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Alternative Fuels for Marine and Inland Waterways

An exploratory study

Kamaljit MOIRANGTHEM

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Contact information
David BAXTER
European Commission JRC
Institute for Energy and Transport
JRC Petten
1755 LE Petten
The Netherlands
david.baxter@ec.europa.eu
Tel.: +31 22456 5227

JRC Science Hub
https://ec.europa.eu/jrc

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Table of Contents

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Abstract

Alternative fuels for marine transport can play a crucial role in decarbonising the shipping sector and ultimately contribute towards climate change goals. Market penetration by alternative fuels have already begun with ship builders, engine manufacturers and classification bodies by introducing greener ships running on cleaner fuels. This can be attributed in large part to the MARPOL (International Convention for the Prevention of Pollution from Ships) regulations in place since the 1970s and progressively more stringent emission standards subsequently introduced by national legislators.

This exploratory report gives an overview of the marine sector, including market share, emission related issues, fuel standards and present legislation. It then considers different alternative fuels, engine types and the introduction of alternative fuels. Low sulphur grade diesel fuels which are available at a higher price than traditional fuel, and possibility of using a scrubber to reduce emissions such as oxides of sulphur (SOx) on ships that run on traditional fuels are also discussed. The report then reviews biofuels such as biomethanol, dimethyl ether (DME), biodiesel, hydrogenation derived renewable diesel (HDRD) and algal biofuel. Of these, methanol has been put into commercial use, although so far derived from fossil sources, to fuel the large Stena Germanica ferry in the Baltic Sea. Among the gaseous fuels, LNG (liquefied natural gas), Bio-LNG and LPG (liquefied petroleum gas) have been discussed. The report also considers electricity (battery operated), FT-diesel (Fischer-Tropsch diesel), pyrolysis oil, hydrogen in combination with fuel cells, solar power and wind energy as potential alternatives.

At the moment, LNG and methanol seem to be the most promising alternatives with good market supply infrastructure in place. The sustainability of producing the alternative fuels and safety concerns has also been reported in the respective sections and also in reviews of some LCAs (life cycle assessments). The report concludes with future recommendations to not only utilise the expertise available at JRC in developing testing standards for the new fuels, but also to assist in formulation of policies that will direct the present positive momentum in the shipping industry as it is doing for the road transport sector.

1 Introduction

Maritime transport of goods is not only a relatively clean form of transportation per kilogram of material (Fig. 1), but also an efficient mode requiring 2-3 grams of fuel per ton*km, compared to road transport by truck which is about 15 grams of fuel per ton*km (McGill, Remley and Winther, 2013). Because of fuel efficiency and the need to improve fuel resource efficiency, marine transport is receiving increased attention and as a consequence is projected to grow at an average annual rate of 5.3% between 2010 and 2035 (Vyas, Patel and Bertram, 2013). However, emissions from the marine transport sector contribute significantly to air pollution globally (EEA, 2012), and in 2013 marine transport accounted for 2.7% of global CO_2 emissions (EC 2015). These emissions are expected to increase by a factor of 2 to 3 by 2050 if no measures are implemented (IMO 2009). Assessment for years 2007 through to 2012 show that international shipping emissions still remains problematic and that these may lead to significant health concerns in exposed populations (IMO 2014). Shipping particulate matter (PM) emissions have already been linked with approximately 60,000 cardiopulmonary and lung cancer deaths annually worldwide (Corbett *et al*., 2007).

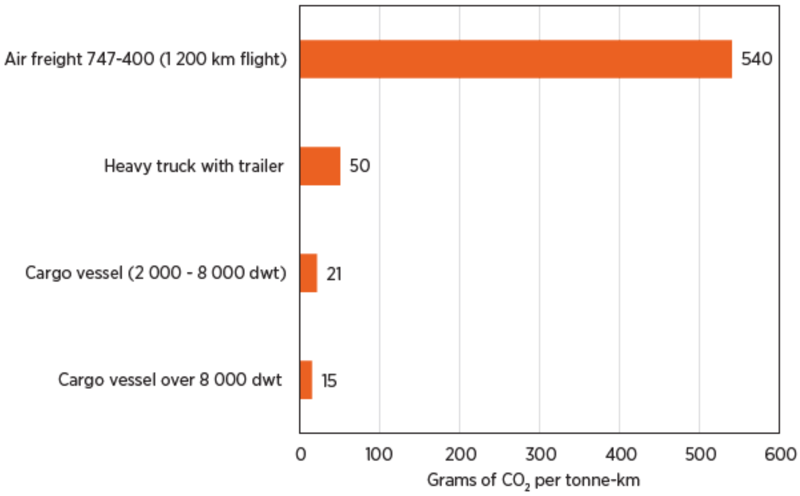

Figure 1. CO_2 emissions of different transport modes (Mofor, Nuttall and Newell, 2015)

Within Europe, 40,600 km of inland waterways and intra-EU maritime transport are used with inland navigation accounting for 1.6 % of final energy consumption in the transport sector (EC 2013). Emissions from this sector contributes to 1-7% of ambient air PM10 levels, 1-14% of PM2.5, and at least 11% of PM1 (Viana *et al*., 2014). In some non-European harbours, contributions have been reported for example of <5% of PM2.5 in Los Angeles (Minguillón *et al*., 2008) and 4-6% of PM2.5 in Seattle (Kim and Hopke, 2008). Contributions to ambient NO_2 levels range between 7-24%, with the highest values being recorded in the Netherlands and Denmark (Viana *et al*., 2014). In many coastal areas of Europe, it has been estimated that ships will be responsible for more than 50% of sulphur release in 2020, (Eyring *et al*., 2009) which could contribute to the formation of acid rain.

This is mainly because traditionally the shipping industry has used fuels with high sulphur content, purchased at a price lower than that of crude oil (Corbett 2004). Accounting for the impacts of these emissions (Petzold *et al*., 2011), stricter regulations for fuels are being implemented by both the International Maritime Organization (IMO) and environmental protection agencies. Alternative fuels can contribute significantly to reducing the carbon footprint of shipping industry (Eide, *et al*., 2012) and to comply with the new regulations. However, much support will be needed to facilitate and assess the sustainability of such a major transition and will involve multiple stakeholders. Table 1 highlights some of the important points regarding the alternative fuels being considered in this report.

Table 1. Fuels overview

Fuels	Pros	Cons
Low-sulphur fuels	Comply with current regulation; presently availability	Still a fossil fuel; availability; compliance after 2016 in question
Methanol/biomethanol	Recommended fuel by CEESA; dual fuel concept	Low flashpoint; toxic in contact with skin; vapour denser than air
Dimethyl ether	Non-toxic; degrades rapidly in atmosphere; accidental spills cannot poison water	Technology readiness level 5;
Biodiesel	Dominant biofuel; can increase flash point of other fuels when blended, increasing safety	Degrades over time; presently relies heavily on Palm oil
Hydrogenation derived renewable diesel (HDRD)	Legally allowed to be used in existing diesel infrastructure and vehicles; good low temperature performance	Limited availability; only few players in the marker
Algae biofuel	Potential to be produced on large scale; safe as diesel; drop-in fuel	Current cost is prohibitive for general use; availability limited; lower heating value
Liquefied petroleum gas (LPG)	Available in market; good supply infrastructure	Heavier than air; explosion safety hazard; premium product; not much experience on use as marine fuel
Liquefied natural gas (LNG)	Availability in market; government support	Cost of retrofitting; fuel storage volume; energy density 60% of diesel;
Biomethane	Chemically identically to LNG; most CO_2 friendly fuel; better quality than fossil LNG	Scattered availability in Europe; costlier than LNG
Electricity	More efficient than diesel engines in energy conversion; can be used to power ships at berth reducing port side emissions	Low energy density; high capital cost
FT diesel	Non-toxic fuel (EPA)	Limited availability; not commercially viable
Pyrolysis oil	Commercially viable technology; potential substitute for residual oil	Not yet certified for use in marine diesel engines; energy content is half of diesel; potentially unstable; limited capability to blend with diesel
Hydrogen and fuel cell	Best energy to weight storage ratio of all fuels	Commercial engines not available; difficult and costly to produce, transport and store

1.1 Current Fuel Standards

The marine transport sector has internationally recognized standards that define the characteristics of fuel oils and what they can contain so that they will be suitable for use on-board ships (Florentinus *et al*., 2012). These include:

- British standard BS ISO 8216-1:2010
- International Standards Organization ISO 8217:2012, the most widely used standard; next edition is expected in 2016 which could include addition of FAME (fatty acid methyl ester / biodiesel) blends as a new series of distillate marine fuel grades. The UK, through British Standards, was essentially responsible for the development of what was later to become ISO 8217 through the publication of BS MA 100
- ASTM-D975 standard by American Society of Testing and Materials
- Europe-based International Council on Combustion Engines by Conseil International des Machines a Combustion (CIMAC)
- There are also internal fuel manufacturing and marketing company specifications (e.g. Mobil, Shell, Sterling)

1.2 Marine fuels and specifications

It has been estimated that as much as 10% to 20% of global petroleum derived fuel is consumed in the marine application (Deniz, Kilic and Civkaroglu, 2010). With 300-400 Mt of the 4000 Mt per year of the world's liquid fuel demands (McGill *et al*., 2013), marine diesel fuel for marine use has the following types (EPA, 2009):

- Distillate fuels: commonly called as "Gas oil" or "Marine gas oil" are composed of petroleum fractions of crude oil that are separated in a refinery by a boiling process called distillation which makes them comparable to off-road diesel fuel in terms of chemical properties and specification limits
- Residual fuels: called "Marine fuel oil" or "Residual fuel oil" or "Heavy fuel oil" are derived from the fraction that did not boil in the distillation process, and are sometimes referred to as "tar"; they are waxy and denser in structure; have relatively high viscosity and high sulphur content
- Intermediate types are called "Marine diesel fuel" or "Intermediate fuel oil (IFO)"; are blends of distillate and residual oils

Specifications for marine fuels officially carry the first letters "D" signifying "distillate fuel," or "R" signifying "residual fuel". The second letter "M" signifies "marine fuel" (EPA, 2009).

