNG engines, and were introduced on the marine market since 2010, but do not appear to be in high demand nor present in considerable numbers for the near term future. LPG (liquefied petroleum gas) can be an alternative fuel to LNG, since it has a higher calorific value and can run on the same engines as those used for LNG. It is a mixture of hydrocarbon gases, mostly propane and butane. However, it is not commonly used as a marine fuel, but rather as a heating fuel.

Qatar is the world's largest exporter of LNG, providing approximately one third of the global supply. Over the years, more countries have started LNG production, and in 2014, a total of nineteen countries exported LNG. The Asia Pacific region (Japan, South Korea, China, India, and Taiwan) consumes about 60% of the total LNG production[18], however, only a small fraction 3-5% of LNG is used as a transportation fuel, as the main applications are for residential and commercial heating and electric power generation[30].

From an emissions perspective, LNG is a suitable fuel for low carbon shipping due to lower CO_2 emissions than distillate and residual fuels as well as the elimination of SOx and PM emissions[31]. Some analysts predict that LNG will become higher in demand, as it contains very little sulphur and can hold more energy per tonne than MDO. However, LNG and associated methane gas leaks do not contribute to solving the fossil fuel dependency nor the climate change related issues. The cryogenic storage vessels designed to transport and store LNG on board take up higher DWT than the conventional heavy fuel storage tanks, and require additional separate safety features. As LNG is also a relatively new marine fuel, access to fueling stations is still limited, and there are also needs for proper LNG storage facilities at ports to facilitate use of this technology. Ships running on LNG fuel also have higher capital cost for the system installation, and thus not a practical fuel for conventional low-cost shipping.

4.4. OTHER FUELS

Spark-ignition engines use different fuels than diesel engines. These fuels include gasoline, ethanol, methanol, natural gas (LNG and CNG), biogas / biomethane, and hydrogen gas. In contrast to diesel, the petrol used in spark ignition engines should have a lower flash point and higher auto-ignition temperature.

Other alternative fuels to diesel and LNG such as dimethyl ether (DME) and water-in-diesel emulsions (WiDE) have also been explored, but are not yet produced at large scale or traded on the commodity market. DME can be applied as a drop-in fuel for diesel engines. It is produced from either methanol or syngas, but there is not yet any commercial biofuel production for shipping vessels, as there is low production capacity and the transport infrastructure is insufficient. DME is a gas at ambient temperatures and as a fuel has so far only been tested on small engines, and its suitability for large engines is still yet to be determined. DME is commonly considered for heavy road transportation.

Water-in-diesel (WiDE) emulsion fuels can be used as a drop-in fuel, compatible with existing diesel engine setup with no additional engine retrofitting. Emulsion fuels are a combination of water and a combustible liquid, which are immiscible with each other. In the case of WiDE, water droplets are dispersed and encapsulated within the diesel oil continuous phase, and an emulsifying agent (surfactant) is added for stability to prevent phase separation[32]. The surfactant encloses the water droplets to prevent water from coming together and coalescing. The most important selection criteria for emulsifiers is their ability to stabilize the emulsion over time, precluding phase separation and minimizing the sedimentation of the dispersed water droplets in the diesel oil. The water droplets must also be homogeneously dispersed, as large water droplets can lead to future coalescence and phase separation[33]. Known advantages of using emulsified fuels include decreasing combustion temperatures and more complete fuel combustion leading to higher fuel efficiency, as well as lower NOx and particulate matter emissions. Emulsion fuels also have the potential to be biofuel based, discussed in the 'Emulsion biofuels' section of this report. The major disadvantage is the low energy density of the fuel and thus large fuel storage volume.

4.5. FUEL HEATING VALUE

An important factor in a vessel's fuel mix is the heating value. The heating value of a fuel is defined as the amount of heat released during combustion of 1 kg of fuel. The fuel in question undergoes complete combustion with oxygen under standard conditions, forming carbon dioxide and water and releasing heat. From the shipping sector point of view, as a rule of thumb, the heating value for shipping fuel should be at least 30 MJ/kg for economical operation. But also fuels with lower values are used.

There are two ways to report a fuel heating value: lower heating value and higher heating value. The higher heating value, or gross calorific value, is defined as the amount of heat released by a specific quantity (initially at 25°C) once it is combusted and the products have returned to the initial temperature of 25°C, taking into account the latent heat of vaporization of water in the combustion products. The lower heating value, also known as the net calorific value, also measures the heat released by a specific quantity (initially at 25°C), but returns the temperature of the combustion products to 150°C, as it assumes that the latent heat of vaporization of water in the reaction products is not recovered.

Linked to the heating value is the energy density of a fuel, which is the measure of energy a fuel contains for a given volume or weight of fuel. On ships, fuel systems deliver fuel based on a specific volume flow rate, and the volumetric energy efficiency is important due in order to minimize the size of the of the fuel storage. Thus, while some fuels might have the same energy content per weight of fuel, on a volumetric basis one might have more energy than the other (e.g. diesel vs. LNG). If a fuel is less dense and has less weight per cubic meter, for the same volume of fuel bunkered, the ship will be lighter and will not be able to travel as far between each bunkering i.e. the process of re-fueling.

Table 7. Energy content and density of select marine fuels[34]

Fuel	Lower heating value (MJ/kg)	Higher heating value (MJ/kg)	Density (kg/m³)
Natural gas	47	52	0.777
LNG	48	55	0.428
LPG	47	50	0.508
Methanol	20	23	0.794
Ethanol	27	30	0.789
Butanol	34	37	0.810
Diesel	43	46	0.837
HFO	39	42	0.991
Gasoline	43	47	0.745
WiDE[35]	41		0.852
Biodiesel (FAME)	38	40	0.888
Vegetable oil	37[36]	40[37]	0.910[38]
HVO/HEFA	43	47	0.779

Biofuels in general have lower energy density than petroleum-derived marine fuels, but also vary between different types of biofuels. This means that on average a higher quantity of biofuels is needed to meet the same final energy content as conventional fossil marine fuels.

4.6. FUEL SPECIFIC GHG EMISSIONS

Another factor to take into consideration on choosing suitable fuels for diesel engines is its GHG emission intensity. In other words, the amount of carbon dioxide emissions produced when burned. To analyze emissions across fuels, the amount of CO_2 emitted per unit of energy output or heat content is measured.

Table 8. Mass of CO_2 emitted per quantity of energy for various fuels[31,39,40]

Fuel	Carbon content (%)	CO_2 emission on combustion (g/MJ)	Life cycle GHG equivalent (g/MJ)
HFO	86	69-76	77-87
MDO	86	71-74	74
Diesel	86	72-74	87
Gasoline	87	67-73	81
Propane	82	60-65	
Natural gas	75	50	63
Bioethanol (1st gen)	52	72-81	34
Bioethanol (2nd gen)	52	72-81	24
FAME	77	75	75-111
HVO	77	75	8-25

The amount of CO_2 produced during combustion is a function of the carbon content of the fuel as well as the combustion engine used. The heat content (or energy density), on the other hand, is determined by both the carbon and hydrogen content of the fuel. Heat is produced when C and H combine with oxygen during combustion. As natural gas is mainly methane, for example, it has a higher energy content by weight relative to other fuels, and thus lower CO_2-to-energy content. Impurities such as water, sulphur, and other non-combustible elements in the fuel reduce its heating values and increase its CO_2-to-heat contents. Diesel engines and gas engines also produce different levels of GHG, SOx, NOx, and PM emissions depending on the fuel in question.

For a reduction of overall GHG emissions, biofuels present themselves as a good option. The highest GHG emissions reduction can be achieved by using residual or waste feedstock streams, such as agricultural residues, waste cooking oil, or municipal waste. Using 1st generation feedstocks such as palm oil for biodiesel production often results in overall higher GHG emissions due to direct or indirect land use change during the feedstock production process.

The life cycle GHG equivalents for the different fuels are measured from well-to-propeller or field-to-propeller for fossil fuels and biofuels respectively. This includes the overall fuel chain from extraction/production of the feedstock at the source to combustion in the marine engine. The values can be used as relative indications of GHG emission levels, but as life cycle analysis and may apply different system boundaries, specific values for GHG emissions can be difficult to compare. Fossil fuels have on average the highest life cycle GHG emissions equivalents, and the numbers reported take into account emissions from extraction, refining, and distribution (well-to-propeller calculation). Biofuel feedstocks capture CO_2 via photosynthesis during their lifetime, sequestering carbon until it is burned as a fuel, and thus the CO_2 from the biofuel combustion itself is not accounted for in life cycle GHG emissions. A field-to-propeller calculation also includes feedstock and biofuel production processes (use of fertilizers, farming methods, drying, processing, etc.) and transportation[31]. The actual life cycle CO_2 emissions for both fossil fuels and biofuels may be higher or lower than those reported here, depending on both the fuel production chain and the calculation method for GHG emissions. However, regardless different emission estimates, the ranking of the fuels with regard to GHG emissions is believed to be valid.

4.7. THE MARINE FUEL MARKET

Marine bunker fuels represented about 3% of the total primary energy supply of the world in 2013[41], and production and consumption has been steadily increasing. The global shipping industry accounts for more than 14% of energy consumption in the passenger and freight transport sector, slightly more than aviation[42]. While it is difficult to calculate the exact amount of marine fuel consumed, the annual demand for shipping fuel was estimated at 330 million tonnes a year in 2014.

Approximately 75% of the liquid marine fuel sold is heavy residual fuel, and the remaining 25% is distillate fuel. Once a shipping vessel is fully built and operational, fuel usage takes up to 50% of the operational costs of running a ship, and is not uncommon to spend 4-5 million USD to refuel an empty large ship when fuel prices are high. From the marine fuel supply side, there are many bunker parties and many small ship owners, but only a small number of very large ship owners and refineries. Thus, the market determinants for bunker fuel prices lie with the few large companies operating large and very large liner ships, as they are the biggest fuel purchasers by volume.

Large container ships have a capacity to store 10 kilotonnes of fuel on board, and consume up to 200-250 tons of fuel per day. Their fuel can be stored on board the ship for up to three months, spread over various tanks. For instance, the Mærsk container ships are able to sail for 68 days, making several port stops without refueling.

Heavy fuel oil is the most consumed marine fuel based on volume, and it is also the cheapest fuel per ton. High sulphur HFO is typically used for large low speed 2-stroke engines, while MDO is used in smaller medium and high speed 4-stroke engines. The IMO estimates that about 80 to 85% of all marine fuel is residual fuel oil with high sulphur levels, used mainly on large long-haul vessels. About 25% of vessels run on residual fuel oil, but account for 77% of global marine fuel consumption.

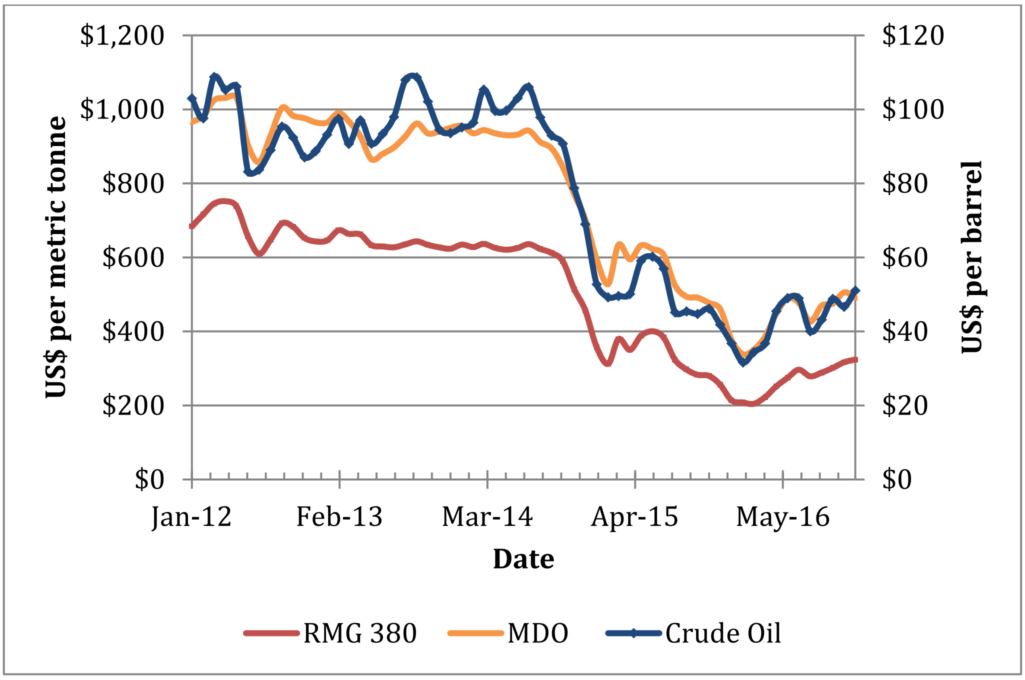


Figure 4. Price of marine fuels (residual fuel RMG 380 and distillate fuel MDO) in US$ per metric tonne compared to the price of crude oil in US$ per barrel[43]

The price of conventional marine fuels varies with the sulphur content of the fuel, where lower sulphur content is more expensive. Prices can vary based on the day and the port location. Bunker fuel prices are lower when they are close to the refinery, and fluctuate constantly due to the speculative nature of oil trading.

Table 9. Average world marine fuel prices October 2015[43]

Fuel	Max sulphur content	Baseline cost (USD / metric ton)	Fuel grades
IFO380	3.5%	252	RME, RMF, RMG, RMH, RMK
LSHFO380	1.0%	462	
MDO	1.5%	461.5	
MGO	1.5%	466	DMA, DMZ 'clear and bright distillate'
Low sulphur MGO	0.10%	470	
LNG	0	220	Energy equivalent of IFO380

Since most commercial ships are small and medium-sized, fuel delivery are mostly done on a short term basis, that is, prices paid for marine fuel are based on spot requests. Larger ship owners, especially travelling on routine scheduled fixed routes, have contract fuel deliveries on a long term basis and can better negotiate on fuel quality and price.

Based on the volume of fuel required for shipping marine fuels needs to be available in large quantities at the scale of kilotonnes at a time. The supply of fuel needs to be continuous, even though ships sail at irregular times. Fuel also has to be cost efficient and stable to transport over long distances and stored over long periods of time. In order to secure fuel supply, hedging i.e. contractual fixation of fuel costs, is a common practice among oil companies to minimize losses against the volatile price of oil[44], though it might only be relevant to a minor extent for the biofuel industry since there is only a limited marine biofuel supply at the moment.

It is predicted that the shipping industry will keep growing for the next decades to come, and while ship engines have become more fuel efficient, shipping vessels have become larger and the demand for marine fuel will therefore increase. The expected demand for marine fuel will depend on the relative prices of fuels (e.g. LNG vs HFO), regulatory issues and how different engine technologies will evolve to become more cost-effective. It is expected that regulations will increase the demand for ultra-low sulphur diesel and residual fuels (sweet crude, as opposed to sour crude) as well as fuel alternatives that can be cost-competitive with low sulphur fuels.

As of 2016, bunker fuel prices are currently very low. Therefore, it is more favorable for merchant vessels to travel around the Cape of Good Hope consuming more fuel instead of passing through the Suez Canal, affecting established shipping routes. Low oil prices have also led large oil tankers to become 'floating storage', as more refined oil products are kept at sea as traders wait for prices to rise again. Fuel traders practice "contango" on the principle that oil futures are worth more than current prices, justifying that higher future prices can account for the cost of storage.

4.8. MARINE FUEL REGULATIONS

Shipping operations are global in scale, as maritime trade routes are usually shared between countries. It is therefore of no surprise that the merchant shipping industry has been among the first to implement international safety standards. It is a heavily regulated industry, as there are many partners at stake. Maritime regulations have thus been developed at a global level, given that the industry is inherently international. Shipping is regulated by the International Maritime Organization (IMO), a specialized agency of the United Nations with 169 member states and three associate members. Its current remit includes safety, environmental concerns, legal matters, technical co-operation, maritime security, and shipping efficiency.

At an IMO meeting in 1973, the International Convention for the Prevention of Pollution of Ships (MARPOL) was signed into place and entered into force in 1983. It was developed in an effort to minimize pollution from ships in the oceans and seas as well as the air. MARPOL is divided into six annexes according to the pollutant, regulating a particular type of ship emission[45]. Annex VI came into force on May 2005, introduced to regulate air pollution emitted by ships, including nitrogen oxides (NOx), sulphur oxides (SOx), volatile organic compounds, and particulate matter (PM). It also establishes the requirements for fuel oil quality, e.g. sulphur content, the prohibition of deliberately emitting ozone-depleting substances, and the creation of emission control areas (ECA).

ECAs are jurisdictions with high marine traffic where strict SOx, NOx, and PM emission targets have been set to control air and water pollution. The current ECAs in place include the Baltic Sea, the North Sea, the English Channel, waters within 200 nautical miles from the coasts of USA and Canada (North American ECA enforced August 2012), and coastal waters around Puerto Rico and the US Virgin Islands (US Caribbean ECA enforced January 2014). There is also a possibility of new ECAs being created in the future, such as the Mediterranean Sea, the Gulf Coast of Mexico, and some areas of the Pacific Rim. At the time of writing, there are no ECAs proposed for the Asian continent. However, some Asian regions have their own locally enforced low-emission zones.

For example, in September 2015 the New South Wales government introduced regulatory requirements for the use of low sulphur fuel (0.1% or less) by cruise ships in Sydney Harbour, Australia[46]. The requirements took effect on 1 July 2016 for both ships berthed and operating in the harbour. Singapore's National Environment Agency also set targets for SOx, NOx, CO, and PM emissions to improve the general air quality around the harbour[47]. On 1 July 2016, Singapore implemented the Green Port Programme (GPP) designed to promote green shipping within the port, requiring vessels to use LNG, fuels with a sulphur content of ≤0.50%, or use adequate abatement technology to achieve low SOx levels. Compliant parties would get a 25% port dues reduction[48].

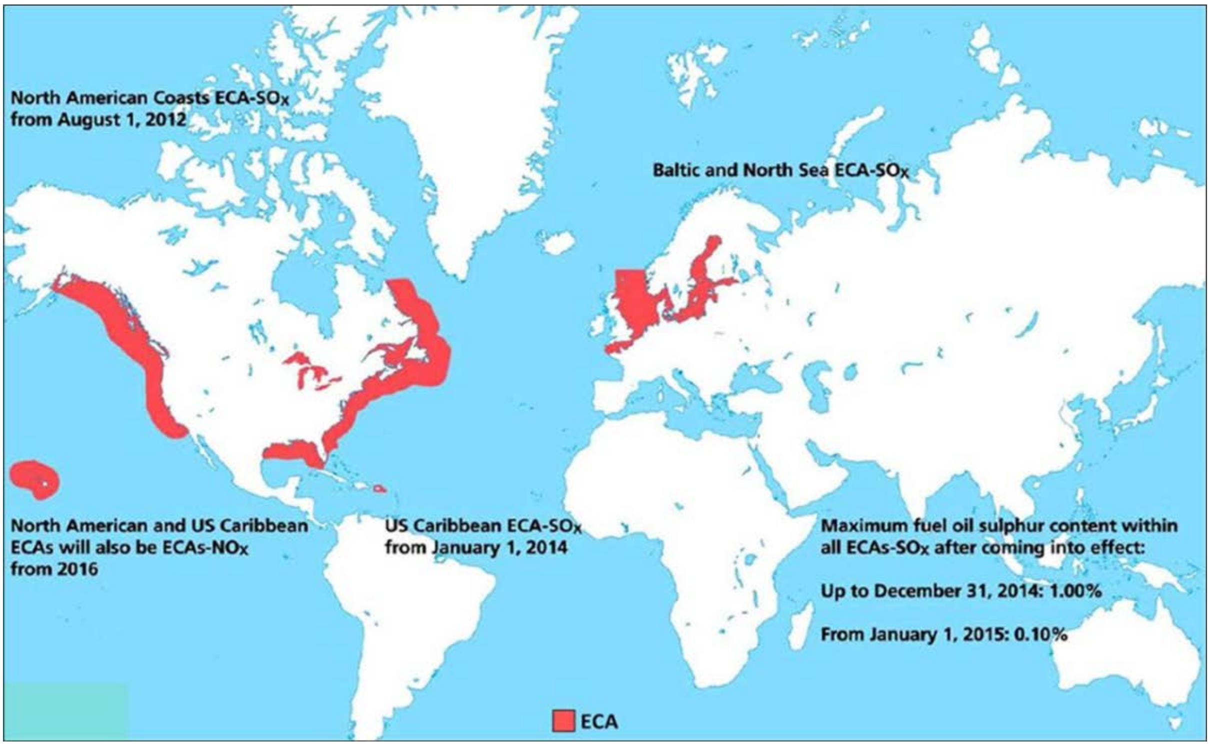


Figure 5. Sulphur and nitrogen oxide emission control areas (ECA)[49]. The Baltic and North Sea will be ECAs-NOx from 2021.

The international shipping sector is the highest SOx emitter in the transportation industry. The sulphur emissions mainly stem from the ship exhaust from heavy residual fuels utilized by the majority of the merchant shipping vessels with diesel engines installed. The SOx formed from diesel exhaust is corrosive, but is partly neutralized by the engine's lubricating oil which is typically basic. However, SOx can combine with moisture in the air to form sulphuric acid, which is then a precursor to acid rain. Furthermore, and of even higher importance are the formation of particles from reactions between SOx and NOx emissions, which in the case of high sulphur fuels will form very high levels of particles in the atmosphere, causing excessive particle pollution in coastal areas.

Environmental and health concerns has led to bunker fuels being regulated for their sulphur emissions by the IMO and the creation of ECAs. The SOx and particulate matter ECAs have been designated under regulation 14 of MARPOL Annex VI[16]. As of 2015, the sulphur limits in marine fuels are 0.1% within ECAs and 3.5% outside of ECAs. Marine fuel consumption in ECAs is estimated at 30-50 million tonnes of fuel a year, and is expected to increase with the future creation of more ECAs. These sulphur emission standards are applicable to all ships regardless of the engine or date of construction.

A stricter future fuel sulphur content limit of 0.5% outside ECAs has been set for January 2020 after a series of agreed-upon amendments adopted in 2008[50]. However, the date for global reduction limit might be changed to 2025 as a result of a feasibility review to be conducted no later than 2018. During the 70th session Marine Environment Protection Committee (MEPC) meeting by the IMO on October 24-28, 2016, it was decided to implement a global sulphur cap of 0.5% m/m by January 1, 2020[1] after an extensive review concluded that sufficient compliant fuel oil would be available to meet the fuel oil requirements. It is estimated that the SOx rules will cost the shipping industry 50 billion USD a year[51].

China has also implemented a marine sulphur limit of 0.50% outside of the IMO MARPOL Annex VI structure. These regulations require ships to use a low sulphur fuel while at berth in key ports along the Pearl River Delta Area, the Yangtze River Delta Area, and the Bohai Sea Area. The sulphur limit was set in effect in 2017. By 2019, the sulphur limit will apply to all operations within all ports in the defined emission control areas[52].

Table 10. Sulphur emission standards inside and outside ECAs

IMO agreement to reduce atmospheric pollution from ships	
Sulphur content of fuel permitted in Emission Control Areas (ECAs)	
Before 1 July 2010	1.50% m/m
Between 1 July 2010 and 1 January 2015	1.00% m/m
After 1 January 2015	0.10% m/m
Sulphur content of fuel permitted outside ECAs	
Before 1 January 2012	4.50% m/m
Between 1 January 2012 and 1 January 2020	3.50% m/m
After 1 January 2020	0.50% m/m

With emission targets in place, ship owners would be expected to use low-sulphur fuel available in the market, undergo engine exhaust after-treatment processes by installing scrubbers to remove sulphur on board, or switch to alternative or dual fuels (LNG, biofuel, diesel/LNG) for compliance in ECAs. Shipping practices along ECAs would also be expected to change. Fuel traders expect the price of high sulphur HFO to decrease once the 2020 mandate begins, as the only purchases would come from vessel operators which have scrubbers installed onboard.

Scrubbers work by sprinkling the engine exhaust gas with salt water, quenching the SOx so that that the exhaust gas can be released from the ship. The water containing washed-off sulphur can be later released in the ocean as long as the sulphur levels fall within the ISO guidelines. The trade-off by using a scrubber is its installation, the loss of cargo space, and energy cost. Scrubbers are costly to produce as they contain special materials to prevent corrosion. They take up cargo space for pumps in the engine room, tanks, and the scrubber body, which might not be easily available on all ships. However, with more optimal space design, scrubbers can be a functional way of reducing SOx emissions, especially on large ocean-going vessels operating in SECAs.

Low sulphur diesel has lower energy content due to heavy fractionation required to remove sulphur from oil, leading to a 1-2% lower fuel economy. Increase demand for low-sulphur fuel will affect refinery operations, as they would need to invest in further hydrotreating and desulphurization facilities. The reduced sulphur in fuel decreases the engine lubricating properties (sulphur combined with nickel forms an alloy increasing lubricity), leading to lower reliability and higher costs for maintenance and repair. This can be solved by switching to a low-BN (less alkaline) lubrication oil on two-stroke diesel engines[53].
From a fuel production and supply systems point of view the increased processing at the refinery and use of low-sulphur fossil diesels will increase the overall CO_2 emissions from maritime transport. Thus the regulation to reduce particle emissions may likely increase CO_2 emissions.

Burning heavy fuels with high oxygen levels results in higher combustion temperatures and efficiency, but NOx exhaust increases proportionately. Unlike SOx emissions, which originate from sulphur in the fuel, NOx emissions originate from reactions of the air during combustion. Nitrogen oxide gases react to form smog and acid rain, and are a major contributor to air pollution. Emission standards regarding nitrogen oxides are set in MARPOL Annex VI regulation 13, and it applies to ships with diesel engines installed on ships on or after 1 January 2000. The NOx limits are set for marine diesel engines according to the engine maximum operating speed. The regulation, however, does not apply to engines used for emergency purposes such as emergency power generator engines, lifeboat engines, etc. There are three different tiers of NOx emission control. Tier I entered into force in 2005 and applies to installed engines in ships built between 1 January 2000 and 31 December 2010. Tier II entered into force on 1 January 2011 to replace the Tier I NOx standard, and applies to new marine diesel engines installed on ships built on or after 1 January 2011. The emissions limit between Tier I and Tier II correspond to a reduction of about 20%. Tier III emission limits came into effect in 2016, applicable to new marine diesel engines with more than 130 kW on ships built on or after 1 January 2016 when operating inside a NOx ECA. The Tier III emission standard comprises an 80% reduction from the Tier I limit. Future NOx ECA zones had the Tier III deadline moved another 5 years to 2021 by the IMO in May 2014. Tier II limits would still be applied outside ECAs.

At the time of writing, there is only one NOx ECA in North America and the US Caribbean, but more are expected in the future. The Baltic Sea and North Sea NOx ECAs have been approved for designation during the IMO's 70th MEPC meeting on October 2016, and will enter into effect on 1 January 2021. This means that marine diesel engines would have to comply with Tier III NOx emission limits when installed on ships built on or after 1 January 2021 and operating in the North Sea and Baltic Sea.

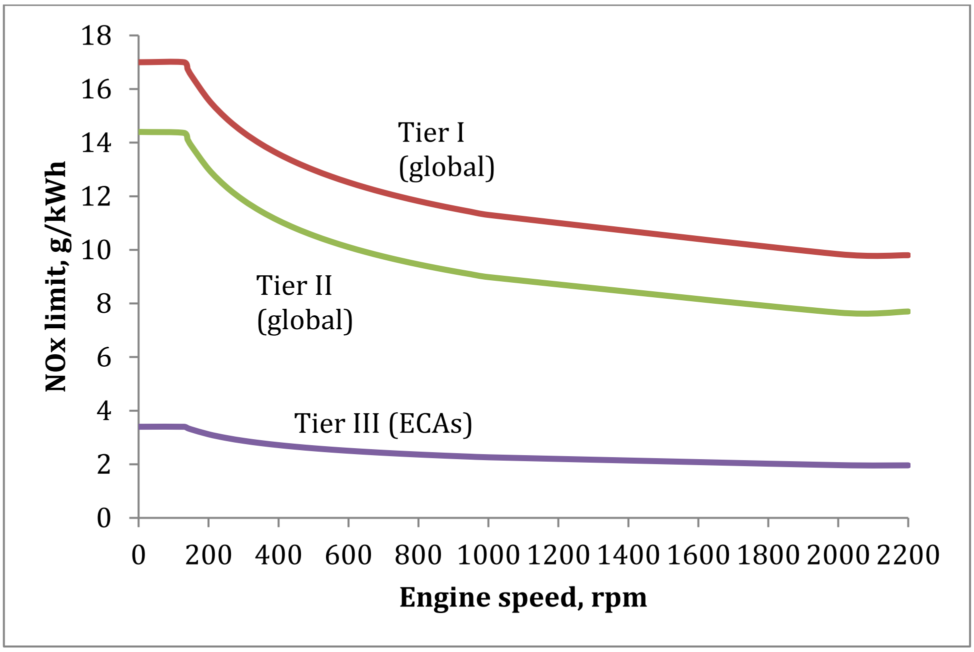


Figure 6. Nitrogen oxide emission standards inside and outside ECAs in accordance to MARPOL Annex VI. The emission limits expressed are a function of the engine speed in revolutions per minute (rpm). Tier I and Tier II limits are global.

There are both primary and secondary methods of reducing NOx. Primary methods include making changes to the combustion process within the engine, such as combustion optimization, water-based control, and exhaust gas recirculation. Secondary methods, or after-treatment, involve treating the engine exhaust gas using a selected catalytic reduction (SCR) system. The SCR system works by using a zeolite catalyst that selectively combines NOx and ammonia to produce nitrogen before releasing it back into the atmosphere. The third alternative is to operate on LNG, which contains no oxygen and has lower NOx emissions than heavy fuels.

The implementation and enforcement of these mandates and regulations lies with different parties at stake. It is the responsibility of only the ship owner (fuel purchaser) to comply with fuel quality and quantity. In other words, there is no liability towards fuel suppliers or bunker parties. The level of ratification and enforcement concerning ship safety and environmental protection lies with the flag state of ships. That is, the country where ships are registered, not the country which owns the ships. Port officials in any country can inspect foreign flag ships to ensure they comply with international requirements, known as Port State Control, thus regulations are enforced in a more or less global basis. The potential of non-compliance with these statutory requirements has led to discussion from ship owners in international forums such as the World Shipping Council, Bimco, the International Chamber of Shipping, and the European Commission Shipping Association. The European Commission has thus established the European Sustainable Shipping Forum (ESSF) to ensure compliance from all relevant parties. More long-term goals in regulating shipping emissions involve reducing the amount of greenhouse gases produced by merchant vessels.

To increase the accountability of ship owners and operators, the IMO has increased mandatory requirements to monitor greenhouse gas emissions from international shipping. New requirements covers of ships 5,000 GT and above to collect fuel consumption data for each type of fuel they use, as these ships account for approximately 86% of the CO_2 emissions from international shipping. These requirements were formally adopted by the MEPC at its 70th session in London on October 2016 in order to build on existing technical and operational measures for ship energy efficiency[54]. Thereby a system for monitoring CO_2 emissions is build up, and can be used when a decision to regulate CO_2 emissions from the maritime sector is made.

The reduction of CO_2 emissions based on current fuel- and engine-technologies depend upon the volume and type of fuel consumed and the engine efficiency[55]. In practice, this could be implemented in three possible ways: change shipping activity patterns (number and frequency of shipping), increase shipping energy efficiency (improve engine specifications or by decreasing speeds), or decrease the carbon intensity of shipping propulsion (switch to high H/C fuels). With the amount of traded goods set to increase, reducing shipping activity are unrealistic. Most realistically, decreasing the carbon intensity of the shipping propulsion by slower speed or changing fuel types. Reducing the speed saves fuel, whereas changing fuels from e.g. diesel to LNG comes with a cost of engine and fuel storage refitting. Mechanisms have also been introduced by the IMO to ensure an energy efficiency standard in ships, known as the EEDI (Energy Efficiency Design Index) for ships built from 2013, and the SEEMP (Ship Energy Efficiency Management Plan) for all ships. State-sponsored CO_2 reduction agreements might also be commonplace in the future, such as a carbon tax or an emissions trading scheme.

The EEDI is only applicable to newly-built ships from 2013 onwards, which will require future ships to meet more stringent fuel economy standards. It was designed to reduce greenhouse gas emissions from international shipping through amendments to the MARPOL Annex VI, and is expected to incentivize ship owners to use new low-carbon technologies and ship designs. The index represents a measure of the relative efficiency of a shipping vessel in moving a given cargo volume over a given distance. Mathematically calculated, it is the amount of CO_2 (grams) emitted per tonne nautical mile for new ships, obtained from ship design and engine performance data.

The IMO has also created guidelines for the voluntary use of the ship EEOI (energy efficiency operational indicator) in 2009. These regulations are designed for ship operators to *operate* their vessel to its most optimal setting. Thus, the EEOI changes depending on how the vessel is operated and what CO_2 abatement measures the ship owners have retrofitted. To calculate the EEOI, it is defined as the ratio of mass of CO_2 emitted per unit of transportation work.

The SEEMP is applicable to all new and existing ships above 400 GT, and establishes a mechanism for ship operators to improve the operational energy efficiency of ships. It is anticipated that global CO_2 emissions will reduce by 10-20% with the implementation of EEDI and SEEMP.

Figure 7. IMO agreement on technical regulations to reduce CO_2 emissions: MARPOL Annex VI, chapter 4 adopted July 2011, entered into force in January 2015. Image source: http://www.ics-shipping.org/shipping-facts/environmental-performance/imo-agreement-on-technical-regulations-to-reduce-ships'-co2

4.9. FUEL TRANSPORT INFRASTRUCTURE (PORTS)

Shipping ports are the gateways for the international distribution of cargo. They link the merchant transport chain by providing an interface to other modes of transportation such as rail and truck. There are 85,094 registered commercial ships worldwide as of 2014, excluding fishing and naval vessels[20]. Over the years, the number and size of ships has continually increased, and adjustments need to be made by expanding port infrastructure and access. Port operations include cargo handling and storage, bunkering, ship maintenance, and safety.

The marine fuels produced from crude oil at refineries, are shipped by suppliers via oil tankers to strategic ports, including Houston in North America, Balboa and Cristobal in Central America, Hong Kong and Singapore in Asia, Fujairah and Sokhna in the Middle East, and Algeciras and Rotterdam in Europe. The major refinery and crude oil storage in Europe are in the Rotterdam and Gibraltar ports, though the supply of refined fuels to bunker stations around Europe is stable and frequent. The major marine fuel supply chain in Europe is along the Rhine.

Access and availability of marine fuels depends on the port location. Ports where there is a high concentration of trade will have frequent and regular supply, while seasonal or small ports do not have the adequate infrastructure to supply fuel on a continuous basis, and thus cope with irregular access to marine fuels. Ports which are close to large populations and large manufacturing centers tend to have the most developed infrastructure and highest demand[56].

Marine fuels are usually transported through road, inland vessels, or piping systems to the bunker station in port areas, where it is stored until further use. Small and medium sized ships have the marine fuel pumped directly to the ship in the port area. Larger ships, which require more fuel and space for bunkering, often have marine fuel loaded on a bunker (barge) vessel, transported and pumped to the ship.