- **Distillate Fuel**: DMA is "marine distillate fuel A," and is the most common compression ignition engine fuel for small and medium sized marine engines. DMB has some limited amount of contamination that DMA may pick up in dirty storage or transfer. DMB is not a fuel that is intentionally manufactured. DMC is intentionally manufactured from either heavier boiling fractions of straight-run distillate, called "cycle oil," or is blended in marine fuel terminals from DMA and residual fuels. DMC is listed in the American (ASTM) and international (CIMAC, ISO) specifications as a "distillate" fuel, but may be considered an intermediate type fuel as the specifications allow blending with residual oil
- **Residual Fuel**: There are fifteen residual fuels in national and international specifications. Individual grades are designated by the letters A through to H, K and L, and a number signifying the viscosity limit. For example, RMA-10 is "Residual Marine Fuel A with a maximum viscosity (at 100^{o}C) of 10 centistokes. The most common **Intermediate fuel oil** grades are called IFO-180 and IFO-380

1.3 Current Legislation

The International Convention for the Prevention of Pollution from Ships (MARPOL) adopted by the International Marine Organisation (IMO) is the main international convention covering prevention of pollution of the marine environment by ships from operational or accidental causes (ICEL, 2011). The Convention currently includes six technical Annexes. Annex VI Prevention of Air Pollution from Ships (entered into force on 19 May 2005) with a chapter update in 2011 is in use (IMO).

Overview

- Sets limits on the emissions of sulphur oxides (SOx) and nitrogen oxides (NOx) from ship exhaust gases
- Provisions for setting up special SOx Emission Control Areas (ECAs). The ECAs currently include the Baltic Sea, North Sea, English Channel and waters within 200 nautical miles from the coast of US and Canada (ExxonMobil, 2015)
- Prohibits deliberate emissions of ozone depleting substances
- Introduces the Energy Efficiency Design Index (EEDI), phased-in from 2013 to 2025. The EEDI creates a common methodology for measurement and improvement of new ship efficiency. This provides a calculated figure for the rate of CO_2 emissions from a ship (McGill *et al.*, 2013).

SOx emissions depend on the sulphur content of fuels (expressed in terms of % m/m – that is by mass). Sulphur limits and implementation dates are listed in Table 2 and illustrated in Figure 2. However, implementation of global sulphur content to 0.5% depends on the outcome of an IMO low sulphur fuel availability study to be completed in 2018. If IMO decides there is insufficient low sulphur fuel available, the 0.5% sulphur limit can be delayed until 2025. However, the EU will mandate 0.5% in EU waters from 2020, irrespective of potential IMO delay elsewhere (DNV GL, 2014). The EU has also extended the regulations from MARPOL Annex VI with their own Directive 2005/33/EC to limit the sulphur content to 0.1% for harbour regions since 2010 (O'Dowd, 2012).

Heavy fuel oil (HFO) is allowed provided it meets the applicable sulphur limit (i.e., there is no mandate to use distillate fuels) (Garcia *et al.*, 2012). Alternative measures are also allowed (in the SOx ECAs and globally) to reduce sulphur emissions, such as through the use of scrubbers. IMO resolution MEPC.184 (59) is the key regulation on acidic scrubber discharges. While the EU is not a member of the IMO, EU Directive 2012/333 presents emission abatement methods, including exhaust gas cleaning systems, and refers directly to this IMO resolution (EC, 2015).

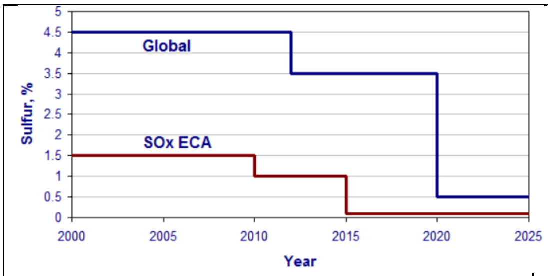

Figure 2. MARPOL Annex VI fuel sulphur content limits for reducing SOx emissions

Table 2. MARPOL Annex VI SOx Emission Limits (McGill *et al.*, 2013) expressed in terms of fuel sulphur content (% m/m – i.e. by mass)

Date	Sulfur Limit in Fuel (% m/m)	
	SOx ECA	Global
2000	1.5%	4.5%
2010.07	1.0%	
2012		3.5%
2015	0.1%	
2020[a]		0.5%

a – alternative date is 2025, to be decided by a review in 2018

NOx emission limits are set for diesel engines depending on the engine maximum operating speed (n, rpm), as shown in Table 3 and presented graphically in Figure 3. Tier I and Tier II limits are global, while the Tier III standards apply only in NOx Emission Control Areas. Tier II standards are expected to be met by combustion process optimization. The parameters examined by engine manufacturers include fuel injection timing, pressure, and rate (rate shaping), fuel nozzle flow area; exhaust valve timing, and cylinder compression volume. Tier III NOx limits will apply to all ships built on or after January 1, 2016, with engines over 130 kW that operate inside an ECA-NOx area. Tier III standards are expected to require dedicated NOx emission control technologies such as various forms of water induction into the combustion process (with fuel, scavenging air, or in-cylinder), exhaust gas recirculation, selective catalytic reduction (SCR) or enhanced exhaust gas recirculation (EGR) technologies. Exhaust gas treatment systems for NOx, (NOx reducing devices) will provide the flexibility to operate ships built after January 1, 2016, in ECAs designated for NOx emission control.

Unlike the sulphur limits, the Tier III NOx limits will not retroactively apply to ships built before January 1, 2016 (except in the case of additional or non-identical replacement engines installed on or after January 1, 2016) (McGill *et al*., 2013).

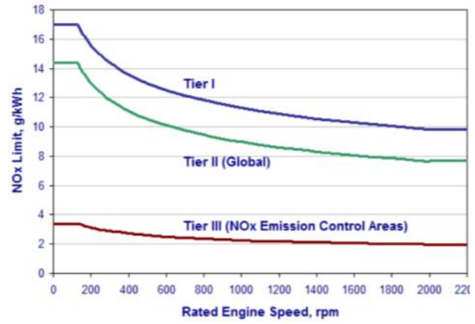

Figure 3. MARPOL Annex VI NOx Emission Limits

Tier	Date	NOx Limit, g/kWh		
		n < 130	130 ≤ n < 2000	n ≥ 2000
Tier I	2000	17.0	$45 \cdot n^{-0.2}$	9.8
Tier II	2011	14.4	$44 \cdot n^{-0.23}$	7.7
Tier III	2016†	3.4	$9 \cdot n^{-0.2}$	1.96
† In NOx Emission Control Areas (Tier II standards apply outside ECAs).				

Table 3. MARPOL Annex VI NOx Emission Limits (McGill *et al*., 2013)

1.4 Marine Engines and Alternative fuels

Vast majority of ships today use diesel engines similar in principle to those in cars, trucks, and locomotives. However, marine fuels differ in many aspects from automotive engine fuels. The viscosity of marine fuels is generally much higher – up to 700 cSt, whereas road diesel fuel rarely exceeds 5 cSt. The quality of marine fuels is generally much lower and the quality band is much wider than are those of land-based fuels. Therefore, marine engines must accept many different fuel grades often with levels of high sulphur content that would seriously harm the function of exhaust gas recirculation (EGR) and catalyst systems on automotive engines (McGill *et al*., 2013). Two engines types are available for introduction of new fuels:

Diesel engines - air is compressed so much that it heats up and ignites the fuel. Different fuels with different auto-ignition temperatures require different engine types. The following fuels work in Diesel engines (Florentinus *et al*., 2012):

- Diesel
- Biodiesel (FAME), vegetable oil, DME (Dimethyl ether), GTL (gas-to-liquid), BTL (biomass-to-liquid), and HVO (hydrotreated vegetable oil).

Otto engine- the fuel-air mixture will not ignite until a spark is created. The compression ratio is much lower (typically 1:11) compared with 1:20 for compression ignition (Diesel). The following fuels work in Otto engines (Florentinus *et al*., 2012):

- Gasoline, ethanol, methanol, natural gas;
- Biomethane (both in compressed (CNG) and in liquid form (LNG))
- Hydrogen

Marine engines have a typical proven lifespan ranging from 10 years (for high speed) to over 20 years for the low speed engines. The robust technology even allows them to stay operational up to 50 years, if maintained properly. Different fuels in the same type of engine need only relatively minor adjustments in terms of fuel lines, filters and injectors. However, converting a Diesel engine to Otto requires major adjustments and large parts of the engine need to be rebuild. Hence, engine manufacturers play an important role in the introduction of alternative fuels, as they provide the guarantee for the engines to run on fuels with specific properties (Florentinus *et al*., 2012). MAN B&W already offers a slow-speed marine gas engine, and Rolls Royce has a medium-speed marine gas engine that meets the Tier III NOx limits that will become effective in 2016 (McGill *et al*., 2013). MAN also confirms the viability of using liquid biofuels in their MAN Diesel medium-speed engines which are originally designed for Heavy Fuel Oils (Florentinus *et al*., 2012).