Marine Infrastructure. The Port of Rotterdam is Europe's largest sea port and a main hub for global and intra-European cargo shipments. Spanning an area of 125 km², the Port covers a complex of distinct port sections and terminals, with good connections by rail, truck, and coastal shipping areas. There are oil and chemical refineries on-site, with a capacity to store 1 million m³ of crude oil and other chemical products. In 2015, the Port partnered with GoodFuels Marine, Boskalis, and Wärtsilä on a two-year pilot to offer vessels the option of sailing on biofuel in order to reduce SOx and CO_2 emissions[57]. The Port of Rotterdam has the ambition to become "the most sustainable port in the world" by promoting greener industries and logistics to improve the quality of the environment. The Port is already home to the world's biggest renewable bio-based industry cluster, with 5 biofuel plants, 2 biochemical companies, and 2 power plants able to generate clean electricity from biomass.

Bunkering can take place at anchor, offshore, or alongside, where barges carrying fuels will be placed alongside a vessel with the assistance of tugboats. Once in place, they follow a strict protocol to ensure safe refueling. The refueling process can take about 9-12 hours for a large ship, typically 10 hours at a rate of 500-700 tons per hour.

As responsibilities concerning quantity and quality of fuel used in vessels lie with the ship owner, it is common practice that ship owners themselves sample the fuel to check whether the fuel delivery align with the specifications and comply with marine legislation.

Deep sea shipping vessels often carry a combination of fuels in their different storage tanks, mainly low-sulphur fuel for operation around ECAs and regular bunker fuel for navigation in open ocean areas outside ECAs.

Distillate marine fuels being low in viscosity are pumped directly into the target vessel and heated on board with a heat exchanger before use. Heavier residual fuels, which are high in viscosity, undergo a more thorough treatment, where they are heated through heat exchangers on board to achieve the right environment for long term storage on board, and go through a secondary cleaning process where it is pumped through a fuel separator and undergoes a viscosity check before the purified and clean fuel is pumped at high pressure and injected into the engine.

LNG as a shipping fuel requires cryogenic storage, resulting in an insulation layer and low pressure containers often cylindrical in shape, additional safety requirements which are reflected in the higher construction cost. This kind of storage typically requires about 4 times the space of regular fuel for an equivalent amount of energy. LNG also has longer fueling times than conventional fuels, along with extra space requirements for the fuel tank. This implies that not all ships will have the capacity to use LNG for neither propulsion nor LNG-powered engines, other than for vessels on short voyages that have sufficient turnaround times for fueling. The most common LNG-powered vessels are chemical tankers.

5. Marine biofuels and conversion technologies

The combined effects of decreasing availability of light crude oil, increased demand for global merchant shipping, and stricter marine fuel regulations have caused a search for competitively produced marine fuel alternatives with low sulphur content and low carbon footprint[13]. Alternative fossil-based fuels such as LNG and LPG have low sulphur and nitrogen oxide emissions, but have a limited contribution to reducing greenhouse gas emissions. Biofuels, however, have a much larger potential to combat climate change and reduce emissions over their full life cycle.

As biomass is a renewable resource and contains very little or no sulphur, biofuels have the potential to become an important part of the fuel mix in the shipping sector, thereby reducing its dependence on fossil fuels as well as GHG emissions.

Biofuels are derived from biologically renewable resources, and by far most biofuels are derived from plant based sugars, oils and terpenes. A small amount is derived from animal fat waste. Bioethanol and biodiesel are commercially produced globally, though they have almost exclusively been utilized by the road transportation sector.

The advantage of producing a marine fuel is that the fuel can be of a lower quality, have higher viscosity, and be less refined than fuels used for aviation or road transport. Thus, marine biofuels may be produced with lower processing costs, eliminating the need for secondary refining.

The established shipping operational procedures make customizing marine engines to run on new compatible fuels a costly process. Thus, it is practical to take advantage of the existing infrastructure (marine engines, fuel transport pipelines, bunkering) and produce a fuel compatible with what is already in place. Such drop-in fuels fit existing infrastructure and do not require a high investment in ship engine or infrastructure changes.

Despite the fact that biofuels are not yet abundantly used in the maritime sector, it is possible that based on existing biofuel technologies, marine biofuels can be designed and produced to be technically compatible with marine engines. Thus, they can be integrated in shipping vessels as drop-in fuels. Furthermore, the very high fuel flexibility of marine diesel engines open for the development of new biofuel processes combining different grades and types of biofuels.

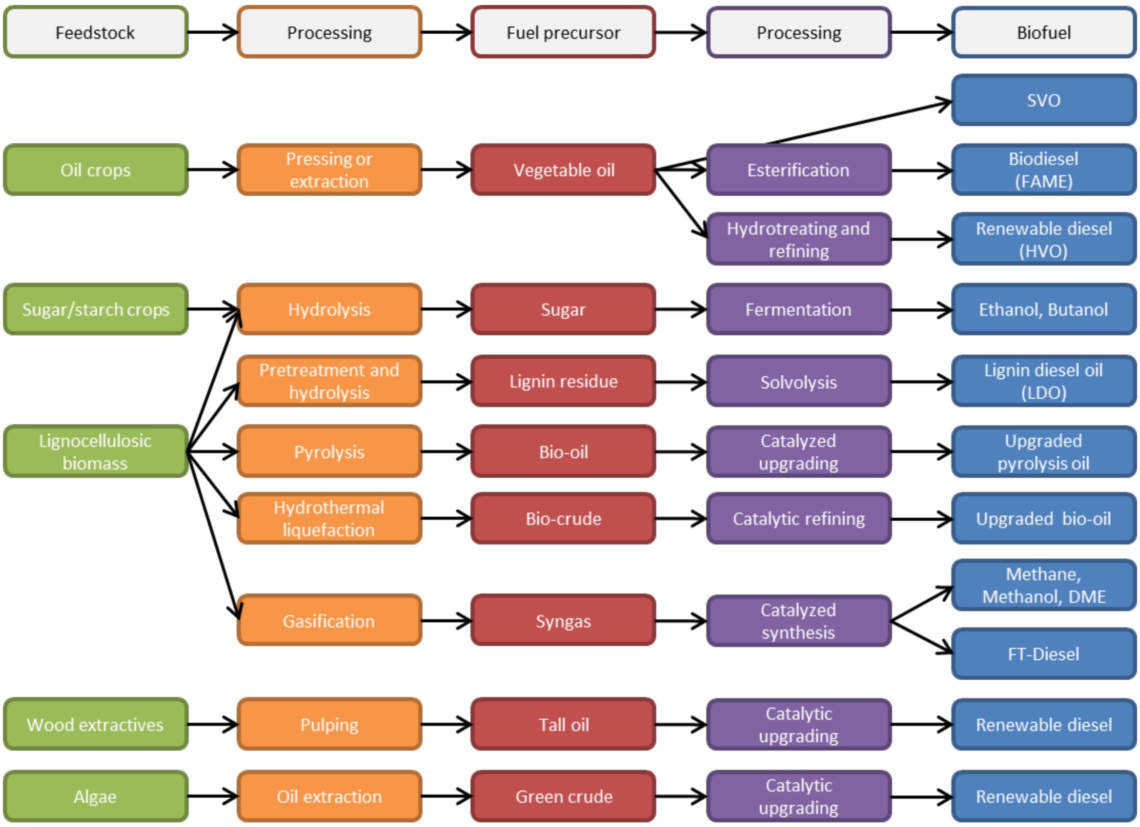


Figure 8. Overview of different feedstock conversion routes to marine biofuels including both conventional and advanced biofuels.

5.1. CURRENT BIOMASS-DERIVED DIESEL FUELS

Straight vegetable oils (SVOs), also known as pure plant oils (PPOs), are oils extracted from plants solely for use as a fuel. These oils do not undergo any intermediate processing steps, but are introduced in diesel engines directly from extraction. Studies have shown that they can be used to replace IFO or heavy oil in low speed engines (all sizes of carriers and cargo ships)[56], though are generally not considered practical fuels for large-scale or long-term use. Due to their higher viscosity and high boiling point, SVOs reduce the engine lifespan due to the buildup of carbon deposits inside the engine and damage to the engine lubricant. It is therefore not recommended to use vegetable oils as raw untreated oil due to the risks of engine damage and gelling of the lubricating oil. Some investigators have worked around the issue by modifying the fuel delivery system to preheat the SVO prior to injection into the engine, or used SVO in blends with conventional fuels in order to mitigate the problem.

Processed biodiesel is produced by a process called transesterification, where various oils (triglycerides) are converted to methyl esters. Glycerol and water are produced as side products, which are later removed as undesirable products. Biodiesel is also commonly known as fatty acid methyl ester (FAME), obtained from vegetable oil or animal fat which has been transesterified with methanol or ethanol. Sodium methylate is commonly used as a catalyst. FAME is a more suitable fuel than SVO for diesel engines, with lower boiling point and viscosity than SVO, leading to better engine performance. Biodiesel has a higher flash point (149°C) and cetane rating than conventional diesel, and degrades quickly in water. FAME, however, has a high cloud point which can result in filter clogging and poor fuel flow at temperatures lower than 32°C.

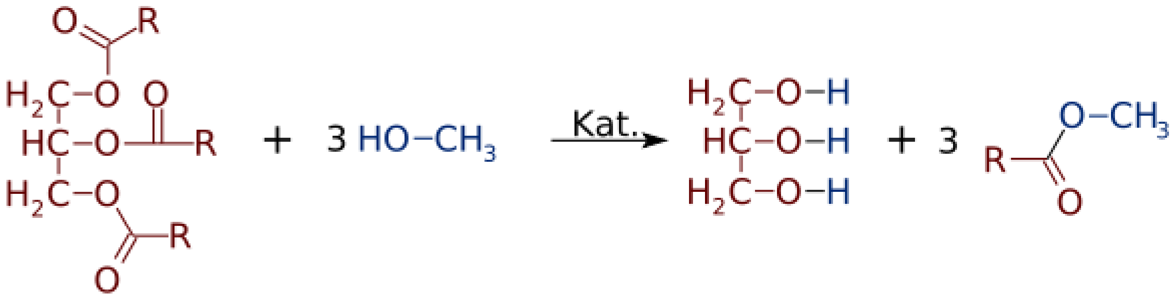


Figure 9 Transesterification of triglycerides with methanol to glycerol and methyl esters for the production of fatty acid methyl esters (FAME)

Biodiesel can be used to replace MDO and MGO in low to medium speed diesel engines (tug boats, small carriers, and cargo ships), though it is more commonly used as a fuel additive and can be poured directly (drop-in) into fuel tanks. FAME as a fuel has good ignition and lubricity properties. It is theoretically possible to run diesel vehicles on 100% FAME, but requires adjustments to diesel engines as well as approval from the engine manufacturers. Therefore, FAME blends of up to 20% with petrodiesel are widely distributed in the retail diesel fuel market as it can be used in diesel equipment with little or no engine modifications.

Biofuel provider. Avril Group (France) is an international agro-industrial group focused on the development of oilseed and protein products from crops founded in 1983. They produce biodiesel from rapeseed oil under the brand Diester, and are the leading producer of biodiesel in Europe. The company incorporates biofuels in diesel blends between 5 and 30% in their company vehicles, while French diesel vehicles use 8%. It is also involved in developing second-generation biodiesel from non-edible plants and agricultural waste as well as animal fats and waste oil. The group participates in BioTfueL, together with Total, a program developing biodiesel and biokerosene from forestry waste. It was designed to transform lignocellulosic biomass and torrified material into biofuel by thermochemical conversion. Its aim is to produce 200,000 metric tons of biodiesel and biojet fuel per year from one million metric tons of biomass by 2020.

One of the main advantages of biodiesel is that it restores lubricity of the engine and reduces smoke, soot, and burnt diesel odor from engine exhaust, at the same time protecting against wear in fuel and injector pumps. The use of FAME in automotive diesel engines has been shown to reduce sulphur oxides, carbon monoxide, and unburned particulate matter. However, the acid degradation products of FAME are suspected of causing damage to fuel pumps, injectors, and piston rings, leading to an acid number limit in marine fuel specifications.

The main technical disadvantage of biodiesel compared to petrodiesel is its lower thermal energy content[58], as biodiesel has a higher oxygen content compared to conventional hydrocarbon fuels. Its higher oxygen content also leads to lower oxidation stability, where it is more prone to degrade over time and form peroxides, acids, and other insoluble compounds. To prevent early degradation, antioxidants can be added to the mixture. Another concern with the use of biodiesel is water contamination which leads to reduced fuel efficiency, increased microbial growth, and accelerated gelling of the fuel at low temperatures.

Although biodiesel is not miscible with water, it is very hydroscopic. The presence of mono- and diglycerides left over from biodiesel processing absorb water rapidly, acting as an emulsifier for this oil-water mixture and making it difficult to separate water and oil. Furthermore, residual water left over from processing or condensation in storage tanks further increases the water content of the fuel, which can lead to an increase in the acid content as water can facilitate the hydrolysis of esters to carboxylic acids when subjected to high temperature or extreme pH. Water also increases the risk of microbial contamination, accelerating the formation of biofilms and microbial colonies which can damage fuel system components. Thus, for pure diesel use, addition of a biocide is necessary to inhibit bacterial growth.

Fuel gelling occurs when molecules aggregate and form crystals at low temperature, leading the fuel to become cloudy. With further cooling, these crystals become larger, increasing fuel viscosity and forming a gel followed by a solid. Gelling complications arise during fuel bunkering and delivery, limiting its use in cold conditions. However, a number of additives are available to lower the pour point of the fuel, and fuel tanks can be insulated and heated prior to delivery. The cloud point of biodiesel varies depending on the combination of esters in the fuel and therefore the feedstock oils used to produce the biodiesel.

Commercially produced biodiesel can derive from a variety of plant- and animal-based feedstocks. Plant feedstocks include rapeseed (most common within EU), soybean (most common in US and South America), coconut (common in the Pacific islands), palm (common in Southeast Asia), and corn. Animal-based feedstocks include tallow (rendered beef or mutton fat), poultry litter, and other animal fats. Used cooking oil has also been used as a feedstock for biodiesel production.

Biofuel Provider. Archer Daniels Midland (ADM) is a publicly traded American multinational food processing and commodities trading company, headquartered in Chicago, USA founded in 1902. While they are mainly established in the food and ingredients business, they have invested heavily in fuel production since 2007. First generation bioethanol from corn and biodiesel from canola (rapeseed) and soy are the main fuels in their portfolio. Their biodiesel is produced through a transesterification process in which the vegetable oils are heated with alcohol in the presence of a catalyst to yield mono-alkyl esters and glycerin. ADM was also involved in a joint project with Daimler AG and Bayer CropScience to develop jatropha as a feedstock for biofuel[59]. Most of their biofuel production, however, is aimed towards the road transportation sector.

First generation biodiesel feedstocks are generally costly and available in limited supply, hence the price of biodiesel also varies depending on the feedstock price. In general, vegetable oils (palm, soy, canola) supply is limited by competition from food, pharmaceutical, and cosmetics industries. An important part of the oil production is the concomitant production of feed and food protein. This especially the case for soybean and canola which are both important sources of vegetable protein. Oil palm, the biggest oil crop is, mainly used as a food product rather than a fuel, and its by-products composted or to a smaller degree used as feed[60].

Biodiesel production around the world is limited to geographical areas with intensive agricultural land use combined with regional regulatory and financial incentives[56]. Likewise, the majority of biodiesel production in the world comes from the EU and the US, at 28 and 24% respectively[63]. The biodiesel produced is generally used for automobile transport and is typically not used 100% in diesel engines, but rather as a blend with petroleum diesel (5-30%). In blends of 1-2%, biodiesel may be used as a lubricity additive, especially with ULSD, which by itself has poor lubrication properties. For blends higher than 7%, additives such as octanol can be added as a co-solvent to prevent phase separation during blending.

Table 11. Oil yield per year of common crops for biodiesel[61]

Crop	Oil (kg/ha)	Oil (L/ha)
Palm oil	6,660-11,000	7925-13090
Coconut	2260	2689
Jatropha	540-3,200	643-3808
Canola	555-1,554	660-1850
Sunflower seeds	544-1,125	647-1339
Soybean	224-463	267-550
Algae[62]	3,190-10,000 (realistic numbers)	3,800-11000

The total feedstock supply for biodiesel production is significantly less than that for petrodiesel, and the rate of biodiesel production cannot fully replace the current rate of consumption, even in blends. Biodiesel can theoretically be used as heating oil or in any standard diesel engine, finding applications in road transport, locomotives, jet aircrafts, and power generators. Consequently, with such high demand and competition from other sectors, it would be economically unrealistic to produce large volumes of biodiesel for use as a low-quality marine fuel.

Biofuel Provider. Solazyme (USA) was a publicly held biotechnology company specializing in the production of transportation fuels from microalgae. The company developed a proprietary biotechnology platform based on heterotrophic algae, using sugar as feed. Its flagship fuel was named Soladiesel, produced commercially in partnership with Chevron Technology Ventures starting in 2007. Solazyme was also awarded contracts from the US Department of Defense to deliver microalgae-based marine diesel fuel for the US Navy in 2012, with 700,000 gallons of HRD-76 biodiesel and 200,000 gallons of HRJ-5 jet biofuel. The 50/50 biofuel blends were provided together with Dynamic Fuels (now part of REG).

In March 2016, Solazyme abandoned its biofuels business and has been renamed to TerraVia. Company strategy has since shifted focus to high-value added products from algae, such as food, nutrition, personal care, and specialty ingredients. Reasons for this shift include very low oil prices, changing market perceptions around the benefits of biofuels, and uncertain US government subsidies. Experts have also stated that algal oil produced for the marine fuel market cost several times more than their equivalent petroleum counterparts, and would be more economical as a heating fuel.

5.2. DROP-IN FUELS

Engine manufacturers find it very expensive to customize a new marine engine for a new fuel, and ship owners will not switch to a different fuel if the fuel supply is not guaranteed for the lifetime of their ship engine. Thus, if new fuels could be made to be functionally equivalent to those already in place, they would be fully compatible to existing fuel infrastructure without the need for extensive investments in infrastructure modifications.

Drop-in biofuels are defined as liquid bio-hydrocarbons that are functionally equivalent to petroleum-derived fuels and fully compatible with existing petroleum structure. By definition, they must meet the following bulk property requirements: miscibility with petroleum fuels, compatibility with performance specifications, good storability, transportability with existing logistics structures and usability within existing engines. Additionally, they are also most compatible with fuel injection systems already in place.

Drop-in biofuels chemically consist of a mixture of many different hydrocarbons and share similar combustion properties as conventional fuels in order to be compatible with petroleum infrastructure. This means the fuel should consist of mostly carbon and hydrogen by mass, with small traces of nitrogen, oxygen, sulphur, and metals. The challenge of producing drop-in fuels from biomass is that the high O content in biomass is not suited for direct conversion, and thus requires additional processing steps such as deoxygenation to obtain a high H:C ratio. Another approach would be through intensive hydrotreating, i.e. adding H_2, which is costly and requires further refining. The desired final result is a biomass-derived hydrocarbon that has low oxygen content, low water solubility, and a high degree of carbon bond saturation[64].

The most common biofuel, bioethanol, is usually blended with gasoline for use in petrol engines, and cannot be used as a drop-in fuel for marine diesel engines. Conventional biodiesel, also referred to as FAME, would function as a drop-in fuel in a marine diesel engine, but is not fully compatible as a drop-in fuel for other types of diesel engines. To produce a biomass-derived diesel fuel fully compatible with diesel engines, drop-in fuel suppliers produce hydrogenation-derived renewable diesel, also known as renewable diesel: For compatibility with existing petroleum infrastructure, animal fats (tallow) and vegetable oils need to undergo a hydroprocessing step to convert into deoxygenated hydrocarbon drop-in biofuels (hydrotreated esters and fatty acids HEFA). It is free of ester compounds, and has lower production costs as it uses existing hydrotreatment process technology currently in operation at petroleum refineries.

To further increase production volumes at a scale suitable for marine shipping, however, the industry would have to introduce lignocellulosic feedstocks into the fuel production mix to keep feedstock and production costs sustainable.

Technologies to produce drop-in fuels are outlined and discussed in an earlier IEA Bioenergy Task 39 report “the potential and challenges of drop-in biofuels”[65]. The focus of this report is on drop-in biofuel production technologies targeted specifically to the maritime shipping sector. This implies not-so-intensive refining process technologies and the production of lower quality fuels compared to road and air transport. Though drop-in fuels are designed to meet the same IMO specifications for marine fuel, new biofuel properties might be sensitive to aspects not covered by these specifications, making them more difficult to introduce in the market at a full scale. With further fuel testing and development, however, drop-in biofuels are an alternative to conventional marine fuels used today.

5.3. ADVANCED BIOFUEL PRODUCTION TECHNOLOGIES

Production technologies for biomass drop-in fuels have been covered in a previous IEA report[65]. Additionally, this report will cover commercial technologies and processes for the production of drop-in fuel for two-stroke diesel engines, as they are the main marine engines in the market today. The remaining section will also cover how these fuels can be introduced and integrated in the marine fuel market, as well as up-and-coming companies involved in the process.

5.3.1. OLEOCHEMICAL

Hydrotreated vegetable oils (HVO) are also known as hydrotreated esters and fatty acids (HEFA), renewable diesel, green diesel, or hydrotreated renewable oils (HRO). They consist of vegetable oils or animal fats that have undergone hydrotreatment and refining, usually in the presence of a catalyst. Hydrotreatment involves the input of hydrogen to the feedstock in a two-stage process: the feedstock is first deoxygenated and their double bonds are saturated to form alkanes. In the second step, the alkanes undergo isomerization and cracking. During this step, known as ‘dewaxing’, alkyl chain length is reduced and hydrocarbon branching increased. This process produces mainly diesel fractions, with only a small portion for jet fuel blends. HVO can be produced in oil refineries, as they are already equipped with hydrotreating facilities. However, there may be some modifications that will require new investments to develop a HVO-only production facility. The overall production process is typically more costly than for FAME diesel, however, hydrotreating vegetable oil leads to a drop-in fuel which can be directly introduced in distribution and refueling facilities as well as existing diesel engines without any further modification.

Biofuel Provider. Neste Corporation (Finland) is a publicly traded oil refining and engineering company producing petroleum products and renewable fuels. Neste produces HVO in four state-of-the-art plants: two in Finland, one in The Netherlands, and one in Singapore. Neste is the market leader in producing renewable diesel from waste and residues with a superior quality compared to traditional biodiesels. The company is the largest producer of drop-in fuels from palm oil, though they have used over ten different raw materials. The production technology is marketed as NexBtL, and is used to make both diesel and aviation fuel.

HVO production is already at a full commercial scale, with Neste being the market leader. HVO is considered an easily accessible fuel that can substitute HFO and reduce GHG emissions and is low in sulphur. Since it is a type of drop-in fuel, it can be either blended with conventional fuels or used neat without any damage to the engine. The advantage of HVO over biodiesel FAME is that the hydrogenation process used to produce HVO removes all of the oxygen from the vegetable oils, leading to higher fuel efficiency and a much longer shelf life as there is a much lower chance of fuel oxidation. The feedstock used to produce HVO need not be as high quality as that for biodiesel, and the end product has much higher cetane number and energy density.

Biofuel Provider. Emerald Biofuels (USA) is a privately held transportation fuel company based in Chicago, Illinois focusing on the production of drop-in renewable diesel fuel from non-edible waste oils[66]. The company has a projected, but yet to be build, production plant at the Dow Chemical site in Louisiana on the US Gulf Coast. The projected capacity of the plant is 82 million gallons per year, using animal fat and natural oils as feedstock. UOP, a Honeywell company, signed an agreement to license their technology to Emerald Biofuels for the production of Honeywell Green Diesel at such facility. The Green Diesel fuel consists of a high cetane value of 80 and improved performance compared to biodiesel.

In September 2014, Emerald Biofuels was awarded a contract with the US Navy to produce HEFA for F-76 (naval distillate fuel) drop-in fuel and private sector transportation needs. The contract is intended to make biofuels competitive with fossil fuels[67].

Despite using renewable feedstocks as a starting material, HVO will have to be blended with conventional marine fuels in order for its production to be feasible in the long run, as the fuel volumes required for short and long distance shipping are still too high for HVO to attain on its own. HVO feedstock prices also vary depending on the source. Palm oil, for example, was at a 10-year high of USD$1,250 per metric ton in February 2011, while used cooking oil sold at its highest for USD$720 per tonne in January 2013[68]. Prices for both commodities have since fallen to $650 and $400[69] per tonne in 2016 for palm oil and waste cooking oil respectively. Not only are lipid feedstock prices seasonal, but are also affected by labor costs and land usage (sustainability), further adding to their volatility. With the additional processing costs to upgrade the fats and oils, HVO would be more commercially beneficial to the aviation sector as a high quality fuel to compensate for the feedstock and upgrading costs.

The food vs. fuel debate has further pushed the case for algal biofuel production, as photosynthetic algae and/or cyanobacteria can be grown using saline and wastewater (non-arable land or marine environments) with higher lipid yields than plants. Fuels produced from algal biomass can have a high flash point, and are biodegradable and compatible with conventional biodiesel. Algal feedstocks show a theoretical potential to be turned into fuels because the strains may have very high growth rates, translating to high biomass yield per hectare. However, these numbers should be approached with great care, as they have not been shown in neither demonstration nor commercial-scale units. When algal oils are hydrotreated, they can also function as a no-sulphur drop-in fuel. The major drawback of biofuel production from algae is the processing cost. To date, there is not yet any commercial algal fuel available on a consistent basis, due to its high capital and operating costs. As a result, algal biomass has a much higher cost per unit mass than other 2nd generation biofuel crops. Algae biofuel companies are still in the technology development phase, often with the support of government funding agencies and/or universities. Commercial algae facilities focus on the production of nutritional additives, lipids and proteins.

Research into algae for mass-production of oil focuses mostly on microalgae, as opposed to macroalgae. Microalgae have less complex structure and faster growth rates than macroalgae and some species produce higher oil content. Genetically engineering algae is one way to select for productivity, lipid content, and thermal tolerance. A few of the difficulties in the commercialization process stem from finding algal strains that fit the stringent criteria of high lipid content, fast growth rate, easy to harvest, and suitability for growth in a cost-effective cultivation system all at once. After harvesting the algae, the biomass needs to be processed in a series of steps. The main bottlenecks to commercializing algal fuels are the lipid extraction process, where the cost of extraction is often higher than the desired products, just as very high amounts of water needs to be handled and processed e.g. recycled. Further information on the potential of algae as a biofuel has been published in an earlier IEA Task 39 report[70]. A more recent State of Technology review on the feedstock potential of algae for bioenergy and bioproducts was also published by IEA Bioenergy Task 39 in early 2017[71,72].

More recent algal fuel investments include Exxon Mobil's $600 million partnership with Synthetic Genomics to develop, test, and produce algal-based biofuels[73]. The research focus of this partnership consisted of algae-growing methods and oil extraction techniques. Additionally, Exxon could potentially invest more to scale up the technology and start commercial production. By 2013, however, the total money spent was around $100 million and Exxon has shifted their biofuels development strategy as the partnership has not yet created fast-growing, high-oil content algae to make mass production commercially viable. Since then, Exxon has partnered with other industries, including REG (formerly LS-9, Inc.), to produce renewable diesel by fermenting renewable cellulosic sugars from agricultural residues[74].

Fuel technology. Chevron Lummus Global (USA) is an engineering license and servicing company combining the hydroprocessing know-how from Chevron and the engineering expertise from CB&I. It is focused on technologies which upgrade heavy oil to sulphur-free gasoline and diesel. Together with Applied Research Associates (ARA), they have been selected to produce 100% drop-in alternative fuels in North America using their Biofuels ISOCONVERSION process. The technology can produce jet, gasoline, and diesel fuel from a diverse array of plant oil feedstocks. ARA has patented a novel catalytic hydrothermolysis process, while CLG has contributed to hydroprocessing technology with operating expenditures similar to petroleum refining.

ARA and Chevron Lummus Global have developed a process to convert renewable fat, oil, and grease from animal, plant, or algae feedstock to drop-in hydrocarbon fuels in high yields, marketed as ReadiJet and ReadiDiesel[75]. Drop-in ReadiDiesel has recently been tested on a US Navy ship, the Naval Surface Warfare Center, Port Hueneme Division's Self Defense Test Ship, taking in 18,000 gallons of fuel in a period of 12 hours to power a gas turbine engine and gas turbine generator. In all, ARA provided 79,000 gallons of ReadiDiesel for the test program[76].

5.3.2. UPGRADING OF PULPING RESIDUES

The pulp and paper industry utilizes lignocellulosic fibrous material to produce pulp. Feedstocks for pulp production include wood, fiber crops, or waste paper. Wood fiber for pulping is a mixture of sawmill residues, logs and chips, and recycled paper. Wood and other plant materials used to make pulp chemically consists of three main biopolymers: cellulose, hemicellulose, and lignin. Chemical pulping processes such as kraft, sulfite, and soda pulping degrade the lignin and hemicellulose into smaller water-soluble components while leaving the desirable cellulose fibers intact.

The extracted cellulose obtained from pulping is further processed to make paper, while the lignin and hemicellulose are burnt to recover the cooking chemicals and provide process energy. Current processes burn lignin for fuel, but research efforts over the last decades have focused on creating higher value products out of the lignin waste stream. There exists the possibility of converting the residual lignin from pulping process into bunker fuels, especially when they do not contain sulphur.

Lignin, once separated after the pulping process, can be converted to lignin oil via thermal conversion (e.g. pyrolysis) using catalysts. The lignin oil, a fuel intermediate, can be further processed into petrol and/or diesel components. The black liquor can also be directly gasified to produce syngas, and subsequently bio-methanol and bio-DME.

Besides lignin and hemicellulose, another waste product from pulp production is tall oil. Tall oil is a dark viscous liquid generated during Kraft pulping as a by-product after treating the spent cooking liquor. The main feedstocks for extraction of tall oil are currently from Scandinavian forests e.g. pine, spruce, and birch. Yields for tall oil range from 30-50 kg per ton of pulp, and production volume is limited by the pulp and paper industry. Tall oil has historically been used as a component of drilling fluids, adhesives, and rubbers. There have been efforts to convert tall oil into renewable diesel for blending with diesel fuel, though the biggest challenge is sourcing the feedstock in large volumes.

Biofuel provider. UPM (Finland) is a multinational forestry industry company focusing on biorefining, timber, energy, and pulp & paper. They developed technology to produce wood-based renewable diesel, branded as BioVerno diesel. The renewable diesel is produced from non-food forest residues, namely tall oil, a residue of pulp production, as feedstock. UPM invested in a commercial biorefinery plant in Lappeenranta, Finland, producing approximately 100,000 annual tonnes of 2nd generation drop-in renewable diesel[77]. Construction of the biorefinery began in 2012 and completed in 2014. Most of the fuels produced are targeted to the road transportation sector, though their final fuel product is suitable for all diesel engines.

Biofuel Provider. SunPine (Sweden) is a company specializing in the production of fuels and chemicals from by-products of the forestry industry. Founded in 2006, the company is focused on sustainable forestry practices and adding value to residual products from the pulp industry. Their production plant is located in Piteå Harbour in northern Sweden, and has been operational since 2010. At the moment, SunPine focuses on extracting tall oil from the pulp and paper industry as a raw material for their renewable products portfolio. Their crude tall oil (CTO) intermediate product is further processed at the Preem refinery to upgrade the tall oil diesel to a higher quality drop-in fuel, branded as green diesel, which can be blended with regular diesel fuel. SunPine also uses tall oil to produce bio-oil and resin.

Hydrogenating the tall oil creates an HVO-like fuel, which can be used as a drop-in diesel fuel or blended with conventional fuels. The production setup is similar to that for HVO production, taking place in traditional refineries using chemical catalysis.

5.3.3. THERMOCHEMICAL

Thermochemical processes for the production of biofuel use high temperature and/or pressure and possibly homogeneous and/or heterogeneous catalysts to convert biomass to liquid fuels and chemicals as well as heat and power. In contrast to lipid feedstocks used for biodiesel and HVO production, feedstocks converted by thermochemical processes are mainly lignocellulosic-based. Thermal conversion begins with biomass (wet or dry) being converted to fluid intermediates (gas or oil) and then catalytically upgraded or hydroprocessed to hydrocarbon fuels.

Pyrolysis treatment involves biomass being subject to high temperature and short residence time in the absence of oxygen and often in the presence of an inert gas. The biomass is treated at 500°C for a few seconds, whereupon a fraction enters a gas phase and another fraction converted to pyrolysis oil, biochar, and syngas (methane, hydrogen, carbon monoxide, and carbon dioxide). Lower pyrolysis temperatures with slow heating rates yield more biochar, while higher temperatures and rapid heating rates yield more gases. It should be noted that the term bio-oil is often used for as abroad term covering pyrolysis-oil as other types of thermally liquefied biomass. Wood and other energy crops are generally used as feedstock, though it is important that the material is milled and dry (less than 10% moisture content) before entering the pyroreactor.

Fuel Technology. Envergent Tech (a Honeywell company) converts cellulosic biomass feedstock into RTP (rapid thermal processing) green fuel using fast pyrolysis technology. It is a joint venture between UOP Inc. and Ensyn, the latter providing the reactor engineering expertise and the former contributing to refinery hydrotreatment catalysts and equipment. RTP green fuel is used to produce heat, drop-in liquid transportation fuels, and generate electricity.

Envergent has a pilot production facility in Tesoro, Hawaii for pyrolysis and upgrading technology to transport fuels. Their RTP for biomass conversion uses a variety of lignocellulosic feedstocks (forest residuals, agricultural by-products, lignin waste from pulping, energy crops) heated rapidly to 500°C by contact with hot sand in the absence of oxygen and circulated through a fluidized bed reactor system similar to fluid catalytic cracking (FCC) technology. The biomass is first vaporized and then rapidly cooled in less than 2 seconds. The resulting fuel has high oxygen and water content as well as low pH, which can be used in industrial burners. To create a drop-in fuel, the resulting RTP green fuel has to be further upgraded by hydroprocessing into renewable gasoline, diesel, and jet fuel.

The product ratio of pyrolysis-oil, biochar, and syngas can be controlled based on the temperature and reaction heating time. For the production of liquid fuels, pyrolysis oil is the most favored fraction, and thus the most widely used pyrolysis system uses 500°C and fast heating rates (fast pyrolysis). Pyrolysis oil is a dark brown liquid with higher energy density than the original starting material. The combustion of pyrolysis oils also produces less SOx and NOx emissions, though particulate matter is quite high. Pyrolysis oil yields during pyrolysis vary depending on the feedstock, process type and conditions, and the efficiency of product collection, and have been reported to be as high as 70-80%[79], though yields as low as 20% are also common[80]. The syngas obtained from pyrolysis can also be used to produce methanol, though in very low yields. Instead, gasification would be a more effective route for methanol production.

Pyrolysis technology cannot yet produce synthetic diesel fuel, but the pyrolysis oil produced can be used as an intermediate material to produce a substitute fuel for petroleum. Pyrolysis oil on its own is very prone to oxidation, and it still contains a level of oxygen too high to be considered a hydrocarbon. The high oxygen content also gives pyrolysis oil a short storage life, and the energy density is lower when compared to bunker fuel. Depending on the pyrolysis parameters, the final water content can be as high as 30%, enough to decrease the thermal energy and promote phase separation during storage periods of less than 6 months at room temperature. A catalytic upgrading step is therefore needed to remove oxygen in the pyrolysis oil and increase its storage stability in order to meet the specifications for a drop-in fuel. Hydrogenation converts the pyrolysis oil to hydrogenated pyrolysis oil (HPO) which then can be suitable for diesel engines. This process can take place in dedicated facilities or co-processed in traditional petroleum refineries, though it is not yet fully commercialized. Chemically, the difference between HVO and HPO is that HPO contains a small amount of aromatic compounds, which is beneficial for aviation fuel, but not necessarily marine fuel.