Marine alternative fuels can be implemented in two main types of use: mono-fuel and dual-fuel. Each type has advantages and disadvantages that are described below (Florentinus *et al*., 2012).

- **Mono fuel**: When the engine type needs to be changed from Diesel to Otto (requiring major adjustments, parts of the engine need to be rebuild), for instance when a shift is made from diesel to CNG, LNG, ethanol or hydrogen; the CO_2 savings are lower than could be expected based on energy content. Marine diesel engines are about 30% more efficient than Otto engines, due to their higher compress ratio. When switching from diesel to CNG (Otto) this results in a combined emission reduction of 10-15% CO_2.
- **Dual fuel**: When gas and diesel are combusted simultaneously in a Diesel engine, the CO_2 savings are as high as can be expected based on energy content. This technology involves two fuel systems on the ship. Typically, a small quantity of marine fuel oil is used as pilot fuel, to initiate the ignition process, followed by combustion of the selected alternative fuel. The ship can run on a variable combination of the available fuels (DNV GL 2014). For instance, a variation of 100% diesel up to 97% LNG and 3% diesel is possible, resulting in high CO_2 savings and high variable cost savings

2 Alternative Fuels

Fuels that have the potential to reduce emissions below required levels can play a significant role in the future as substitutes for Heavy Fuel Oil (HFO) and Marine Diesel Oil (MDO). Additionally, fuel (LSF) consumption in the ECAs is estimated at approximately 30-50 million tonnes of fuel per year and it is going to increase as more areas are included in the ECAs in the future (DNV 2015). Both the demand for low sulphur fuels, as well as the need to reduced GHG emissions can be addressed by the introduction of alternative, low carbon fuels, provided that these fuels and the necessary technology are offered at competitive price levels.

The alternative fuels that are most commonly considered today are Liquefied Natural Gas (LNG), Electricity, Biodiesel, and Methanol. Other fuels that could play a role in the future are Liquefied Petroleum Gas (LPG), Dimethyl Ether (DME), Biomethane, Synthetic fuels, Hydrogen (particularly for use in fuel cells), Hydrogenation-Derived Renewable Diesel (HDRD) and Pyrolysis Oil. Additionally, fuels such as Ultra-Low-Sulphur Diesel (ULSD) can be used to comply with the regulations and support the transition to alternative fuels.

2.1 Ultra-low-sulphur Diesel (ULSD) Fuel

ULSDs are diesel fuels with very low sulphur content (15ppm mass basis), and low sulphur residual fuel (LSRF) are diesel fuels that contains up to a maximum of 500 ppm sulphur. For ULSD the amount of sulphur can vary from country to country (McGill *et al*., 20130). For example in the United States and Canada it is 15 ppm and in other countries it can be as low as 10 ppm or high as 50 ppm. As of 2006, almost all of the petroleum-based diesel fuel available in Europe and North America has been of a ULSD type (Patel and Shah, 2015). The lighter ULSD or low-sulphur diesel (LSD) is currently in use in many marine engine installations or can be used in current marine engines because of their similarity to the fuels that are in use today.

The low-sulphur residual fuels have a higher price than the high-sulphur residual fuels because of the cost of the desulphurization process and increasing demand. The existing price difference (based on available public bunker prices) between distillate (0.1–0.5% sulphur) and residual fuel (2.0–3.5% sulphur) is about $300 USD more per ton for distillate (McGill *et al*., 2013). The prices of marine fuels at two European ports in July 2012 are summarized in Table 4.

For ships normally burning residual fuel, special procedures must be observed when transitioning to the lower-viscosity distillate fuels. Sulphur (a natural inhibitor of microbial growth) reduction requires a lot more vigilance in preventing microbial growth in fuel tanks getting out of control (Bell Performance, 2013). Lubricity concerns have been addressed at the refinery level that give the ULSD fuel the right amount of lubrication (Bell Performance, 2013). The diesel engine manufacturers have developed a "Smart Switch" to facilitate this operation, and there are publications and bulletins available for switching to and operating on low-sulphur fuels. For ships that do not operate for a substantial amount of time in an ECA, the owners/operators may choose to use lower-sulphur fuels only when transiting an ECA. Most of the ports that currently offer high sulphur fuel oils also have available the low sulphur fuel oil of the same grade. It is conceivable that these fuels will suffice for the marine industry for low-sulphur fuels until 2016 when the NOx requirements are effective (McGill *et al*., 2013).

Table 4. Marine Fuel Prices in July 2012 in USD/Metric ton (Mt) by Port (McGill *et al*., 2013).

Port	High-Sulfur Heavy Fuel (IF 380)	Low-Sulfur Heavy Fuel (LS 380) (1% S)	High-Sulfur Heavy Fuel (IF 180)	Low-Sulfur Heavy Fuel (LS 180) (1% S)	LSMGO (0.1 % S)	MDO
Copenhagen	$597.50	$658.50	$630.00	$683.50	$907.50	$865.50
Rotterdam	$580.00	$631.50	$602.00	$653.00	$865.00	-------

2.2 Biofuels

Early trials in 2006 demonstrated the commercial and technical feasibility of the use of biofuels for marine applications (Mofor *et al*., 2015). Since then, experimentation with biofuels started on large vessels and preliminary results are encouraging (DNV GL, 2014). The maritime industry and government agencies are exploring the possibility of using alternative bio-based fuels for achieving their long-term sustainability goals. Examples of such collaborations include Progression Industry BV's MOU with Maersk Oil Trading to develop sustainable marine fuel using lignin as a feedstock (Green Car Congress, 2013).

Biofuels derived from plants or organisms biodegrade rapidly, posing far less of a risk to the marine environment in the event of a spill; flexible as they can be mixed with conventional fossil fuels to power conventional internal combustion engines or act as replacement. Example, biogas/biomethane produced from waste can be used to replace LNG. However, considering that the land required for production of 300 million tonnes of oil equivalent (Mtoe) biodiesel based on today's (first and second generation biofuels) technology is slightly larger than 5% of the current agricultural land in the world, securing the necessary production volume is a challenge. By 2030, biofuels are set to play a larger role, provided that significant quantities can be produced sustainably, and at an attractive price (DNV GL, 2014). Maersk envisages ~10% of the world's shipping fleets could be powered by biofuels by 2030 (EBTP- Biofuels in Shipping).

2.2.1 Methanol and Biomethanol (EN 228)

Each day, roughly 70,000 metric tonnes of methanol are shipped from one continent to another, sufficient to fill 777 rail cars (Methanol Institute). There are many players in the methanol market. Methanex (Vancouver) is the world's largest producer and supplier of methanol (Methanex 1) and Enerkem (Edmonton, Canada) has a commercial-scale MSW to methanol plant. The Enerkem facility converts MSW to syngas, which is converted to methanol. Methanol price are shown in Figure 6.

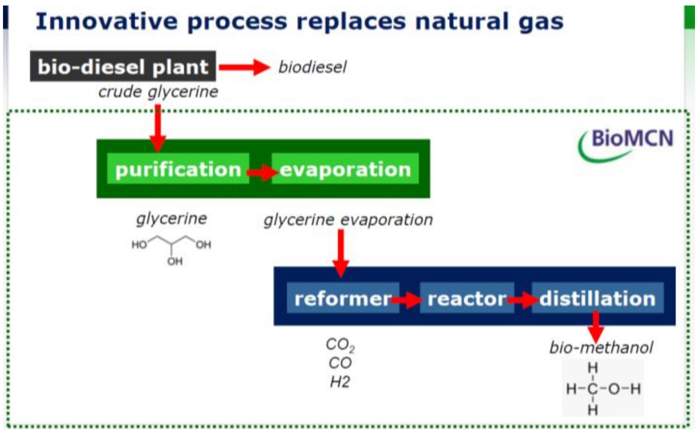

Figure 4. Bio-methanol production (BioMCN, 2011)

BioMCN (Netherlands) is the first company in the world to produce market and sell industrial quantities of biomethanol, using glycerine as a feedstock (EBTP – Methanol) – Figure 4. Table 5 compares methanol with biomethanol. This first-of-a-kind commercial plant (technology readiness level, TRL8) in the Netherlands, cracks crude glycerine (a residue from biodiesel production) to syngas, and synthesises to methanol at rate of 250 ML/y. It is also the largest advanced biofuel plant in the world. BioMCN plans to build a 250 ML/y commercial scale plant using wood feedstocks (the Woodspirit project), which was recently awarded NER300 funding. Uhde also have their 130 ML/y Värmlandsmetanol project in planning, looking to use forestry feedstock (ARUP URS, 2014). Production of methanol from biomass, e.g. cellulosic material, is technically feasible, but currently limited.

On an industrial scale, methanol is predominantly produced from natural gas by reforming the gas with steam, and then converting and distilling the resulting synthesized gas mixture to create pure methanol (Methanex 3). The result is a clear, liquid, organic chemical that is water soluble and readily biodegradable. When produced from natural gas, a combination of steam reforming and partial oxidation is typically used, with up to about 70% energy conversion efficiency. This corresponds to production emissions of about 24 kg CO_2/GJ fuel and 68.8 kg CO_2/GJ fuels for the use of fossil methanol, resulting in a total of 92.8 kg CO_2/GJ fuel, which is similar to diesel fuel emissions. Methanol produced from gasification of coal relies on cheap, widely available resource, but the GHG emissions are about twice as high as from natural gas at 182-190 kg CO_2/GJ fuel (DNV GL, 2015).