For marine fuel applications, pyrolysis oil can be used as a component in emulsion biofuels to increase its thermal efficiency and reduce particulate emissions when used in diesel engines[81]. Emulsifying pyrolysis oils not only enhance the stability of the fuel, the addition of emulsifiers (surfactants) act as viscosity modifiers to create more optimal fuel properties.

Hydrothermal liquefaction (HTL) technology converts biomass into crude-like bio-oil using moderate temperature and high pressure[82]. The crude-like bio-oil product has high energy density with a lower heating value of 34-37 MJ/kg and 5-20% wt oxygen. The HTL process involves short residence times, measured in minutes, and uses homogeneous and/or heterogeneous catalysts to optimize product conversion yields. Most processes operate at temperatures between 250 and 550°C with pressures of 5-25 Mpa with catalysts for 20 to 60 minutes. The difference between

HTL and pyrolysis is that it can process wet biomass and produce a bio-oil with higher energy density. Water present in the biomass at these temperatures and pressures is either subcritical or supercritical, and acts as a solvent, reactant, and catalyst to facilitate the liquefaction process[83]. A few companies are working to commercialize this technology to bring HTL-produced fuels to market, though it is still behind HVO production technology.

Carbon and hydrogen components in biomass are thermochemically converted to hydrophobic compounds with low viscosity and high solubility. Oxygen present in the biomass is removed via dehydration (loss of H_2O) or decarboxylation (loss of CO_2). Ideal feedstocks are non-chemically/biologically processed agricultural residues and woody biomass, where there is a mix of carbohydrates and low lignin content to reduce the risk of charring. The end product thus results in a high H/C ratio favorable for drop-in fuels. The liquid fuel produced is suitable for use in heavy engines, such as marine and rail, or can be upgraded further to other transportation fuels such as diesel, gasoline, and jet fuel.

steeper ENERGY
The Renewable Oil Company™

Fuel Technology. Steeper Energy is a Danish-Canadian company developing and commercializing their HTL Hydrofaction platform for conversion of organic feedstocks to drop-in fuels. Their patented Hydrofaction technology uses high pressure-temperature or super critical water to transform low energy density organic feedstocks to high energy density oil suitable as liquid fuel for large compression engines (used for electricity generation or rail and marine propulsion). The chemistry of the liquefaction process involves both solvolysis and pyrolysis including a gas phase. As of 2013, the company has partnered with Aalborg University and the Port of Frederikshavn to initially produce around 50-100,000 tons of sulphur-free biofuel annually to comply with SECA regions[84]. Their plan is to develop an Industrial Scale Pilot Plant to commercialize biomass-to-liquids technology (2,000 barrel per day industrial scale demonstration project) using lignocellulosic forestry residues or agricultural non-food waste.

Licella

Fuel Technology. Licella[85] is an Australian company that uses a proprietary Catalytic Hydrothermal Reactor (Cat-HTR) process technology to convert waste biomass into a stable bio- oil. Feedstocks that can be processed include wood waste, energy crops, and agricultural residue such as sugar cane bagasse. The bio- oil can be further refined in a conventional refinery into biofuels and other high-value biochemicals, which is done by Licella Refining, a subsidiary of Licella. Products include kerosene and diesel. In May 2016, Licella formed a joint venture with Canfor (Canada) to integrate Licella's Cat-HTR upgrading platform with Canfor's kraft and mechanical pulp mills to convert biomass into bio-oil. The venture would allow Canfor to optimize their pulp production capacity and diversify into the bioenergy business.

Fuel Technology. Altaca Energi Inc. (Turkey) is an alternative energy company using CatLiq (catalytic liquefaction) technology to convert wet organic waste and biomass into a high quality green crude oil. The CatLiq technology was invented by SCF Technologies (Denmark), and Altaca bought all the IP rights to the technology in 2011. In this process, waste biomass is treated with water at supercritical conditions (high temperature, pressure, humidity) in alkaline anaerobic conditions to generate a synthetic fuel[86]. The bio-oil is then further refined to fuels for road and marine transport using homogeneous and heterogeneous catalysts.

Altaca Energi has been operating a pilot facility in Gebze, outside of Istanbul, since 2012, and their Catliq plant in Gönen for the production of liquid transportation fuels has been planned to be put into operation by the end of 2015[87]. 200 tons of organic waste will be used daily, and the plant is targeted to daily produce 20-30 tons of green crude. The company also produces biogas from waste from the surrounding farms and food facilities for power generation.

Fuel Technology. Renmatix is an American company using hydrothermal (water-based) liquefaction technology to turn biomass into sugars for industrial use. Renmatix developed the Plantrose process to convert non-food biomass into industrial sugar-derived chemicals and polymers. It is free from enzymes, solvents, and acids, providing a low-cost method for biomass deconstruction. It is a continuous 2-step process which first separates the hemicellulose stream, followed by cellulose/glucose separation, and uses the residual lignin solids as heat energy by burning-though lignin can potentially have high-value applications like thermoplastics or adhesives.

Renmatix has received investment funding from Total, BASF, UPM, Waste Management, and Bill Gates. They have three production facilities in North America, one in New York for feedstock processing, one in Georgia as a demonstration scale facility of the Plantrose technology, and another in Pennsylvania dedicated to pilot scale and R&D activities.

Gasification technology involves the conversion of biomass at high temperature (900°C) and pressure in the presence of little oxygen and/or steam to gas, where the intermediate product is referred to as synthesis gas (syngas). Chemically, gasification breaks down the starting material into its most basic components (CO, H_2, and CO_2), which can be used directly as a fuel to power gas engines and turbines, produce heat, and generate electricity. For the production of liquid transportation fuels, the syngas can be further processed using Fischer-Tropsch catalysts and hydrotreating into a broad range of hydrocarbon liquids such as methanol, diesel, or other synthetic fuels. It is a very energy-intensive process, but does possess some advantages over direct combustion of the starting material. The final product has higher stability over time compared to using pyrolysis. Feedstocks can range from woody biomass to agricultural residues (lignocellulosic waste streams).

Commercially, biofuels produced via gasification are known as BtL (biomass-to-liquids) or synthetic Fischer-Tropsch (FT) fuels. The technology to produce FT fuels stems from traditional syngas production using coal or natural gas. This technology has been applied at an industrial scale for decades to produce synthetic liquid hydrocarbons from non-liquid hydrocarbon sources (hydrogen and carbon monoxide). The FT production process is also a viable route for the production of bio-kerosene for the aviation industry, and in most cases, is even more cost competitive.

Fischer Tropsch biomass to liquid (BTL) production technologies use thermal energy to gasify the raw material into synthesis gas rich in hydrogen and carbon monoxide. The gas is cleaned to remove sod and tar, which after purification is converted via Fischer-Tropsch (FT) catalysts to liquid hydrocarbons such as synthetic diesel and bio-kerosene. FT diesels tend to be less energy dense than natural gas and contains more impurities. However, it is an attractive process to produce low-sulphur diesel fuel. Historically FT-fuels was used at a large scale by Germany during WW II and South Africa during the apartheid embargo.

Fuel Technology. Velocys (formerly Oxford Catalysts) is a catalyst company focusing on small-scale GTL and BTL, turning natural gas or biomass into premium liquid products such as diesel, jet fuel, waxes, and base oils. Based in the USA and UK, they have developed and patented FT technology (reactor and catalyst system) for the production of raw FT products with carbon chain lengths 5 or greater, and have commercial and technology centers in the US and UK. Commercial projects include a GTL plant built in collaboration with ENVIA Energy using landfill gas and natural gas as feedstock (completed in 2016) and a BTL plant built in Oregon, USA in collaboration with Red Rock Biofuels. The BTL plant will convert forest-derived biomass to liquid transportation fuels using FT technology from Velocys[78].

Biofuels produced via gasification have a stronger potential in the aviation fuel market in comparison to marine fuels, as the value-added price of aviation fuel outweigh the energy and refining costs of producing a higher-quality clean fuel. For shipping fuel applications, fuel-grade methanol can be produced from the syngas obtained via the biomass gasification process. The biogas produced is catalytically converted to bio-methanol with yields as high as 75%.

As an alternative to the Fischer-Tropsch processing, syngas produced during gasification can also be converted to dimethyl ether (DME) by methanol dehydration or methane via the Sabatier process. For the production of DME, methanol is currently, for the main part produced, from natural gas, but it may also be obtained from (bio)syngas or (bio)methane derived from coal and oil or from organic waste and biomass. DME can be used as a fuel in diesel engines, petrol engines, and gas turbines. The advantage of DME is that very low levels of particulate matter, NOx, and CO are emitted during combustion. However, special issues rise with lubrication as DME is absent of lubricating.

Another pathway is the Sabatier process involves reacting hydrogen gas with carbon dioxide at elevated temperature (300-400°C) and pressure in the presence of a catalyst to produce methane and water. Though methane can be used as a transportation fuel, it is mostly used to generate combined heat and power. Methane can, however, be stored as CNG or LNG to be used as a petrol or diesel fuel.

Solvolysis is a thermal process where biomass is liquefied in a closed chamber with supercritical organic solvent under pressure. It is similar to hydrothermal liquefaction, but utilizes an organic, low-boiling solvent instead of water. Feedstocks include the whole biomass or leftover hydrolysis lignin obtained from 2nd generation bioethanol production plants. Organic solvents that have been tested are methanol, ethanol, 1-propanol, and 1-butanol. The reaction product is a bio-oil, which can be further processed to a low-oxygen drop-in fuel. Depending on the starting material, the end product is sulphur-free and is suitable for blending or as a drop-in fuel. The entire process is catalyst-free and does not need any hydrotreating before blending with diesel fuels.

The solvolysis process involves treating the biomass at elevated temperature (typically between 300 and 450°C) and pressure in organic solvent at short residence times. The process has been tested at the laboratory scale, and there are plans to move on to pilot scale production. During solvolysis, the ratio between solvent and biomass is an important parameter in terms of cost. Reactions at 350°C offer a good compromise between yield and solvent consumption in laboratory-scale tests. Laboratory scale yields approximately 40% oil and 40% char, with the remaining converted to gas or unaccounted for.

The advantage of the solvolysis process, as opposed to other thermal processes such as hydrothermal liquefaction, is that it is suitable for high-lignin content feedstocks. The Danish Technical University and the University of Copenhagen patented a process to directly liquefy lignin via solvolysis without the use of catalysts[88]. The bio-oil produced is of superior quality to pyrolysis oil as it is non-acidic, stable, and can readily blend with fossil diesel without the need for exhaustive deoxygenation. The so-called lignin diesel oil (LDO) is low in oxygen, which is ideal for a drop-in fuel or MDO blend with a high heating value. Considering that hydrolysis lignin is a sulphur-free starting material, this direct lignin liquefaction process increases lignin valorization and is suitable for the production of other value-added lignin-derived chemicals. One of the concerns with using hydrolysis lignin as a feedstock is its high concentration of accumulated silica (ash) from the original biomass, especially when using agricultural residues such as wheat straw. Multiple batch experiments have shown that during solvolysis, the silica originally present in the starting plant material is retained in the ash and not recovered in the oil fraction, and thus no further processing steps are necessary to create the drop-in biofuel.

5.3.4. HYBRID TECHNOLOGIES

The production of marine biofuels can potentially be integrated into a biorefinery focused on bioethanol production from e.g. pulp & paper processing or 2nd generation lignocellulosics, where the residual lignin waste can serve as a feedstock for further fuel upgrading. Hybrid technology refers to the production of fuels by both biochemical (fermentation of carbohydrates) and thermochemical (thermal upgrading of lignin) processes. While bioethanol is not a drop-in fuel, the residual lignin can be converted to a drop-in fuel via thermal treatments such as gasification or solvolysis. During these thermochemical processes, the residual lignin is converted to fluid intermediates (gas or oil) which are then catalytically upgraded to hydrocarbon fuels[89], thereby upgrading low-value lignin to a transportable liquid bunker fuel.

5.3.5. BIOETHANOL

Production of bioethanol involves the microbial fermentation of sucrose, starch, or cellulose (glucose-based feedstocks) to ethanol. Bioethanol is currently the most consumed and transported biofuel to date, with the US being the largest producer, followed by Brazil[90]. First generation bioethanol feedstocks include sugar cane, corn, and sugar beets. Second generation cellulosic ethanol produced from non-edible biomass has also been successfully commercialized over the past few years. Commercial production of bioethanol is almost twice as much as biodiesel, with the majority of the fuel used for automotive transportation. Bioethanol has a lower cetane number and lower energy content than biodiesel, though its use reduces the emissions and carbon footprint of shipping operations[91]. The advancement of new multifuel diesel engine technologies can potentially open the marine fuel market for bioethanol, but it will be decades before these technologies can be found in a larger number of the vessels.

Fuel Technology & Fuel Provider. BetaRenewables (Italy) was established in 2011 as a joint venture between Biochemtex (Italy), Texas Pacific Group (USA), and Novozymes (Denmark). BetaRenewables owns the PROESA technology, a patented process to produce second generation biofuels and biochemicals at a commercial scale. The company has tested their technology on various lignocellulosic biomass, including energy crops, woody biomass, and agricultural residues for bioconversion to ethanol. At the end of 2012, BetaRenewables, partnered with Biochemtex, completed the first commercial 2nd generation bioethanol plant in Crescentino, Italy to showcase their PROESA technology. The bioethanol produced is derived from wheat straw and giant reed, which are locally available within a 70 km radius from the plant. PROESA first involves a biomass pretreatment step, followed by saccharification and fermentation of C5 and C6 sugars to ethanol. BetaRenewables is still actively developing the biorefinery process, and future plans include fermentation to other C5- and C6-derived chemicals such as butanol, fatty alcohols, and ethylene glycol[92].

First generation bioethanol production uses sugar- or starch-based feedstocks, such as sugar cane or corn. The carbohydrates obtained from these crops are relatively easy to extract and hydrolyze to glucose before fermentation to ethanol. Advantages of using first generation feedstocks for bioethanol production are that the infrastructure for planting, harvesting, and processing is already in place. The bioconversion process is also simple. However, crops such as sugar cane and corn are also food staples in many regions around the world, and would not be a viable solution to meet the world's energy needs due to their low yields per hectare. Bioethanol production interest has therefore shifted to 2nd generation fuels.

For 2nd generation ethanol production, lignocellulosic feedstocks are the most common. These include woody biomass, agricultural residues (corn stover, wheat straw), and grasses. Extracting and processing the carbohydrates for fermentation to ethanol using these feedstocks is more energy-intensive and requires more steps. Because the carbohydrates in 2nd generation feedstocks are not easily accessible in their native state, the starting material needs to first undergo a pretreatment process (steam, dilute acid) before its cellulose content can be hydrolyzed by cellulolytic enzymes. The glucose produced from the hydrolysis step is then fermented to ethanol, where it is vacuum distilled and processed as a fuel. The residual solids from distillation is mainly lignin[93], referred to as hydrolysis lignin, which can be used directly as a heating fuel or converted to further value-added products. The entire production process is sulphur-free or very low in sulphur depending on the initial pre-treatment, thus ensuring the ethanol and lignin co-product would be compliant with the IMO sulphur directives, if they are introduced to the marine fuel mix.

Fuel Technology & Biofuel Provider. POET-DSM Advanced Biofuels is a joint venture between POET (USA) and Royal DSM (the Netherlands) making cellulosic bioethanol competitive in the renewable liquid transportation fuel market. POET has a history of being one of the world's largest ethanol producers from grain, while DSM is a leading biotechnology company with expertise in scaling up industrial and biotechnological conversion technologies.

The company inaugurated Project LIBERTY, the world's first commercial cellulosic ethanol plant, in Emmetsburg, Iowa on September 3, 2014, converting 285,000 tons of corn crop residues to 25 million gallons of cellulosic bioethanol annually[94].

The hydrolysis lignin obtained from 2nd generation bioethanol production has a potential to be used as a sulphur-free feedstock for the production of advanced marine biofuels, as covered in the 'Biofuel production technologies – Hybrid technology' section in this report.

5.3.6. BIOMETHANOL AND BIOGAS

Methanol is a colorless, volatile, flammable liquid that is industrially used as a chemical reagent, a solvent, and antifreeze. It is also used as a reagent in the transesterification reaction for the production of biodiesel. Methanol has only recently gained interest as a shipping fuel due to its high abundance and relatively low cost of production. Like for ethanol, methanol is a compatible fuel in multifuel marine diesel engines. Industrially, the most economical way of producing methanol is from methane. In this process, natural gas (methane) is mixed with steam, heated, and passed over a heterogeneous catalyst in a steam reformer. The gas/steam is transformed to syngas, which is then pressurized and converted to methanol over a catalyst, and finally distilled to remove water and impurities to yield pure methanol. The most effective catalysts for methanol synthesis are copper, nickel, palladium, and platinum. Methanol is also produced from coal, predominantly in China. Methanol can also be produced from biomass, but most large-scale projects to develop such technologies are currently stalled.

Methanol synthesis from captured CO_2 is a technology under development to a semi-commercial scale. Both Iceland and Japan have plants that combine CO_2 and H_2. On the back of a pilot plant operating since 2007, Carbon Recycling International (CRI) launched operations for the first commercial demonstration plant in Iceland, in 2011, with access to low-cost, geothermal power and produces 5 mtpa of methanol. CRI aims to use surplus and intermittent renewable energy sources to produce chemicals and fuel from CO_2 captured from coal power and coking plants. In 2008, Mitsui Chemicals Inc. launched a pilot plant in Osaka to synthesize methanol from CO_2 and H_2, producing 100 mtpa. The installation uses captured CO_2 emitted from nearby factories and H_2 obtained from water photolysis.