Table 5. Methanol versus Biomethanol (BioMCN, 2011) *ISCC-International Sustainability & Carbon Certification

	Methanol	Bio-methanol
Purity	>99,85%	>99,85%
Feedstock	Natural gas	Crude glycerine
CO_2 reduction		-/- 77%
Capacity		200.000 mton
Sustainability		ISCC

Table 6. Methanol prices as of 28th October 2015 (Methanex 2)

	Price	Date Last Changed
Europe (Valid October 1 – December 31, 2015)		
Methanex European Posted Contract Price (Posted September 17, 2015)	Euro 295/MT	Oct. 1/15 (-70/MT)
North America (Valid November 1 – 30, 2015)		
U.S. Gulf Coast	USD 1.05/Gal *	Nov. 1/15 (-.05/Gal)
Methanex Non-Discounted Reference Price	USD 349/MT	
Asia Pacific (Valid November 1 – 30, 2015)		
Asian Posted Contract Price	USD 305/MT	Oct. 1/15 (-10/MT)

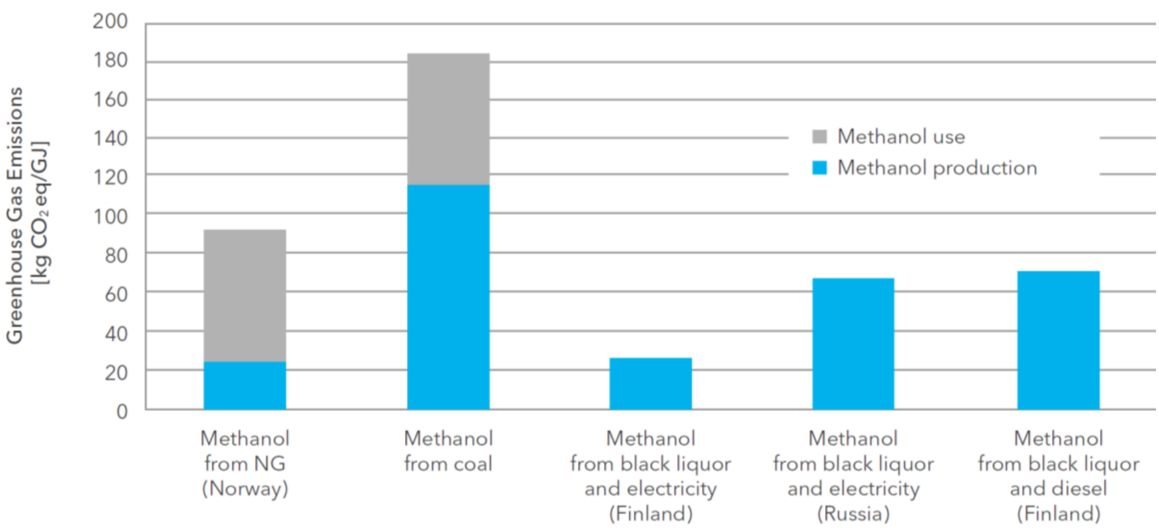

Figure 5. GHG emissions for various scenarios of methanol production showing the impact of local conditions and production methods (DNV GL, 2015)

However, biomethanol can also be made from black liquor in pulp and paper mills as a biofuel. The estimates summarised in Figure 5 show that for special cases, like in major refurbishments of chemical pulp and paper mills in countries with low emissions related to electricity use, such as Finland, Sweden, Portugal, and Spain, it is possible to produce methanol with a low CO_2 footprint. Another interesting possibility for producing methanol with a low CO_2 footprint is directly from hydrogen following electrolysis using geothermal electricity and CO_2 from the same geothermal source. This is currently being tested in Iceland (DNV GL, 2015).

Interest in methanol as a shipping fuel increased after Stena Line's decision to retrofit one of its vessels for using methanol, as a solution to low sulphur fuel requirements (DNV GL, 2015). Stena Line launched the world's first methanol powered ferry in 2015, the Stena Germanica, on the Kiel–Gothenburg route. Dual fuel technology is used, with methanol as the main fuel, but with the option to use Marine Gas Oil (MGO) as backup. This decision was driven by economic considerations: the fuel is readily available in Sweden where the vessel is bunkered, and the cost of retrofitting for methanol is much lower than the cost of retrofitting for LNG, due to the properties of the fuel (DNV GL, 2015).

Methanol as a general fuel has also been recommended by CEESA, an interdisciplinary research cooperation from Denmark. Although methanol itself is slightly costlier than LNG, the trade-off between methanol and LNG involves the complexity of the fuel system versus the cost of the fuel (McGill *et al*., 2013). Methanol has properties that are similar to those of methane when it is injected into an engine. Hence, methanol is also used in a dual-fuel concept.

Methanol has a relatively low flashpoint, is toxic when it comes into contact with the skin or when inhaled or ingested and its vapour is denser than air (DNV GL, 2014). The risk & safety analysis in the SPIRETH project (2014) has contributed to the development of ship classification society rules for methanol as a ship fuel. The work has also contributed to the International Maritime Organization's draft IGF code (International Code of Safety for Ships using Gases or Other Low-Flashpoint Fuels) and class rules (SPIETH project, 2014). In July 2013, DNV released rules for using low flashpoint liquid (LFL) fuels such as methanol, as bunker fuel (DNV, 2014). The Methanol Safe Handling Manual 2013 has also been provided by Methanol Institute.

The European methanol market is expected to remain volatile beyond 2015 as the region remains dependent on imports to satisfy domestic demand (European Petrochemicals Outlook, 2015). Importantly, biomass-to-methanol/DME is foreseen to be the most energy-efficient pathway to procuring transport energy by 2050 (McGill *et al*., 2013).

2.2.2 Dimethyl Ether – DME (EN 590)

DME (di-methyl ether) is a clean burning, high-density liquid fuel that can be used as a direct replacement for diesel fuel in power generation, transportation, heating, marine and a wide variety of other applications. It is in essence dehydrated methanol; two methanol molecules are combined to produce one molecule of DME and one molecule of water. For the last 20 years, DME has been a known substitute for diesel (Florentinus *et al*., 2011). MAN Diesel & Turbine has developed Tier-III-compatible DME engines for marine applications (Anselmo and Sullivan, 2015). With two new injection concepts, the ME-LGI (liquid-gas-injection) concept greatly expands the company's multi-fuel portfolio and which – apart from methanol – will include LPG, dimethyl ether (DME), and (bio) ethanol, as well as several other, low-sulphur, low-flashpoint fuels. Unlike compressed natural gas (CNG) or liquid natural gas (LNG), most importantly, DME can also be used in compression engines, which substantially impacts the potential applications of this fuel. DME can also be used along with spark ignition, diesel, turbine or fuel cell engines (Anselmo and Sullivan, 2015).

DME is non-carcinogenic, degrades rapidly in the atmosphere and is not a global warming agent. Accidental spills cannot poison water, DME will not sink to the water table and it is not absorbed by the soil (Anselmo and Sullivan, 2015). It is gaseous in ambient conditions and requires a pressure of about 5 bar to stay liquid, but does not require cryogenic storage (Marine Methanol, 2015). DME behaves similar to propane, has the same requirements for handling and storage precautions as LPG. It is stored and transported at ambient temperatures in tanks similar to those used in the propane industry (Volvo Trucks). In terms of infrastructure availability, unlike CNG and LNG, the global propane infrastructure is robust, inexpensive and extensive. Hence, propane distributors can use their infrastructure to move and store dimethyl ether. The price of DME versus diesel is lower in most global markets (Anselmo and Sullivan, 2015).

The concept of converting the by-product black liquor from pulp mills/paper mill residues via syngas to DME (BioDME) has been demonstrated by the four-year BioDME project funded by the EU's 7th Framework Programme, Swedish Energy Agency and participating companies (Landalv *et al*., 2014). The world's first BioDME production plant is at Smurfit Kappa paper mill in Piteå, Sweden. The pilot plant was inaugurated in 2010 with a capacity of about 4 tons (1,600 gallons) per day using forest residues as feedstock. The estimated cost of the plant was EUR 14 million (EBTP- BioDME). Up until the summer of 2013 more than 500 tons of BioDME had been produced and distributed to 10 heavy duty trucks, which in total accumulated more than 1 million km in commercial service (Landalv *et al*., 2014). The overall TRL level of Bio-DME is only 5, since Chemrec's pilot plant in Sweden has not expanded. Significant scale-up of at least 30 times will be required to reach full commercial scale (ARUP URS, 2014).

Currently, Asia-Pacific is the largest market of DME, accounting for nearly 95.66% of the total market size in terms of value in 2014. DME produced from coal accounted for the largest market share among other raw materials such as methanol, natural gas, and bio-based feedstock in 2014. The European market by volume is comparatively mature (Markets and Markets, 2015). The major players of DME include Akzo Nobel N.V. (The Netherlands), Royal Dutch Shell Plc. (The Netherlands), the Chemours Company (U.S.), China Energy Limited (Singapore), Mitsubishi Corporation (Japan), Ferrostal GmbH (Germany), Grillo Werke AG (Germany), Jiutai Energy Group (China), Oberon fuels (U.S.) and Zagros Petrochemical Company (Iran) (Markets And Markets, 2015).

2.2.3 Biodiesel or FAME (EN 14214, ASTM D6751, EN 590)

Fatty acid methyl aster (FAME) is produced from vegetable oils, animal fats or waste cooking oils by transesterification. For quality control, FAME is produced to specifications set by the American Society for Testing and Materials (ASTM) and the European Union (EU) (McGill *et al*., 2013). In Spain, Ecoproductos Ibericos SA (ECOPRIBER) and INMASA have developed and patented two efficient processes for the production of biodiesel. The first method (with methyl acetate), does not produce glycerine as a by-product and the second method, improves the efficiency of the conventional processes with methanol (EBTP- FAME).

For marine vessel operations, from a technical integration perspective biodiesel blends (up to 20%) have been reported as the most promising bio-based alternative fuel (Florentinus *et al*., 2012). Standard EN 14214:2008 (CEN, 2008) also highlights that biodiesel can be used in marine diesel engines and can be blended with distillate fuels. IMO 2007 even reports that low blends of biodiesel up to 20% (B20) could be used without any fuel system degradation (Florentinus *et al*., 2012). Many marine engine manufacturers have also certified their engines for operation on biodiesel or a blend of biodiesel and diesel fuel. However, the original engine manufacturer should be consulted for the amount of biodiesel their engines can burn (i.e., B20, etc.) (McGill *et al*., 2013). In 2014, the U.S. Navy put out a tender seeking at least 37 million gallons of drop-in biofuels as part of its F-76 marine diesel and JP-5 shipboard jet fuel supply (Mofor *et al*., 2015).

For road transport, blends are commercially available as diesel replacement and use of biodiesel as a low-blend component in road transport fuel (up to 7 % in Europe for the time being according to EN 590) does not require any changes in the distribution system, therefore, avoiding expensive infrastructure changes (EBTP-FAME Facts). Within the ISO 8217 framework, FAME is currently being adapted as a blending component for heavy marine fuel. It is foreseen that a volume concentration of up to 7% will be allowed in the near future (McGill *et al*., 2013).

However, the technical standard ISO 8217 lists some concerns/challenges around biodiesel or FAME (Florentinus *et al*., 2012):

- A tendency to oxidation and long-term storage issues
- Affinity to water and risk of microbial growth
- Degraded low-temperature flow properties
- FAME material deposition on exposed surfaces, including filter elements

Additionally, biodiesel can degrade over time forming contaminants in the form of peroxides, acids, and other insoluble particles. If biodiesel is stored for more than two months, the fuel should be closely monitored and tested to see that it remains within specification. However, the main problem with FAME is sustainability because FAME production relies heavily on palm oil production, which is often in conflict with the preservation of natural rain forests (McGill *et al*., 2013).

The flash point is a significant safety indicator during the storage, transportation and operation of fuel. Naval marine fuel, which has a flash point below 60°C, is not allowed to be stowed below deck according to the IMO Safety of Life at Sea (SOLAS) Convention (Knudsen and Hassler, 2011). The flash point of marine fuel DMA or RMA blended with at least 5 vol % biodiesel could reach 63°C or above, which can not only conform to the IMO SOLAS Convention, but also reduce the extent of problems such as fire hazards, which can be caused by the lower flash point of fuel (Lin, 2013). Thus, biodiesel increases fuel safety during operation and storage periods. It is also commercially available at prices comparable to those of marine diesel fuel (McGill *et al*., 2013).

E2 2014 predicts biodiesel to be the dominant biofuel until 2018. Application of low blends of biodiesel in distillate marine fuels could be introduced relatively easily. If biodiesel blends become accepted, whether or not endorsed by the ISO standard, the blending could take place at the bunker fuel terminal or even earlier in the supply chain (Florentinus *et al*., 2012). The EC has funded the following projects (Table 7) for biodiesel.

Table 7. EC-funded projects on FAME (EBTP- FAME Facts)

ALGFUEL	Biodiesel production from microalgae
ECODIESEL	High efficiency biodiesel plant with minimum GHG emissions for improved FAME production from various raw materials
SUPER METHANOL	Reforming of crude glycerine in supercritical water to produce methanol for re-use in biodiesel plants
InteSusAl	Demonstration of Integrated & Sustainable enclosed raceway and photo-bioreactor microalgae cultivation with biodiesel production and validation
AllGas	Industrial scale demonstration of sustainable algae cultures for biofuel Production (Biodiesel and Biogas)
BioFAT	Microalgae to biofuel demonstration

2.2.4 Hydrogen Derived Renewable Diesel – HDRD (ASTM D 975)

Hydrogenation derived renewable diesel (HDRD) is the product of fats or vegetable oils—alone or blended with petroleum—refined by a hydrotreating process known as fatty acids-to-hydrocarbon hydrotreatment. Diesel produced using this process is called renewable diesel to differentiate it from biodiesel, for example FAME, which is a product of the transesterification of animal fats and vegetable oils. HDRD is similar to petroleum diesel fuel, compatible with new and existing diesel engines and fuel systems. It is produced to meet current diesel fuel specification ASTM D 975 and is as safe as diesel fuel (McGill *et al*., 2013). This allows it to be legally used in existing diesel infrastructure and vehicles. HDRD derived from domestic biological materials is considered an alternative fuel under the Energy Policy Act of 1992 (AFDC). It can be blended with petroleum diesel so that, like biodiesel (FAME), it may find its way into marine use either as a "neat" fuel or as a blend with petroleum diesel. It has a lower production cost because it uses existing hydro-treatment process equipment in a petroleum refinery (McGill *et al*., 2013).

HDRD has better low-temperature operability than biodiesel; thus, it can be used in colder climates without gelling or clogging fuel filters. HDRD made from certain feedstocks, such as waste vegetable oils or animal fats, are cost competitive with distillate fuels but not residual fuel. However, current availability is limited. There are only a few companies that have invested to produce hydrogenation-derived renewable diesel. Currently, U.S. capacity for HDRD is 297 million gallons, and in Europe, Neste Oil has a capacity of 800,000 metric tons (approximately 244 million gallons), and new capacity is being added. UK-based Renewable Diesel Europe is the exclusive agent in Europe for the stand-alone renewable diesel technology developed by Cetane Energy (McGill *et al*., 2013).

2.2.5 Algae Biofuel

This fuel is produced to a hydrotreated renewable diesel (HRD) -76 specification. Algae can grow at very high rates compared to farmland crops. However, current costs are prohibitive for general commercial use other than experimentally or for performance-based demonstrations and commercial availability is limited.

Algae diesel fuels are as safe as petroleum diesel fuel, but have a slightly lower heating values than those of fossil counterpart (McGill *et al*., 2013). Blending with petroleum diesel negates these drawbacks so the blended fuel's performance compares favourably with petroleum diesel. Blending also lowers the sulphur content of the regular diesel to be diluted proportionally. Algae fuel contains almost no sulphur, so the SOx exhaust emissions are practically zero. When blended with 50% petroleum diesel it must meet the requirements for petroleum diesel F-76. In terms of compatibility with the fuel system and engine components it is considered to be a drop-in fuel.

The U.S. Navy is the primary user and developer of the fuel for marine use. Testing by the U.S. Navy showed no adverse effects from using a 50/50 blend of algae fuel and petroleum diesel fuel on engine and fuel system components during the demonstration within the "Green Strike Force" programme that took place in 2012. There are plans to use the fuel in a green fleet by 2016. The US Navy plans for biofuels to comprise up to 50 percent of the fuel used by deploying ships and aircraft throughout the fleet in calendar year 2016 (McGill *et al*., 2013). Currently, Solazyme has a contract to provide 450,000 US gallons of algal biofuels for ongoing US Navy trials (EBTP- Biofuels in Shipping).

2.3 Gaseous Fuels

Natural gaseous fuels are not only very low in sulphur content, but its combustion results in significantly lower emissions of NOx, PM, and CO_2 than their liquid counterparts. Currently, the cost is typically 70% less than residual fuel and 85% less than distillate fuel. Furthermore, the Energy Information Administration expects it to hold this price advantage through to 2035 (McGill *et al*., 2013).

Rules for the safe construction of ships using natural gas–based fuel have been developed and published by the classification societies such as Det Norske Veritas (DNV) and Lloyd's Register (LR) (McGill *et al*., 2013). However, compared to conventional fuels, in general the level of standardization is sparse for gaseous fuels. ISO 13686:1998 "Natural gas - Quality designation" and a standard for compressed natural gas" ISO 15403 Natural gas for use as a compressed fuel for vehicles" have been issued by ISO (IEA 2014).

Additionally, the extraction process (hydraulic fracturing or "fracking") remains a controversial technology. Natural gas is also not compatible with existing liquid fuel systems and requires the modification of existing engines and changes or additions to the existing shipboard fuel systems, as well as other changes for safety reasons. Table 8 shows the costs associated with converting three vessels of different sizes to accommodate natural gas service (McGill *et al*., 2013).

Table 8. Costs Associated with converting Marine Vessels to LNG Operation

Type	Size (tons)	Engines	Engine Cost	Fuel System Cost	TOTAL CONVERSION COST
Tug	150	2 × 1,500 HP	$1.2 million	$6.0 million	$7.2 million
Ferry	1,000	2 × 3,000 HP	$1.8 million	$9.0 million	$10.8 million
Great Lakes Bulk Carrier	19,000	2 × 5,000 HP	$4.0 million	$20 million	$24 million

Natural gas can be carried in a compressed state referred to as compressed natural gas (CNG) or in a liquid state referred to as liquefied natural gas (LNG).