As described methanol can be produced via the conversion of syngas from gasification of fossil sources. During gasification, organic or fossil fuel-based carbonaceous materials are converted to carbon monoxide, hydrogen, and carbon dioxide. This resulting syngas (biogas if using biomass) mixture can be upgraded to methanol using catalysts at high pressure and low temperature. The most widely used catalyst is a mixture of copper and zinc oxides supported on alumina at a temperature range between 220 and 275°C and pressures of 50-100 bar.

Enerkem

Fuel Technology. Enerkem is a private Canadian cleantech company with technology to convert waste biomass and municipal solid waste into clean transportation fuels and chemicals. Enerkem's gasification and catalytic conversion technology produces syngas, methanol, and ethanol fuels. The company currently has one pilot plant, one demonstration plant, and one commercial facility, all located in Canada. The City of Edmonton and Alberta Innovates partnered with Enerkem to build and operate the commercial scale plant in 2014, with the aim of saving municipal solid waste from being landfilled and thus converting it to syngas and then methanol[95]. The commercial facility has a capacity to produce 38 million liters of methanol and ethanol a year.

Methanol fuel has some advantages over LNG as it is a liquid fuel at ambient temperature, and more compatible with existing liquid fuel infrastructure. However, the low energy density makes it less attractive for deep sea vessels, as bunkering is required at a 2-3 times higher frequency compared to current liquid fossil fuels. While there are abundant reserves of natural gas globally, processing methanol or cooling to LNG are both energy intensive processes.

However, it must be recognized that although the production of methanol from natural gas or other fossil feedstocks, is an established and large-scale industry, it is basically not a viable solution to reduce the environmental and climate impact of the maritime sector. Only if methanol is produced on the basis of renewable resources i.e. biomass-based syngas can it be considered viable. Bio-methanol can also be produced from e.g. biogas by an oxidation of methane to methanol, however, this process implies a large loss of energy density due to the oxidation and is not considered viable.

Fuel end user. Stena Line is a Swedish private family-owned international shipping company and one of the world's largest ferry operators founded in 1962. They operate ferry lines as well as crude tankers, RoRo vessels, and offshore drilling vessels, mainly serving Northern European markets (Irish Sea, North Sea, and Scandinavia).

Stena Line launched the world's first methanol powered ferry in March 2015 on the *Stena Germanica* ferry, carried out in collaboration with the engine manufacturer Wärtsilä. The retrofitting process took a few months, where the *Stena Germanica*'s fuel systems and engines were adapted to dual fuel technology, using MGO as backup[96]. The ferry travels on the Kiel-Gothenburg route with methanol fuel supplied by Methanex Corporation[97], which produces methanol on a commercial scale from natural gas. However, research and development efforts are underway to produce methanol from forest products and biomass in order to further reduce CO_2 emissions. Stena Line is constantly looking into other alternative fuels for vessel propulsion such as batteries to comply with environmental regulations and become more energy-efficient by reducing energy consumption.

Biogas made from anaerobic fermentation is potentially a feedstock for producing liquefied biogas (LBG). The only technical requirement for processing biogas into LBG is that the methane is purified by removal of the CO_2 associated with the fermentation. This purification process is already common at biogas plants connected to a gas grid.

5.3.7. EMULSION BIOFUELS

Emulsion fuels have long been used as heating fuels in diesel power-generating stations. These fuels are known to enhance combustion efficiency in addition to decreasing NOx, smoke, and particulate emissions. There are several ways of creating emulsion biofuels. One involves animal fats or vegetable oils converted to biodiesel and emulsified with water and a surfactant[98]. Another method involves mixing pyrolysis oils with biodiesel and emulsified in the presence of a surfactant[99]. In some cases, oxygenated compounds such as methanol, ethanol, and dimethyl carbonate are added to the formulation to improve the ignition quality of the fuel. The stability of the fuel can vary, with phase separation occurring within minutes or in a matter of days, depending on the water and surfactant concentration[100].

Emulsion biofuels have a low energy density, but have been tested on ocean going vessels, and as such are known to the shipping companies. They have the potential to be used for long distance shipping, as they have high thermal efficiency and are compatible with diesel engines. However, there is no commercial production of emulsion biofuels to date. Note that the emulsion fuels are not included in figure 9, as basically they can be based on any carbon based fuel or material.

5.4. BIOFUEL BLENDING

Blending conventional fossil fuels with biofuels is an alternative to reduce fossil fuel consumption while introducing compatible drop-in fuels in the fuel mix. Low-level fuel blends available in the road transportation sector include E10 (10% ethanol, 90% gasoline), B5 (5% biodiesel, 95% diesel), and B2. In Europe, North and South America, biodiesel blends from B7 to B20 are available for the automotive market.

In the case of marine fuels, renewable fuel blending mandates are still not in place, and biodiesel blends are not yet available in the shipping fuel market, though production and distribution is available through set contracts. Testing of biofuel blends onboard ocean going vessels has been reported for 7% to 100% biofuel blends, of which results have shown that biofuels can be effectively blended with regular fuel with no drastic effects on the engine[101].

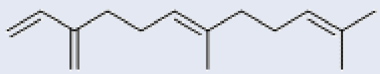
Fuel technology. Progression Industry (Netherlands) is a spin-off company of the Eindhoven University of Technology specialized in developing and commercializing automotive technologies. One of their main projects is CyclOx, a diesel fuel made by mixing cyclohexanone with diesel. Cyclohexanone delays the diesel combustion process, thus allowing the diesel to mix better with oxygen so that less NOx and soot are emitted during combustion. This means that a higher combustion temperature can be permitted in the engine, in turn reducing NOx. Once blended with diesel, cyclohexanone also decreases soot emissions[102]. CyclOx fuel has the potential to be produced by extracting oxygenates via depolymerization of lignin, thus making it a second generation biofuel[103,104]. Progression Industry has been collaborating with Mærsk, the world's largest container shipping company, to develop this lignin-based marine fuel since 2012.

Guidelines and legislation regarding marine biofuel blending are still under implementation and development. To start introducing marine biofuels into the fuel mix, biofuel blending with conventional marine fuels is a necessary starting point to stimulate biofuel demand, as biofuel production is not yet at full commercial capacity. Using blends also help ship engines transition from conventional fuels to drop-in fuels. As mentioned previously, biofuel blends can help ship owners comply with low sulphur content in their fuel and reduce overall carbon emissions, though the guidelines regarding the blending parties are not yet clear.

Blending can occur at the refinery, at the fuel storage facility, on the bunker ship, or on board the receiving ship. According to current market practices, it would be best done at the bunker level, as biofuels have a different supply chain than fossil based fuels. The biofuel would be mixed with fossil fuels on the bunker ship, and the bunker tanks would get emptied and cleaned before the next bunker fuel is loaded. This means bunker parties would be responsible for taking the initiative to provide biofuel blends, though ultimately the decision to use biofuel blends lie with the ship owners.

The advantage of biofuel blending onboard ships is that biofuels can be stored separately from fossil-based fuels, thus maintaining better fuel properties. Biofuels would be kept in separate storage tanks, and then blended with fossil fuels in the main engine when needed, for example, when passing through sulphur ECAs. However, handling and maintaining a separate fuel tank requires additional operational costs which would not be favorable for ships owners. For example, fuel would have to be sampled from every storage tank containing a different fuel, and crew would have to be trained in handling a biofuel tank. Therefore, blending at the bunker level would require the least amount of infrastructural changes to the supply chain, as the fuels are already pre-blended on board, and ship owners have no need for dedicated biofuel tanks onboard. However, in most cases there are separate fuel systems for main and auxiliary engines, and with the introduction of ECA areas, many ships use separate high and low sulphur fuels.

Fuel technology. Amyris (USA) is a public biobased chemical company specializing in converting plant-sugars via fermentation to fuels and chemicals, from pharmaceutical ingredients to fragrances to fuels. Their flagship product is farnesene, shown below, a microbially produced terpene made from low-priced sugar in Brazil in partnership with Bunge, an American agribusiness and food company.



(E)-β-farnesene, $C_{15}H_{24}$

The company has ongoing testing programs with the US Department of Energy and the US Navy. Amyris renewable diesel (ARD), a sugar cane-derived fuel, has been used as a test drop-in fuel over a two-week period in September 2012 as part of a project from the US Maritime Administration in cooperation with the US Navy[105]. The biofuel provided by Amyris was chemically comprised of over 95% farnesene, of which it was blended 33/67 with ULSD for testing and future use in commercial vessels.

Amyris has partnered with the French oil company Total to commercialize production and distribution of farnesene as a diesel and jet drop-in fuel as well as a starting material for specialty fluids and chemicals. Amyris renewable jet fuel blends have been provided to commercial airlines (Cathay Pacific) to improve fuel efficiency and reduce CO_2 emissions compared to aircraft using fossil fuels. At the time of writing, most of the company's resources have now been dedicated to the production of pharmaceutical, flavor, and fragrance ingredients rather than fuel, as the profitability on value-added chemicals is higher.

A few initiatives have also been taken to blend biofuels at the refinery level. A few companies have adopted fuel co-processing technologies, where traditional refining companies use technology for the production of hydrotreated vegetable oil (HVO) while mainly upgrading fossil fuels. ConocoPhillips, BP, Petrobras, Total, Haldor Topsøe, Nippon Oil, Preem, Ensyn, and AltAir are such companies operating small scale platforms before moving on to larger investments. HVO co-processing involves HVO production in a traditional refinery's desulphurization unit where vegetable oils are mixed directly with fossil diesel. The process is easier to implement than pure HVO production, and uses the hydrogen produced onsite the crude refining units. The final product is already blended and is of higher quality than biodiesel, all the while starting with cheaper feedstock.

Biofuel provider. Galp is a Portuguese energy company operating several crude oil refineries around the world. It also incorporates biofuels into the petroleum products that it sells.

The company has mainly focused on palm oil grown in Brazil as a raw material for biofuel production, though they have been involved in other projects to produce biodiesel from non-food waste in collaboration with Enerfuel (Portugal).

As part of their sustainability and innovation efforts, the company aims to produce 2nd generation renewable diesel using HVO co-processing technology in collaboration with Brazilian energy corporation Petrobras at the Sines biorefinery by 2020[106]. Feedstocks include waste oils and animal fats. This is part of the 2020 target set by the European Energy Commission, with the aim of achieving 10% renewable energy into road transport.

6. Status of marine biofuels

The funding and focus available for the development of new marine fuels is tied to the current price of crude oil. When oil prices are low, there is little economic incentive to switch to an alternative fuel considering the already established infrastructure catering to fossil-based fuels. There are, however, environmental and regulatory incentives to develop fuels that complement conventional fossil-based fuels.

The development for biofuels compatible with marine engines is still in its infancy. Having an abundant feedstock supply and reliable processing technologies to produce price-competitive biofuel at a large scale remains a challenge. Starting with the biomass feedstocks, the price and supply of agricultural residues has increased due to growing world population and changing food habits, but supply markets are getting more volatile due to climatic extremes. Additionally, the price of industrial wood as a raw material has decreased since 1960s; however, there is a steady increase in price due to growing demand from the bioenergy sector.

Regardless of the feedstock, the selling price of biofuels is still tied to the price of oil. Experts argue that biofuels derived from agricultural waste will not be competitive against conventional fuels until the oil price rises to at least $60 per barrel. Thus, when crude oil prices are low, the demand for biofuels decreases. From a vessel operator's point of view, up to 50% of operational costs are largely dominated by fuel costs, thus fossil marine fuels have a further comparative advantage. However, biofuels reduce ship emissions and increase local air quality, in addition to showing ultra low sulphur content. Therefore, once stricter sulphur emissions are enforced, biofuels can be introduced to the shipping sector to meet the obligations, and be more cost effective as demand will be higher. While ship operators also have a choice in buying low-sulphur fossil-based fuels or use scrubbers, the current environmental policies combined with future global GHG emission limits[17] will also create a demand for drop-in biofuels, as it will limit the use of fossil fuels. In other words, biofuels are attractive in markets where fuel costs are low relative to total operational costs and clean air is seen as a marketable asset.

Technical developments of biofuels in general are expected to reduce the cost. However, it should be recognized that compared to fossil fuels, the biomass conversion technologies are still in their infancy; only the sugars are currently converted to fuel products at a commercial scale, whereas the lignin conversion tough under development is currently not at a commercial scale. Therefore there is a substantial potential for increasing the biomass value addition, as technologies capable of converting lignin to fuels and higher-value chemicals are further developed and introduced.

First generation biofuels such as vegetable oil based biodiesel or bioethanol from corn or sugarcane can typically compete with fossil fuels at oil prices around 60 USD/barrel. 2nd generation biofuels have higher production costs as they are younger and less optimized technologies. A number of 2nd generation biofuel technologies will start to become economically competitive at oil prices around 100 USD per barrel[12]. Although high prices above 100 USD has been observed for 1-3 year periods, such high prices are not likely to become permanent within the foreseeable future, given the historical oil prices. This is further supported by the fact that new fracking technologies has introduced more oil and gas resources on the market, just as the development of wind and solar energy technologies, will reduce the demand for oil or natural gas.

Assuming that biofuels are technically developed and available for the maritime sector in large quantities, a wider initial introduction of biofuels in the sector is likely to depend upon increased environmental regulation of particle and greenhouse gas (GHG) emissions or new business models including low carbon footprint, as part of the transport service. For a number of consumer goods, the transport costs are only a small part of the total cost, and as seen for other consumer products and services there may be a demand for low-carbon transport services[107].

An example of biofuel market expansion through regulation is the European Renewable Energy

Directive (RED), which mandates a 2% share of 2^{nd} generation biofuels or electric vehicles in the road transport sector. The international maritime sector is currently not covered by any regulatory framework on GHG emissions.

Thus an estimate for when and how 2^{nd} generation biofuels will become on par cost-competitive with fossil fuels needs to rest upon assumptions of technology development, oil-prices and regulatory frameworks, all of which has their own level of uncertainty. Using current technologies and the oil-price as benchmark for cost-competitiveness, the break-even between fossil fuels and biofuels is in the range of 100-120 USD/barrel. Including a forecast of technical development with lignin-based fuels and biomass derived chemical products, this level may drop to 70-90 USD/barrel. If specific biofuel or low-carbon fuel mandates are introduced in the maritime sector, there will within the mandate not be any competition with fossil fuels, and a separate market setting the price for maritime biofuels will be established.

More extensive use of marine biofuels will most likely be first implemented in inner city waterways, inland river freight routes and coastal green zones, particularly SECAs. Ship operators would be forced to comply with regulatory mandates and use cleaner fuels around densely populated areas. The ports of Rotterdam and Amsterdam are good examples of this as is cruise ships in Sydney harbour are such examples. If conventional fossil fuels are to remain an option, with new emission regulations, HFO would need further upgrading to create a 'cleaner' fuel. However, further refining also needs to be justified by a higher value of the refined fuel compared to the additional cost of refining. Therefore, it is predicted that the future fuel supply with emission mandates in place would consist of a mixture of fuels produced from different sources, such as crude oil, natural gas, biomass, electricity, and even nuclear power.

With both regulatory and market drivers in place, biofuels could make up between 5 to 10% of the global marine fuel mix by 2030[108] equal to a market of 16-33 million tons of biofuel. Estimates for the global biofuel production by 2020 are around 115 million tons oil equivalents. The formation of a global ECA and financial incentives in ports for ships that produce fewer emissions would increase the biofuel demand even further. To keep prices competitive, biofuel production facilities should be located near major ports or bunker stations. Assured availability of marine biofuel is one of the key elements to successful implementation. The short sea shipping sector, with fixed routes and high shipping activity, is an ideal starting point for a consistent biofuel supply. These vessels operate 'point to point' in the vicinity of ports, thus benefiting from regular fueling at designated stations. Operations in this category include ferry routes or short sea merchant shipping. The first volumes will be geographically concentrated around ports with strict emission controls, such as Western Europe, the Nordics, and the North American west coast.

The acceptance of biofuel use in deep sea shipping, on the other hand, would take longer to implement and can only take place if the fuels can be produced in large quantities at a competitive price or by mandate around the world. Given that large ocean-going container ships use tens of kilotonnes of fuel before refueling, vessels have not yet been operating on pure biofuel, as the availability of biofuel is not yet at the desired level. However, biofuel blending with conventional fuels can solve the lower emissions and price competitiveness issue. Drop-in fuels would thus be the best option in the long run before the shipping sector switches to a future more energy efficient propulsion method.

Given the high efficiency of the diesel engine, a large scale switch to a different standard marine propulsion method in the near-midterm future seems unlikely. Thus, much of the effort in developing biofuels for marine merchant vessels is finding compatible fuels to run with diesel engines. So far, biodiesel blends of up to 20% with MDO/MGO look promising; as it has been done in the road transport sector. Hydrotreated vegetable oil is also a technically good replacement of HFO and is compatible with current engines and supply chain.

Newer fuels like DME (dimethyl ether), bioLNG, bioethanol, and (bio)methanol are compatible with modern marine diesel engines, though their widespread acceptance in shipping is limited by availability. There is also no available infrastructure and investment in the fuel supply chain to introduce these new fuels, even though they can be compatible with newly build ships.

6.1. MARINE BIOFUEL PRODUCTION START-UP

For all new biofuel or biofuel blends that are produced, fuel testing will be required to check its compatibility with the engine and verify that it complies with all the fuel standards and requirements. Typically 0.2 to 3 liters of fuel are required for a fuel analysis, which is usually done before the fuel is introduced onboard a ship. For a new fuel, testing requirements are much more rigorous. Starting with a fuel stability test, 10 to 25 liters of fuel are required. At this stage, it is seen whether the fuel has any phase separation or bacterial growth over an 8 month period, for the same amount of time it is stored onboard a ship. The fuel also undergoes vigorous centrifuging in order to see whether any phase separation occurs, and which size of particle filters to install. The fuel stability test is also done to determine the fuel's oxidation stability and at what temperatures can the fuel be heated to. Further on, a fuel pump test is done, of which 10 to 200 liters are required. Here, it is determined whether the fuel can circulate through the system without phase separation.