2.3.1 Liquefied Propane Gas -LPG

Propane or LPG is mentioned from time to time as a potential marine fuel candidate. Its global market is projected to grow at a compound annual rate of 3.4% during the period of 2014 to 2020. In 2013, the global liquefied petroleum gas (LPG) market was worth US$233.83 billion and by 2020, the global liquefied petroleum gas (LPG) market is expected to be valued at US$299.05 billion (TMR, 2015). However, there seems to be very limited information available on LPG's viability as a marine fuel. The general view around the globe seems to be that LPG is a premium product and as such, is priced accordingly and is too expensive compared to other alternative fuel options. Figure 6 shows the price difference between propane and crude oil. Therefore, although the supply is in place, its current markets are in automotive transportation and domestic heating and cooking, markets that have a different price reference than shipping. In terms of safety, propane is heavier than air and thus presents an explosive safety hazard if it were to accumulate in the bilges or low sections of a ship's engine room in the event of a leak in the fuel system; thus, it is not considered safe for shipboard use (McGill *et al*., 2013).

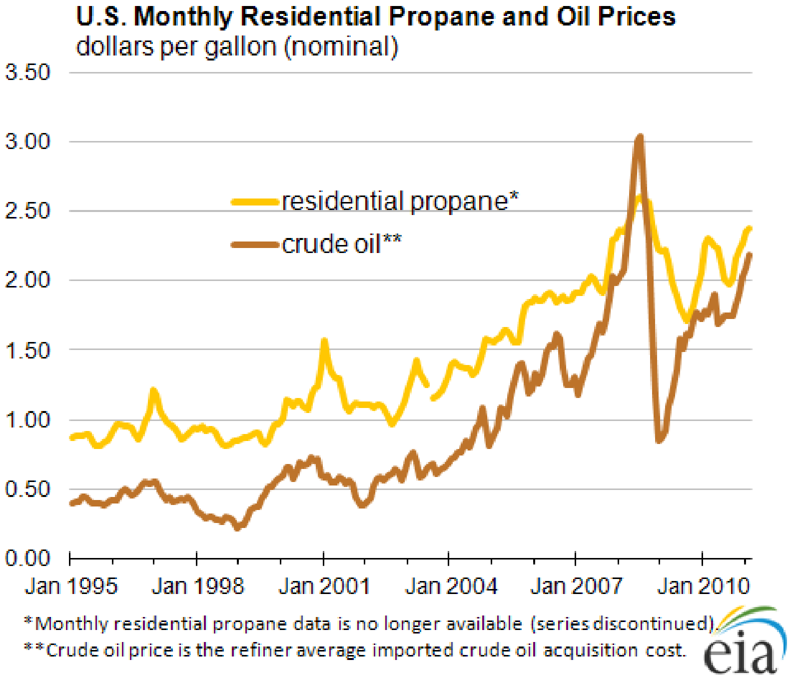

Figure 6. Propane and Crude oil prices (EIA Propane)

2.3.2 Liquefied Natural Gas - LNG

Ships

LNG has been used to fuel diesel propulsion systems of LNG vessels since delivery of the Provalys in 2006 (Adamchak, 2013) and is now a proven and available solution, with gas engines being produced covering a broad range of power outputs (DNV GL, 2014). It was first utilized as a fuel by LNG carriers in the 1960s, taking advantage of the fuel available on board in the form of boil-off gas and was enabled by virtually zero fuel costs when the vessels were loaded. The first LNG-powered vessel (excluding LNG carriers), was a ferry built in Norway in 2000. Since 2010, the growth in LNG-powered ships has accelerated, resulting in 59 ships in operation (April 2015), as well as another 80 under construction, with planned deliveries by 2018 (DNV GL, 2015).

Engines

Most of today's marine fuel demand relates to ships with engine capacities ranging from 5 MW to more than 50 MW. Natural gas fuelled engines are already offered for the full range of required engine capacities. These are 4-stroke, medium speed engines, operating on the Otto cycle ignited by pilot fuel or by spark ignition. For the highest capacity range, natural gas fuelled, Diesel-cycle 2-stroke engines are also offered (DNV GL, 2015). LNG can be used in dedicated mono-fuel engines (Otto cycle) with lower efficiency as diesel engines. When LNG is mixed with the inlet air in a diesel engine (dual fuel process) the high efficiency is maintained, while a large part of the diesel consumption can be reduced (Florentinus *et al*., 2012). Methane slip (leakage contributing to GHG emission) during combustion is practically eliminated in modern 2-stroke engines, and further reductions should be expected from 4-stroke engines (DNV GL, 2014).

Challenges

The cost of installing a gas or dual-fuel engine, LNG tanks, appropriate piping and related equipment can increase the price of a new vessel by up to 30% compared with conventional propulsion technology (DNV GL, 2015). When stored as LNG, the fuel takes up twice as much space as liquid fossil fuel, and if stored as CNG, it takes up to five times as much space (McGill *et al*., 2013), leading to a decrease in payload capacity. The size of the tanks is affected both by the energy density of LNG, by the additional insulation required, and by the cylindrical shape of existing tanks, which make suboptimal use of the space. The energy density of LNG is 2.4 times that of CNG or 60% of that of diesel fuel. It is anticipated that prismatic tanks, when they become commercially available, will drive down the space requirements to some extent (DNV GL, 2015).

For retrofitting a vessel, the logistics of taking the vessel out of service for a few months must be included in the calculation along with the cost of the equipment. Guidelines are available to help ship owners prepare for such a solution (DNV GL, 2015). Hazards include flammability and low freezing temperature (−163°C or −260°F), such that marine regulations require extra safety precautions like double wall piping, gas detections systems, etc., in engine rooms.

There is need for LNG storage facilities and de-bunkering (or emptying the fuel tanks) at ports to facilitate use of this technology. The de-bunkering step is necessary when a ship is to be anchored for an extended period of time. Unless special LNG de-bunkering facilities are available in the port, the gas would boil off, causing huge methane losses to the atmosphere (McGill *et al*., 2013). Re-liquefaction of boil-off gas (BOG) requires about 0.8 kWh/kg gas. One large LNG carrier, such as Qatar Q-max, requires 5–6 MW of re-liquefaction power, corresponding to a boil-off rate of 8 tons/hour (McGill *et al*., 2013). LNG bunkering for ships is currently only available in a number of places in Europe, Incheon (Korea) and Buenos Aires (Argentina), but the world's bunkering grid is expanding (DNV GL, 2014). The port of Stockholm, Sweden, has established a LNG bunkering port with dockside fuelling and a special purpose ship that performs ship-to-ship LNG fuelling. Norway already has an established LNG infrastructure (for short sea shipping). In the U.S., the U.S. Department of Transportation Maritime Administration (MARAD) and the U.S. coast guard (USCG) are studying the development and implementation of a regulatory approval process for LNG bunkering operations and associated technological and procedural risk management requirements at permitted facilities (Holden, 2014).

Despite the lack of regulatory drivers to reduce methane slip in marine engines, various technologies can be employed for tackling this problem:

- For **Otto cycle engines**, unburned methane can be reduced by using exhaust gas recirculation (EGR), which improves combustion stability, or by exhaust gas after-treatment with methane oxidation catalysts using special catalytic materials, such as palladium or platinum (CIMAC, 2014).
- In **diesel cycle engines**, a high-pressure injection, dual-fuel concept can be used which comes at the cost of a smaller reduction in NOx emissions. In this approach, the natural gas is not premixed with air before entering the engine. Instead, it is injected directly into the combustion chamber during the compression stroke following a diesel pilot injection. Engine manufacturers claim that this technology limits methane slip to 0.2 gCH_4/kWh (or about 0.1% slip), practically eliminating the problem (DNV GL, 2015).

The European Clean Power Directive requires all larger sea ports and Trans-European Transport Networks (TEN-T) core inland ports to have LNG-bunker facilities by 2025 (Ministry of Infrastructure and the Environment, 2014). In principle, Europe is well prepared for the future as local LNG production is up and running in Norway (McGill *et al*., 2013). The reasons behind the emergence of LNG-powered ships in Norway include a combination of readily available natural gas, eagerness to explore new technical solutions, and a financial support scheme called the Norwegian NOx fund. The NOx fund is incentivised by a governmentally imposed NOx tax, and provides financial support to participating enterprises who want to implement NOx reduction measures. This financial support acted as a boost for technology development and gaining experience, which, in turn, has helped the commercial viability of LNG technology in other parts of the world (DNV GL, 2015).

LNG uptake is expected to grow fast in the next 5 to 10 years, first on relatively small ships operating in areas with developed gas bunkering infrastructure, where LNG prices are competitive to Heavy Fuel Oil prices (Pawlak, 2015). A number of large LNG import terminals already exist, with some of these having or planning an export facility, which is a necessary step towards small-scale LNG distribution (McGill *et al*., 2013). It has been estimated that there will be a consumption of 2.4 Mt of LNG in 2020, and 15–20% of the new ships built between 2012 and 2020 are expected have the capacity for burning LNG as a propulsion fuel (McGill *et al*., 2013). The international classification society Bureau Veritas (BV) has given approval in principle for the basic design of a 14,000-TEU (twenty foot equivalent, which gives a measure of the number of standard 20 ft containers that can be carried) containership to be powered by LNG. A feature of this design is that the vessel can also run on HFO if required, thereby increasing flexibility in the period before LNG bunkering becomes widely available (McGill *et al*., 2013). The Rolls-Royce Bergen K gas engine has been certified to power the world's first major car and passenger ferries running on LNG (EBTP-Biofuels in shipping).

An IMO 2009 study projects 5–15% CO_2/ton-mile savings by 2050, with LNG used as a major low-carbon fuel along with the marine diesel oil (MDO). Only if the methane is produced as bio-LNG will fossil CO_2 be substantially reduced (Florentinus *et al*., 2012).

2.3.3 Biomethane – Bio LNG

Biomethane which is methane produced from biomass is an interesting fuel to support the transition from fossil fuels to renewables and to achieve the greenhouse gas emission reduction targets (IEA, 2014). Since it is chemically identical to fossil LNG there is increasing interest to use it in the shipping sector, also because it can benefit from the growing LNG infrastructure. LNG terminals in Europe currently can be found in Belgium (1), the Netherlands (1, with several others under development), UK (4), Denmark (1), Sweden (1), Norway (>40), and with plans for about 20 additional LNG terminals in North West Europe (Florentinus *et al*., 2012).

Biomethane is generally considered to be the most CO_2-friendly fuel of all (McGill *et al*., 2013). Bio-LNG is of better quality than fossil LNG according to van der Gaag (2012). It can be produced by upgrading biogas or by thermo-chemical conversion of lignocellulosic biomass, or other forms of biomass, to bio-SNG. Biogas upgrading includes increasing the energy density by separating carbon dioxide from methane. Furthermore, water, hydrogen sulphide and other contaminants are removed, sometimes before the upgrading process to avoid corrosion or other problems in downstream applications. The technical feasibility to produce biomethane from biogas on a large scale has been demonstrated over the last decade. The production of biomethane via thermo-chemical conversion is still at a demonstration stage with very limited commercial market penetration so far. There is a range of national standards in Europe for the injection of upgraded and purified biogas to the natural gas grid (IEA, 2014) and CEN has drafted a European standard (CEN, 2014).

Biomethane could be applied in exactly the same way as LNG and therefore not lead to any additional challenges. However, to switch from LNG to bio-LNG investments, technological development is needed to produce the required amount of biogas. At this point in time the scattered availability of biogas in Europe would limit the introduction of bio-LNG, as long as no intra-European biogas certification scheme allows local biogas production facilities to introduce their biogas to central LNG terminals within Europe. The EU had more than 300 biomethane plants in 2014 (IEA Bioenergy Task 37, 2015).

2.4 Electricity

Electrification has generated strong interest, particularly for ship types with frequent load variations (DNV, 2014). The challenge with respect to shore-based electricity for powering ships is related to the energy density of batteries and other storage solutions, limiting the range of the ships. Electrification in shipping can have two distinct forms: as a hybrid propulsion system, or as a pure electrical propulsion system (DNV GL 2015).

Corvus Energy (leading lithium-ion energy storage system supplier) was the winner of the Supplier of the Year award at the 2015 Electric & Hybrid Marine Awards in Amsterdam. Their hybrid technology powers more than 35 commercial hybrid and electric vessels around the world, with an installed capacity totalling over 30MWh. Offshore supply vessels like the Viking Lady OSV and Edda Ferd PSV that employ the Corvus ESS have been field-tested and proven to exceed performance and safety requirements. These vessels have been reported to run at peak efficiency for longer periods of time, saving fuel and maintenance costs and dramatically reducing emissions (Corvus 2015).

Although a number of hybrid ships have been built and are being used for testing batteries in shipping, purely electric ships have now started to be developed. The first fully electric ferry was scheduled to enter service in Norway's Sognefjord during 2015, in a cooperative effort between Siemens and the Norwegian shipyard Fjellstrand. The ferry has a capacity of 360 passengers and 120 cars, and uses two 450 kW electric motors which emit no direct emissions over the 6 km crossing. Each crossing uses approximately 150 kWh from lithium-ion batteries that are recharged between crossings using power from the shore-based grid. Ships powered by shore-based electricity can offer significant benefits in terms of improved energy efficiency and reductions in emissions. The benefits in energy efficiency arise from eliminating combustion engines, which are associated with significant efficiency losses. The most efficient marine engines today are not more than 50 % efficient, whereas a battery may have a charge/discharge efficiency of more than 90%. Hence, depending on the method of power generation in the grid, energy losses can be decreased (DNV GL 2015).

In addition to using on-board batteries for propulsion, shore-based electricity can also be used to power ships at berth (cold ironing or alternative maritime power (AMP)). There are a few ports around the world where AMP is already established, with significant benefits to the local air quality and noise levels. Benefits in terms of reduction of GHG emissions can also be achieved, depending on the local electricity mix. AMP can also have financial advantages for ship operators, contingent on the cost of required on-board equipment, local electricity prices, and the fuel quality requirements at port (DNV GL 2015). Standardization of the systems and equipment required is important to ensure compatibility between different port installations, so that a ship can use AMP at all ports without additional requirements.

The main barrier for introducing batteries in shipping is their high capital costs, which are typically in excess of $1000/kWh. This initial high outlay has to be recovered through operational savings, through reduced costs of energy and lower maintenance requirements. In areas with low electricity prices, such as Norway, the capital costs can be recovered relatively quickly, ranging from a few months to a few years, depending on the type of ship and its operation.

2.5 FT Diesel

Fischer-Tropsch (FT) diesel can be derived from a number of sources such as natural gas, coal, biomass, and co-feeding of the three. After pretreatment of the feedstock, the central process involves production of synthetic gas (a mixture of CO and hydrogen) which can subsequently be reacted over a catalyst in the FT synthesis process to produce hydrocarbons of varying carbon chain length. In a typical FT plant, three groups of hydrocarbons are produced: FT naphtha (C5–C9), FT middle distillates (C10–C20), and FT wax (>C20). FT middle distillates (diesel and jet fuels) are the premium fuel components that contain virtually no sulphur and have a high cetane number (a measure of the ignition quality of diesel fuel; the higher the number, the easier it is to start a standard direct-injection diesel engine).

Diesel made from natural gas is approved by the US EPA as Non-Toxic (ANGTL, 2009) and is currently used for road transportation and as jet aviation fuel. Mushrush *et al*. (2009) reported an ASTM procedure required to test storage stability of blends with petroleum diesel. The formation of 3 mg/100 mL of fuel sediments or less means the fuel will be stable in storage for a period up to two-years. The authors reported a 50/50 blend of FT diesel and petroleum middle distillate to be marginally compatible, resulting in the formation of 1.7 mg solids/100mL as sediments.

In Europe, there are 2 full-scale demonstration plants planned and awarded funding under NER300 (Vapo Forest BTL and UPM Stracel), another similar project on the NER300 reserve list (UPM Rauma), a 5 ML/y small demonstration plant planned for 2017, and a handful of pilot plants under 1 million litres. These demonstration plants (135-150 ML/y) are approaching full commercial scale. However, these plant sizes require scale up by at least 30 times from the development and pilot test facilities in operation over the last few years. Scale-up will be a major challenge. In the US, around four pilot plants are currently operating, but only intermittently and at scales up to 1 ML/y. There is another pilot under construction and another planned, along with the proposed Fulcrum Bioenergy plant (Sierra Biofuels) which awaits funding (ARUP URS, 2014).

2.6 Pyrolysis oil (ASTM D 7544)

Pyrolysis oil is a dark-brown liquid made from biomass by a thermochemical process called fast pyrolysis, whereby biomass particles are heated in the absence of oxygen, vaporized, and condensed into liquid. The process is also known as flash pyrolysis since biomass is heated in the absence of oxygen with a very short retention time of typically less than 2 seconds at around 500°C. The process typically yields 65-70% liquid bio-oil (dry feed basis), 15-20% char (a black charcoal-like powder), and non-condensable gases. Pyrolysis-derived fuels have not yet been certified for use in marine diesel engines, although they can potentially substitute residual oil, light fuel oil or natural gas in other applications such as pulp mills, stationary diesel engines, power plants, and industrial boilers (Bradley, 2006; Adom, 2013).

On a volumetric basis, the energy content of pyrolysis oil is about half that of diesel and the oil has high oxygen content, typically 25% water content, and a pH of 2.5-3 (DNV GL, 2015). The high oxygen and water content renders pyrolysis oil unstable in nature. This may result in phase separation and polymerization when the oil is stored over a long period of time (Han *et al*., 2011). Hydrotreatment to reduce the oxygen content in the oil is essential for its stabilization, although it requires significant amounts of hydrogen. Additionally, pyrolysis oil does not auto ignite in a diesel engine and it also cannot be blended with diesel fuel (Speight, 2011). The oil may be used directly in boilers and turbines if corrosion resistant materials are used, but in order to use it as an engine fuel and to be able to store it for long periods, upgrading (typically using hydrogen) is required (DNV GL, 2015). In recent work aiming at market development, pyrolysis oil has been upgraded for use in polygeneration and for trade (EMPYRO, 2015).

DNV GL (2015) reporting on previous work in 2014, compared the emissions and cost for the crude pyrolysis oil delivered in Rotterdam using: 1) Wood from Canada (10.4 kg CO_2/GJ, 19$/GJ) and 2) Wood from Finland (7.8 kg CO_2/GJ, 23$/GJ). For comparison, typical emissions of MGO are of the order of 88-90 kg CO_2/GJ; thus a 90% reduction in GHG emissions seems possible. In that report, transportation costs from Finland to the Netherlands were also reported to be only slightly lower than transportation costs from Canada to the Netherlands; which results from fuel prices for tankers operating in the North European ECA being higher than in the North Atlantic. This example illustrates how the costs of producing a fuel can lead to decisions with negative environmental impact. Figure 7 below shows the cost and emissions from the DNV GL (2015) study.