An engine test will require between 250 to 2000 liters of oil, and after the fuel has passed the requirements, it is ready to undergo a service test on a ship. This will require a minimum of 100 tons of fuel, though 2000 tons would be ideal. Once the fuel supply is guaranteed, it is relatively easy for a shipping vessel to switch to a drop-in biofuel or blend.

Once production facilities are running, the fuel supply infrastructure needs to be established. This includes biofuel bunkering and storage, as well as ensuring long-term availability of these fuels. Handling biofuels on board will also require knowledge from ground staff regarding rules for safe use of fuels, as well as operations of new systems catered to biofuels or biofuel blends.

6.2. BIOFUEL FEEDSTOCKS

Current feedstocks for the production of first generation diesel engine-compatible biofuels are mainly plants with high lipid content, including palm, soybean, and rapeseed[109]. The high lipid content in the seeds from oil crops are desirable for the production of straight vegetable oil fuel or biodiesel. These feedstocks, however, are generally difficult to source cheaply and sustainably for an expanded commercial production of marine biofuels. Rapeseed oil is the preferred feedstock in the EU due to its favorable properties (stability towards oxidation, high yields per hectare). Even though palm oil yields higher amounts of lipids per hectare compared to other plant-based oils, its high melting point limits its use in colder climates, but it can be used as a blended fuel.

The use of first generation biofuel feedstocks is not without controversy, as the feedstocks all form part of the food, land, and water vs. fuel debate. Food crops being diverted to produce fuels can increase the price of food and increase the use of more agricultural land. For 2020 European regulation has set a limit to the use of biofuels from food crops to 7% and now a debate is going on for the 2020-2030 regulation. Most likely the proposal will be to decrease this limit. This tendency to reduce the use of first generation biofuels should be considered when developing a market for marine biofuels. In the case of palm oil production, it is generally accepted to cause deforestation, directly or in-directly of virgin jungle, when forest is cleared to make way for palm oil plantations for mainly food and cosmetics use, but also to an increasing extent biodiesel[110]. Despite studies defending the use of palm oil for biodiesel[111], palm oil is advised to be considered a non-sustainable resource considering the land use changes and impact on the environment. These considerations on lack of sustainability will also apply although to a smaller extent for other vegetable oils derived from soy bean or canola seed. For the latter the main sustainability issue is the emission of nitrous oxide during farming.

Social, environmental, and economic pressures push the sourcing of biofuels from sustainable practices. In order to ensure long-term sustainability and availability of renewable feedstocks, raw materials should ideally be sourced from waste residues or non-edible plant matter. In terms of just the cost of carbon, lignocellulosics are generally five times cheaper than lipid feedstocks. For example, the price of hard logs was USD$121 per ton in September 2016, while palm oil was USD$644 per ton during the same period. Lignocellulosics include forest biomass (hardwoods, softwoods, pulp and sawmill residues) and agricultural residues (corn stover, wheat straw, rice straw, sugarcane bagasse, palm oil residues). Other potential feedstocks for second generation marine biofuels include municipal solid waste, used cooking oils, and waste animal fat.

Biofuel provider. Sunshine Biofuels (USA) is a Florida-based company founded in 2011 specializing in liquid biofuels from biomass that can substitute diesel and heavy fuel oil. Their biodiesel is produced using recycled cooking oil, is low in sulphur, and has a higher flash point than biodiesel. The company collects used cooking oil from local restaurants and food processing sites, which is then processed at a central location and delivered to select fueling stations or private customers[112]. Branded as Sunshine Renewable Diesel, it is compatible with low, medium, and high-speed marine diesel engines and can be used as drop-in fuels. Sunshine Renewable Diesel can also be used with other diesel engines in commercial trucks and power generators, or as heating oil.

Sourcing biomass feedstock for fuel production is dependent on geographical location. Agricultural residues such as corn stover are widely available in the USA and China, whereas wheat straw can be found in Europe and pockets of Asia and North America. Sugar cane bagasse is most common in South America, with Brazil dominating the market, rice straw production is centered in Asia, while palm oil residues is sourced from palm oil-producing countries in Southeast Asia, in particular Malaysia and Indonesia.

Waste lignin, a low value product from 2nd generation biofuel production or pulping processes, can also be a viable raw material for biofuel production as it has the highest energy density of all biomass components.

Algal oils are also a known feedstock for biodiesel production, categorized as third generation feedstocks. Algae can under ideal conditions produce more biomass per unit area in a year than other forms of biomass. Most research into mass production of algal oil focuses mainly on microalgae or blue-green algae (cyanobacteria)[113], as they have a less complex structure, faster growth rate, and higher oil content (for certain species). However, commercial production of algae-based fuels are believed to be a long-term option.

6.3. FUEL AND FEEDSTOCK POTENTIALS

Regardless of the type of biofuel and the technology applied for its production, the final potential of marine biofuels entering the market will ultimately be limited by the amount of feedstock that can be made available, and the price customers are prepared to pay.

Assessment of biofuel feedstocks potentials is not straightforward, as they are part of a highly complex and integrated system of forestry and agriculture with a number of interconnected markets and mechanisms. A simple but robust approach for assessment of biomass potentials is to look at the production from current agriculture and forestry, i.e. what can be achieved by adapting the agricultural crops and technologies without compromising food production or increasing land use. Another approach is to look at optional biomass production from expanding the agricultural area or from biomass production e.g. energy crops on marginal lands such as switch grass on the prairie or forestation of semi-arid areas.

The latter approach may show extremely high biomass potentials, but are also associated with high levels of uncertainty and requires a major effort to introduce new agricultural management. The potential from already established crops and agricultural systems may be lower, but has the advantage that there is already an established infrastructure, and in many cases it is a question of only increasing the biomass collection when harvesting takes place.

For this report a simple assessment of biomass and biofuel potentials based on existing agriculture and forestry as well as current biofuel production is presented. The assessment does not represent all data and studies, and the specific numbers should be used with caution. However, they do show the scale of the resources that can be made available and whether or not the potential feedstock and biofuel potentials are substantial or incremental.

For the oleochemical-based biodiesels, i.e. derived from plant oils or animal fats, the current global production of plant oils is approximately 185 Mt. The major consumption is for food and cosmetics, and the 2016 global biodiesel production was approximately 25 Mt[114]. In a thorough analysis, Johnston and Holloway[115] estimated the global biodiesel potential based on existing oil crops and animal fats. In their analysis they included the projected oil crop production including yield increase on existing agricultural land as well as the increasing demand for vegetable oil used in food and other applications. Not included in the study was an expansion of the agricultural area or the introduction of new oil crops such as Jatropha marginal land. The result of their analysis show an upper limit of approximately 45 Mt of biodiesel using existing crops and agricultural land. In this number, the contributions from used cooking oil (UCO) and tall oil-derived diesels from the pulp and paper industry are not included.

Estimates for the UCO potential are few and based on limited data, but technical potentials of 4,5-9 kg per capita are suggested[116]. Only a minor fraction of the technical potential can be realized and a conservative estimate of UCO biodiesel production of 10% does not seem unrealistic. With a world population of 7 billion this adds another 3-6 Mt of potential biodiesel production. For tall-oil based biodiesel a more accurate assessment can be done: based on the size and production at relevant pulp mills gives a total potential of 2.6 Mt[117]. Together this will give a biodiesel potential of 54 Mt, approximately a doubling of the current production.

For fuels based on lignocellulosic feedstocks global assessments vary widely depending on feedstock and fuel type, just as many of the technologies still are at an experimental level. However, using 2nd generation bioethanol as an example, a simple overall assessment can be made using only the residues being produced from existing agriculture and forestry, i.e. no extra resources of land or input of fertilizers would be needed. The total residues from agriculture and forestry is between 3.3-6 Gt[118]. Assuming that 50% of these residues are used for biofuels and with a yield of 250 kg fuel/ton of biomass, this would provide 400-750 Mt of biofuel. The numbers including existing bioethanol production are summarized in Table 12.

The biofuel and feedstock potential show that from a strategic point of view only lignocellulosic fuels have the potential to fully replace fossil fuels in the maritime sector. This does not mean that oleochemical fuels does not have a future role in the shipping sector, but they have a smaller potential. However, apart from tall oil derived biodiesel, there are no other commercial-scale lignocellulosic fuels that are compatible with maritime diesel engines.

Table 12. Comparison of fuel consumption in the maritime and aviation sectors with current and potential biofuel production based on current crops and feedstocks from existing agriculture and forestry.

Consumption / potentials	Mt oil equivalent
Maritime fuel consumption	330
Aviation fuel consumption	220
Biodiesel production 2016	26
Biodiesel potential	50-54
Bioethanol production 2016	55
Lignocellulosic fuel potential	455-805

Another aspect is competition for biofuel feedstock with other sectors. Currently, bio jetfuels are made from hydrotreated vegetable oils, leading to direct competition for oleochemical feedstocks between the maritime and aviation sectors. Another potential competition for feedstock can be with animal fats, as fats from typically slaughterhouse waste are used in the biogas sector.
The ongoing electrification of road transport, will at some point beyond the year 2025 reduce the demand for oleochemical biofuels for the road transport sector, and more biofuel may be available for the marine and aviation sectors.

For the lignocellulosic based fuels, woody biomass is currently used for heat and power production, which competes with the use of lignocellulosic biomass for fuels. However, in the medium to long term, the use of biomass for heat and power is expected to decrease, due to the growth of other renewable energy sources.

7. Marine biofuel regulations

Regulations have been a major driver in stimulating bioenergy supply and demand, since most bioenergy technologies are not yet financially competitive with fossil fuels. Most regions with interest in biofuel production and/or consumption are either already large fuel consumers (North America, EU) or profitable feedstock producers (South America, Southeast Asia). Local governments can place different mandates for biofuels, such as biofuel targets, excise reductions, and tax incentives.

Regulations regarding the use of biodiesel have progressed faster in the automotive transportation sector than the merchant shipping sector. The European Commission appointed a mandate to develop standards concerning minimum requirements and test methods for biodiesel in 2003: EN 14214 in order to standardize biodiesel fuel. The American Society for Testing and Materials (ASTM) has also published standards for biodiesel fuel ASTM D-6751-02 for B100 and blends for distillate fuels. The use of biofuels in ships, however, is not taken into account in IMO legislation.

The European Commission established the Renewable Energy Directive (RED) in 2009 to set mandate levels of renewable energy use within the European Union. The directive also lays down the sustainability criteria regarding biofuels and bioliquids, and there is a target of 20% energy originating from renewables by 2020. In the regulated transport sector, defined as road and rail transport, the 2020 target is to achieve a 10% share of renewable energy, of which the majority is expected to come from biofuels[119]. However, renewable energy deployment progress has been slow, where the EU share of renewable energy in transport reached 5.4% in 2013. However, in countries such as the Netherlands, biofuels for both road and marine transport are counted as part of national climate targets. On 30 November 2016, the European Commission published a proposal for a revised RED, the so-called RED II, to make the EU a global leader in renewable energy, and increased the target of at least 27% renewables in the final energy consumption in the EU by 2030, expected to enter into force 1 January 2021[120]. The incorporation of marine fuels into the RED target is dependent upon regulation via IMO, which is currently still under discussion.

Biofuels have to meet certain sustainability criteria before being marketed as RED-compliant and counted towards the EU renewable energy target. There are four categories of sustainability criteria: biofuels must achieve GHG emission reductions when compared to the alternative fossil fuels to guarantee carbon savings (RED article 17.2), feedstocks cannot be obtained from biodiverse areas in order to protect land with high natural diversity such as primary forest and grasslands (article 17.3), feedstocks cannot be grown in certain excluded areas to protect carbon stocks and land use changes (article 17.4), especially peatland areas with high carbon stock (article 17.5).

Likewise other jurisdictions, e.g. Canada, are evaluating whether to include marine fuels in their list of renewable transportation fuels as it updates its Clean Fuel Standard review[121]. The challenge in implementing such schemes is that the market incentives to comply with these regulations must be made to benefit or affect all parties within the biofuel supply chain, otherwise no party would switch from the traditional status quo[56]. Thus international regulation of marine biofuels are important.

7.1. MARINE BIOFUEL DEPLOYMENT INITIATIVES

In North America, much of the initial research and development work on marine biofuels has been sponsored by federal funding across several departments in the US: the US Department of the Navy, US Department of Agriculture (USDA), Department of Transportation (DOT), and the Department of Energy (DOE). These initiatives were taken to develop the domestic biofuel industry and reduce the US dependence on energy imports. In 2009, through the American Recovery and Reinvestment Act, the DOE invested more than $31 billion to support a wide range of clean energy projects, of which renewable energy development from biomass was one of the prioritized areas. The same year, a total of USD$564 million in agency funding was then awarded to build multiple commercial scale industrial biorefineries to domestically produce cost-competitive drop-in biofuels that are competitive with conventional petroleum fuels without subsidies[122]. Subsequently, more grants have been awarded to other biorefinery projects to produce drop-in fuels from biomass at a research-, small-, pilot-, demonstration-, and commercial-scale over the following years.

In addition to expanding marine biofuel production, fuel testing onboard marine vessels has also been an integral part of the funding package, and the US Navy has been the main partner. It is also, along with the US Coast Guard, the largest user of marine grade fuel in the US. The US Administration calls for drastically reducing the country's dependence on foreign oil, and have thus focused on alternative forms of energy. The Navy's "Great Green Fleet" initiative was established in 2009 and aimed to have 50% of their energy coming from alternative renewable sources by 2020. A select number of Navy ships, aircraft, and aircraft carriers known as the Carrier Strike Group (CSG) will be used to demonstrate military operations using alternative fuels, including nuclear power and renewable biofuels[5]. The Great Green Fleet demonstration allows the Navy to test, evaluate, and demonstrate the cross-platform utility and functionality of advanced biofuels in an operational setting.

Starting 2010, the Navy has been testing and deploying ships and aircraft with biofuel blends. Most ships used a 50% blend of hydrotreated renewable diesel fuel, and showed no performance issues[4]. On July 17, 2012, a military replenishment oiler delivered 900,000 gallons of 50-50 blend of advanced drop-in biofuels and traditional petroleum-based fuel to the Navy's aircraft carrier in the Pacific Ocean as part of the Rim of the Pacific (RIMPAC) multinational maritime exercise[123]. The biofuel was a hydrotreated renewable diesel fuel, named HRD76, produced from a mix of waste cooking oil and algae oil provided by Solazyme and Dynamic Fuels. By law, these fuels have to be priced on par with conventional fuels.

In 2013, the USDA in collaboration with the US Navy unveiled the "Farm to Fleet" program, aiming to locally develop the biofuels industry by linking farming communities with biorefineries in the US[124]. As the largest consumer of petroleum fuel in the US, the US military has agreed to purchase cost-competitive domestically produced drop-in biofuels, to be blended with petroleum fuels at 10-50%, as part of their plan to diversify their fuel mix and decrease their dependence on petroleum-derived fuels.

The US Coast Guard has also conducted tests with marine biofuels in their fleet and developed standards for biodiesel use in marine engines. It first tested a 50-50 blend of diesel and algal oil in 2012[125], which was met with success, and in 2013 started testing renewable isobutanol-blended gasoline as a drop-in fuel, in partnership with Gevo, for the Coast Guard gasoline engine fleet[126].

Fuel Technology & Biofuel Provider. Gevo is a publicly traded American company producing bio-based isobutanol as a drop-in fuel for marine and recreational boat engines with spark-ignition. Isobutanol is approved for blending with gasoline, though it is still not a mainstream biofuel. It has higher energy content and is less hydroscopic than ethanol, and can also serve as a platform molecule for specialty chemicals in addition to the fuel market.

Starting with plant-based first and second generation feedstocks, these are processed using the Gevo Integrated Fermentation Technology (GIFT), consisting of genetically engineered yeast and continuous *in situ* recovery of isobutanol from the fermentation broth.

Gevo also produces other high-value products such as protein-rich animal feed. The company has a fermentation plant in Luverne, Minnesota, producing both ethanol and isobutanol concurrently, operational since 2010. Production target for isobutanol is set at 2.8 to 3.8 million liters, simultaneously with 56-64 million liters of ethanol in 2016. In 2011, Gevo started operating its biorefinery in Texas, where it takes the isobutanol produced in Luverne and converts into hydrocarbon products such as jet fuel, octane, and polyester building blocks. In July 2013, Gevo started to supply the US Coast Guard R&D Center with isobutanol-gasoline blends. In May 2016, they entered into an agreement with Clariant Corp., a leading specialty chemical and catalyst supplier, to develop catalysts for Gevo's ethanol-to-olefins (ETO) technology.

Their main competitor for bio-based butanol production is Butamax, a joint venture between BP and DuPont.

The Royal Australian navy, with its close ties to the US Department of Defense, has also followed the US Navy's environmental initiatives and may start to acquire oil from a pilot biodiesel plant in Queensland's Gladstone in collaboration with Southern Oil[127]. Fuels would be produced from recycled old tires, human waste, waste beef fat, weeds, and sugar cane residues[128], however, the current status of the plant is not disclosed.

Large merchant shipping companies are the world's largest consumers of marine fuel (approx. 70% of the marine fuel available), and thus have the potential to become the largest biofuel end users.

Fuel technology. Lloyd's Register Group Limited (UK) is an engineering, technical, and business services organization providing compliance, risk, and technical consultancy. Lloyd's is also a maritime classification society, where it historically recorded the state of merchant sea-going vessels in the *Register of Ships*. As of 2010, it has been involved in a two-year project together with Mærsk Line and a consortium of Dutch subcontractors to test the use of FAME biodiesel in marine engines. The feasibility study was done aboard the container ship *Mærsk Kalmar*, where 30 tons of FAME from rapeseed oil (5-7% blend with biodiesel) was loaded onto an auxiliary engine (for electricity production).

Fuel end user. Mærsk is a publicly held Danish company specialized in global container shipping and logistics. The company owns the world's largest container fleet, holding 15% of the global TEU, and is at the forefront in marine fuel efficiency optimization technology. Mærsk purchases only 3-4% diesel fuel, while the rest is heavy fuel oil. Mærsk envisions around 10% or more of the world's shipping fleet to be powered by biofuels by 2030.

In 2011, Mærsk Line collaborated with the US Navy on testing 7-100% algae biofuel (Soladiesel provided by Solazyme[129]) on the Mærsk Kalmar auxiliary engine as part of an initiative to lower GHG and sulphur emissions through the use of alternative bunker fuels[130,131]. Despite the high early costs in the project, Mærsk remains committed to their search of new second-generation biofuel alternatives. As of 2013, they have been involved in two projects for developing lignin-based bunker fuels[132]: one with Progression Industry (the Netherlands), and the other with DONG Energy (Denmark).

Biofuel provider. Eni (Italy) is an energy company founded in 1953 with operations in 79 countries worldwide. Though mainly focused on oil and gas, Eni has expanded operations in a large number of fields including nuclear power, renewable energy, mining, chemicals, and plastics. Eni has converted its refinery in Porto Marghera, Venice, to the production of biofuel from vegetable oil and biomass[133]. The plant produces green diesel, naphtha, and LPG from palm oil, but plans to expand their feedstock base to second generation biomass. They use their trademarked Ecofining process, developed together with Honeywell-UOP in the San Donato Milanese laboratories, for the production of biofuels using the catalytic hydro-desulphurization section of a traditional refinery. The biodiesel produced has been used by the Italian Navy's offshore patrol vessel Foscari.

Biofuel provider. Evoleum, formerly QFI Biodiesel, is a Canadian producer of advanced biofuels for the maritime, trucking, and energy utility industries founded in 2010. Flagship products are biodiesel and biobunker fuels. The biobunker fuels are made from industrial and domestic waste, including recycled vegetable oil. Aside from biofuels for shipping, Evoleum also offers solutions for other road and off-road transportation sectors. Production and research facilities are located in Quebec, while their distribution network expands to both Canada and the US.

Several niche markets can lead the way to faster introduction of biofuels in ships. Ferry service, for example, would be an ideal starting place for the implementation of biofuels or biofuel blends. Ferries generally run on fixed chartered routes along high population density coastal areas, most likely within SECAs. Navigating around populated areas would also require a higher quality diesel fuel instead of the heavy residual fuels used for deep ocean shipping. Washington State Ferries (USA), for example, has begun testing B20 biodiesel on a year-long pilot test project as part of its Clean Fuel Initiatives program in 2004. In the meantime, the company has also started to convert their entire fleet to using low sulphur diesel fuel. As of February 2013, all of Washington State Ferries' vessels use B5 biodiesel from soy, animal fats, or cooking oils.

The eco-tourism industry has also taken the initiative to use biodiesel in charter boats. Sanctuary Cruises (California, USA) runs whale-watching vessels with biodiesel power. Part of the cost of running vessels with biodiesel is taken on by customers, who in some cases are willing to pay a premium for environmental reasons, even though the experience and/service remains the same. Channel Islands National Park, off the coast of Southern California, uses B100 biodiesel in their vessels and stationary power generators as an initiative to make the islands petroleum-free.

Biofuel trading. GoodFuels Marine (Amsterdam, the Netherlands) is a fuel trader and service provider, currently selling a high quality hydrotreated drop-in fuel targeted to the MGO market. GoodFuels is the first marine biofuel company focused on the global commercial fleet. The company has created a one-stop shop for marine industry customers integrating the entire supply chain for sustainable marine biofuels. Though GoodFuels does not own marine biofuel production sites, it acts as a service provider to construct the supply chain between vessel operators and fuel producers. GoodFuels sells only 2nd generation biofuels, and has been working to expand their portfolio of sustainable marine biofuels. GoodFuels follows on the footsteps of sister company SkyNRG, which is also committed in their sale and distribution of sustainable biofuels for aviation.

GoodFuels is involved in feedstock development and trading, though the fuel production and refining is outsourced to third parties. GoodFuels works with logistics and fuel distribution partners to expand the marine biofuel fleet, and are planning to move into the fuel commodities market in Western Europe and Scandinavia.

GoodFuels has partnered with Boskalis (leading dredging and marine expert) and Wärtsilä (marine engine supplier) on a two-year pilot program in 2015 to accelerate the development of sustainable, scalable, and affordable drop-in biofuels for the commercial shipping sector[134]. They are providing high quality renewable diesel made from bio-derived feedstocks such as waste frying oil, industrial waste residues, and lignocellulosic biomass. This comprises of three different steps: fuel testing and development, sustainable production, and production on a commercial scale.

The company aims to make biofuels cost-competitive with fossil fuels while ensuring sustainability, safety, and production quality. In July 2015, GoodFuels achieved a milestone by receiving the highest standard of certification from the Roundtable of Sustainable Biomaterials (RSB)[135]. To date, they continue to work with different partners to source the most sustainable feedstocks (energy crops, waste oils, pulp and paper residues) based on geography and production scale. At the time of writing, GoodFuels offers marine biofuel that is compatible with MGO (grade 1) and HFO (grade 3), which can be blended with conventional fuels or used as heating fuels. Future plans include producing a fuel from lignin waste streams (GoodCrude) by 2020.

GoodFuels is part of the GoodNRG group, operating under various labels in the sales, marketing, trading, R&D and production of sustainable biofuels for transport (marine, road, and rail).

Biofuel provider. Renewable Energy Group (USA) of Ames, Iowa, is a producer of drop-in renewable diesel and heating oil for transportation and power generation respectively, and has 12 active biorefineries throughout the USA. REG has a fuel marketing and distribution network throughout North America, and is actively expanding their biorefinery operations.

The company produces renewable biodiesel and jet fuel from a variety of feedstocks, including animal fats, grease, and vegetable oils using different patented process technologies. REG recently acquired Dynamic Fuels in Geismar, Louisiana, which was a joint venture between Syntroleum Corp. and Tyson Foods, in 2014. The plant produces renewable biodiesel from the vast supply of left over animal fats, enough to produce 150 million liters of biodiesel a year. Tyson Foods, a meat processing company, provides the feedstock while Syntroleum provides the biorefining technology using Fischer-Tropsch to convert lipids to renewable synthetic fuels. The company has previously received $12 million from the US Navy to supply renewable fuels, representing the single largest biofuels purchase in US government history.

Products in their pipeline also include renewable diesel, blended fuels, heating oil, and glycerin (co-product of biodiesel production). The feedstocks to produce these chemicals and biofuels are mainly natural fats and oils. Though most of the biodiesel processing facilities use traditional refinery methods, REG also has a fermentation facility in Florida specializing in the production of specialty chemicals.

A few research groups in the UK have also looked into the potential of using glycerine, a by-product of FAME biodiesel production, as a marine fuel. The Glycerine Fuel for Engines and Marine Sustainability (GLEAMS)[136] project campaigns for using glycerine as a fuel, since it is obtained from plant sources, is sulphur-free, can reduce NOx emissions, and can be easily retro-fitted to modern marine diesel engines[137]. With the production of FAME on the rise, glycerine is becoming a widely available but under-used fuel, which has potential to be utilized in ECAs by the shipping sector as a non-toxic and non-volatile fuel.

Biofuel trading. Targray Technology International (Quebec, Canada) is a private multinational renewable energy company supplying solar, optical media, and lithium-ion battery materials. The company launched their biofuel marketing and trading division in 2011, and has marketing agreements with several biodiesel producers across the US and Canada while continually expanding their supply network. Targray is an experienced global distribution company and a renowned international supplier of biodiesel, delivering biodiesel to ocean vessels worldwide. Targray sources from all major biodiesel producing regions worldwide, and trades in both the European and American markets.

Transport user. Heineken International is a Dutch brewing company owning more than 165 breweries in 70 countries around the world. Besides its flagship beer, Heinekken also brews and sells local, regional, and specialty beers that are distributed worldwide. In response to rising global demand for their beers, the company has been at the forefront of reducing its carbon footprint as part of its sustainability initiatives[138].

To reduce CO_2 emissions while exporting beers to the USA from Mexico, Heineken started using sea transportation routes instead of land in 2014, taking advantage of sea ports in the Eastern US, and thereby saving more than 10,000 tons of CO_2 a year and improving delivery times[139]. The company is also partnering with GoodFuels for sourcing of low carbon marine biofuels.

7.2. BIOFUEL DEPLOYMENT CHALLENGES

One of the major concerns regarding the use of biofuels, or any new alternative fuel, in shipping vessels is the lack of long-term fuel test data to guarantee the safety and continued reliability of the selected fuel. Along these lines, the fuel price and supply guarantee are also major challenges to be solved before shipping vessels switch operating on a new fuel.

The performance of standard petroleum-based fuels in diesel engines is quite well understood. However, the same cannot be said for new biofuels at the moment, as they are produced from different feedstocks and processes. Thus, significant amount of testing and standardization needs to take place in order for the renewable fuel sector to develop proper drop-in biofuels that are entirely compatible and as effective as an alternative to conventional fuels. While current commercially produced biofuels have been shown to be chemically compatible with fuel structure, the biological stability during transport and especially long-term storage remains an issue of concern.

ISO standards on bio-derived fuels for the shipping sector are still work-in-progress. There is a need to address fuel stability towards oxidation (acid number of no more than 2.5 mg KOH/g), minimal water content to inhibit microbial growth, and low-temperature flow properties of biofuels. At the moment, regulations do not allow for biodiesel blending with marine distillate or residual fuels as they are seen as contaminants, but fuel tests have been carried out with blended fuels to determine their compatibility with marine engines. FAME content in marine fuels cannot exceed 0.1 volume % in distillate fuels, as there is still no significant amount of data gathered concerning storage, handling, and treatment in a marine environment. As for residual fuels, ISO standard 8217 for bunker fuels does not address any standardized testing method for biofuels, and thus is considered a contaminant in the supply chain.

Biofuels have a tendency to oxidize and degrade during long-term storage of 6 to 10 months. As biofuels are derived from natural sources, they tend to degrade in water faster than conventional fossil-based fuels. This is positive in case of an oil spill, but would cause problems for long-term storage of the fuel. Fuel lubricity and conductivity are also areas of concern. Fuel lubricity is important in a diesel engine as the moving parts are often lubricated by the fuel. This is also the case for ship operators when they switch to ULSD, which requires different additional lubricity additives. Even though biodiesel acts as a good lubricant[140], it loses its lubricity over a long period of time due to oxidation of unsaturated molecules present in the fuel and increased water from moisture absorption[141]. Electrical conductivity is important for fuel as static charges can build up as the fuel is pumped through pipelines, thus requiring the use of anti-static additives to prevent static discharge during transfer, transport, and pumping.

When it comes to setting up the biofuel supply chain, it is important to note that biofuel funding packages tend to include fuels for other transportation sectors such as jet and automotive fuels in addition to marine fuels. In fact, government policies, subsidies, and mandates over the past decades often focused on fuels for domestic road transport rather than for air or shipping. This implies that biofuel developers have mainly focused on fuels for road transport (e.g. cars, trucks, rail). Jet fuel production has also become a trending research area, as air cargo has become more popular in recent years despite higher freight costs, as merchant goods take much shorter time to arrive at airports. Air transport passengers have also increased over the past decade, naturally increasing the demand for jet fuel. As of late 2016, more than 2,500 commercial flights have flown using renewable fuel blends, and the number is growing[142]. The volume of aviation fuel demanded by the sector is also slowly approximating that of merchant shipping (275 Mt vs 330 Mt aviation vs shipping respectively). In order for marine biofuels to stay relevant, it would be advantageous to produce both aviation and marine biofuels simultaneously, as aviation could use the higher quality fractions and the residues could be used for bunker fuel.

8. Conclusions

Maritime transport is and remains one of the most vital forms of freight transport. Maritime merchant shipping is among the fastest growing sectors within the transportation industry, and plays an important role in the world's economy and environment. Marine shipping is a relatively low-energy mode of long-distance transportation, and continues to improve its energy efficiency and cost-competitiveness to survive in a competitive market with alternatives such as road and aviation transport. There are also operational advantages in utilizing maritime routes instead of road transport, as goods can arrive faster via ports and at the same time achieve a reduction in GHG emissions.

With the current fuel volumes demanded by the merchant shipping industry and new regulatory fuel requirements, there is a strong market potential for biofuels, particularly biofuel blends. While the first generation bioethanol and biodiesel industries have already been commercially established, as of 2016, there has been slow development and shifting support for the production of second generation biofuels[143]. Nearly all policies regarding renewable liquid transportation fuels have been geared towards the road transportation sector, while mandates promoting the use of renewables for shipping, aviation, and rail transport have been lagging.

The use of biofuels in shipping presents itself as an opportunity to lower GHG emissions and improve air quality, given that biofuel feedstocks contain very little or no sulphur. Developing the infrastructure and supply chain for biofuels is also a chance to build a sustainable bioeconomy. As commercial marine biofuel production takes off, it is possible that the feedstocks for marine biofuel production will compete with other liquid transportation fuels, especially for aviation. However, the refining processes for marine fuels will be much less intensive, and could even be integrated together with aviation fuels.

The environmental benefits, along with current regulatory policies and governmental support schemes make a strong business case for biofuel production. The transition to biofuels or biofuel blends will likely be led by 'forward thinking' shippers, large freight shipping companies, and shipping companies with high-end customer profiles such as ferry and cruise companies[144].

Biofuels does with a few exceptions offer a net reduction of carbon cost, especially those produced from second generation feedstocks, and thus lower the carbon emissions produced by the shipping sector. An overall reduction of GHG emissions in the merchant shipping sector would most likely be achieved through a combination of improvements in ship design, port infrastructure, and fuel technology. Presently, the EEDI and RED II can serve as a business case for promoting advanced biofuels: EEDI encourages the ship owners/operators to use more energy efficient and low-carbon technologies to power their ships, while at the time of writing it is unclear how RED II will cover the maritime sector, it is an example of how fuel suppliers and/or bunker parties may be given an obligation to deliver biofuels to the market.

Figure 10. SWOT analysis of marine fuels from biomass.

The biofuel market is not without its challenges. The industry still struggles with establishing a stable price-competitive feedstock supply, and the technologies for 2nd generation biofuel production are only for bioethanol in an early commercial phase, whereas the thermal conversion technologies require more R&D before commercial production can be established. Marine biofuels have also not to any significant level been integrated in the current fuel supply chain, leaving ship owners hesitant in switching to operating on biofuels. The largest operational drawback at the moment is the lack of long-term data on biofuel use, as they are still relatively new in the sector. Thus, for less purified or more crude biofuels, industry concerns about oxidation, storage, and microbial stability of biofuels are still a challenge for biofuel suppliers. Additionally, the use of biofuels in marine engines has only been tested at an experimental stage or in small-scale applications, leaving doubts about the scalability of the operations. Considering that merchant vessels remain operational for more than 30 years, ship operators would be taking a big risk using a fuel that is not yet guaranteed to work with the installed engines for such a long period of time.

The technical challenges of biofuels for the maritime sector seems to be of a nature that can be resolved, but the future of biofuel introduction to the marine fuel mix will be highly dependent on the implementation and enforcement of international shipping regulations. Regulation in the form of statutory requirements for ship exhaust emissions, blending mandates, port regulations, and government initiatives would speed up the marine biofuel infrastructure and industry development. In addition there must be a technical way to track biofuel use in shipping vessels - via bunker facilities, biofuel producers, or ship owners in order to evenly distribute the benefits of using biofuels[54]. Using cleaner, low-sulphur, renewable fuels pose environmental benefits for coastal areas as well as deep seas. However, the current lack of a stable policy framework for biofuels leads to uncertainty among biofuel suppliers to build large-scale advanced biofuel plants. The enforcement of emission targets and encouraging ship owners to use energy efficient operational practices also remains a challenge, due to the global nature of the shipping sector, as strict adherence to protocol is more prevalent in industrialized nations compared to developing countries.

On the production side, biofuels are still more expensive to produce than conventional petroleum-based fuels, and will most likely remain so for the foreseeable future. Feedstock collection and transport remains a challenge, though it can turn into an untapped employment potential for the biofuel industry[145]. There are also high costs involved in running small technology demonstration plants. Though costly, they are necessary for developing the technology and attracting investments, which then in turn lead to fuel production scale-up. In comparison to the aviation sector, fuel technology advancements are not far behind for the shipping sector. However, there is not yet a commercially viable biofuel at the quantities required for deep sea merchant shipping. There has been progress on the short sea shipping and passenger ferry sector, as they operate on different business models. A different scenario may be approaching, as the introduction of multifuel engines will open a market for bioethanol, putting deep sea operations on biofuels within reach, however, the same issues with lack of proper testing and experience remain as well.

The advantage of shipping fuels is that marine engines have a much higher operational flexibility on a mix of fuels, and shipping fuels do not need to undergo extensive refining processes as road and aviation fuels. Thus, for entering the biofuel market, a small-scale biofuel producer should target the coastal and short distance shipping market, where fuel requirements are more stringent and the allowed fuels command a higher price. There is also a potential market for specialized marine vessels such as dredgers, as seen in the Boskalis/GoodFuels Marine case study.

Biofuels for the shipping sector is a technical and economical opportunity for biofuel producers, just as biofuels meet the coming fuel regulations within the sector. However, larger scale introduction of biofuels requires involves a directed effort between engine manufacturers, biofuel suppliers, ship owners and infrastructure (port) operators.

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