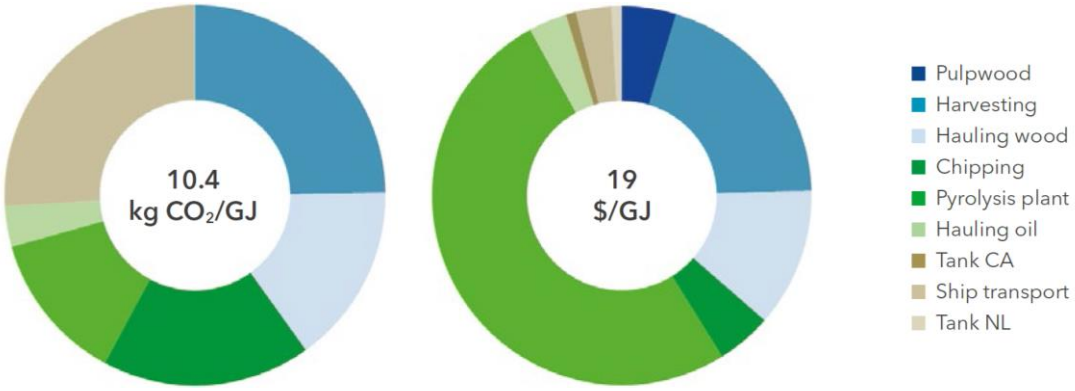

Figure 7a. Emissions and costs for pyrolysis oil derived from wood, produced in Canada (CA) and transported to Rotterdam (NL)

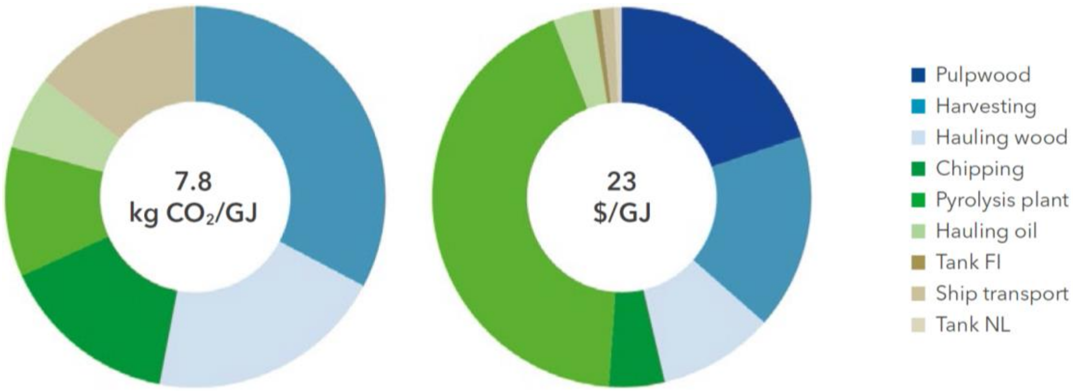

Figure 7b. Emissions and costs for pyrolysis oil derived from wood, produced in Finland (FI) and transported to Rotterdam (NL)

Commercial manufacture of pyrolysis oil started following completion of a 100-tpd (tones per day) plant in Canada in 2005 (Bradley, 2006). Empyro in Netherlands is Europe's first-of-a-kind commercial polygeneration flash pyrolysis plant (Sherrard, 2015). The Empyro plant has a design capacity to convert 5 tonnes per hour of woody biomass into 3.3 tonnes of pyrolysis oil, 4.5 MW of steam and 435 kW of electricity with self-consumption of heat and power taken into account. A 10 tonne per hour plant design is just a matter of duplicating the modular units. If larger outputs are required then additional plants can be set-up in cascade keeping CAPEX low and revenue coming in once the first unit is running (Sherrard, 2015).

2.7 Hydrogen and Fuel Cells

Hydrogen is the smallest and lightest of all gas molecules, thus offering the best energy-to-weight storage ratio of all fuels (DNV GL, 2014). In principle, internal combustion engines and turbines can also be used for combustion of hydrogen (DNV GL, 2015). Commercial engines for combustion of hydrogen are unavailable, and focus is primarily directed towards pilot projects including fuel cells which have superior fuel to electricity conversion efficiency. However, hydrogen as fuel can be difficult and costly to produce, transport, and store.

Fuel cells are the most commonly used devices to convert the chemical energy of hydrogen into electricity. When a fuel reformer is available, other fuels, such as natural gas or methanol can be used to power a fuel cell (DNV GL, 2014). Examples include, FCS Alsterwasser, a 100-pax fuel-cell-powered passenger vessel based in the port of Hamburg (Germany). Additionally, in 2012, as part of the FellowSHIP project, a 330 kW fuel cell was successfully tested on board the offshore supply vessel Viking Lady, operating for more than 7,000 hours. This was the first fuel cell unit to operate on a merchant ship, with the electric efficiency estimated to be 44.5% (when internal consumption was taken into account), with no NOx, SOx and particulate matter (PM) emissions detectable (Mofor *et al*., 2015). Although operational experiences have shown that fuel cell technology can perform well in a maritime environment, further R&D is necessary before fuel cells can be used to complement existing powering technologies for ships (DNV GL, 2014).

There are two main pathways for producing hydrogen (DNV GL, 2015):

1. Electrolysis of water: Emissions associated with this are related only to power generation for the electricity. If renewable power is available, hydrogen can be produced emission-free, but for a typical electricity grid mix, emissions are significant.
2. Reforming of natural gas: Hydrogen is produced by the reaction of methane with steam, CO_2 is separated and (should be) used as a by-product. An advantage of this method is that the CO_2 can be captured at its source.

Compressed hydrogen has a very low energy density by volume requiring six to seven times more storage space than HFO (DNV GL, 2014). It is estimated that depending on the pressure, the tank size must be 10-15 times larger than required for heavy fuel oil. Liquid hydrogen on the other hand, requires cryogenic storage at very low temperatures (-253^{o}C or 20K), associated with large energy losses, and very well insulated fuel tanks. The hydrogen storage tanks, due to their size, can additionally result in loss of cargo space. These increased costs of the fuel and the limited gains in CO_2 emissions, combined with challenges regarding storage of hydrogen, safety, and the cost of fuel cells, mean that hydrogen and fuel cells are unlikely to play a major role in propulsion of shipping in the next ten to twenty years (DNV GL, 2014).

The overall energy efficiency of producing hydrogen through electrolysis and using it in a fuel cell to produce electricity and power an electric motor appears to be substantially lower than the efficiency of the charging a battery and using this electricity to power the same electric motor. Charging a battery is associated with small energy losses, of the order of between 5 and 10%. Producing hydrogen through electrolysis has an efficiency of approximately 65%, while additional losses of at least 30 – 35% should be expected from a well-performing fuel cell. As shown in Figure 8, the energy losses associated with the use of batteries are significantly lower than those of producing hydrogen and using it to power a fuel cell. Hence, from an energy utilization point of view, the use of hydrogen cannot be recommended. However, hydrogen could be a viable solution in applications where a long cruising range does not allow the use of existing battery technologies due to space and weight limitations, provided that the size of the hydrogen tanks is not prohibitive (DNV GL, 2015).

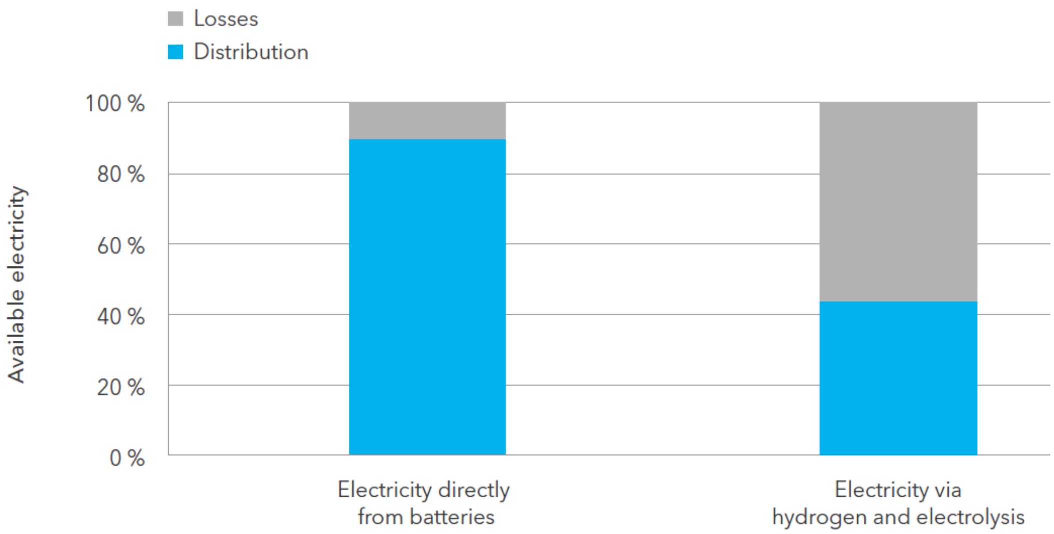

Figure 8. Comparison of energy losses when charging a battery compared with using electricity to produce hydrogen and run a fuel cell (DNV GL, 2015)

Special consideration has to be given to storage of hydrogen on board ships to ensure safe operations. For ship applications, reductions in size and weight are also of immense importance, while response at transient loads also remains a big challenge.

2.8 Solar and Wind

While solar and wind renewable energy may have some potential to mitigate carbon emissions, this is not seen as a viable alternative for commercial shipping.

Current market leaders in soft sails for ships include Greenheart's 75 dwt (deadweight tonnage) freighter, B9 Shipping's 3000 dwt bulker and Dykstra/ Fair Transport's 7000 dwt Ecoliner. The latter two designs feature versions of Dyna-Rig systems (proven on the super yacht Maltese Falcon) that are operated automatically from the bridge, enabling wind to be harnessed more easily, keeping crew sizes comparable with fossil-fuel powered ships and allowing easy access to hatches for loading and discharging cargoes. Italian shipping innovation company Seagate, has patented folding delta wing sails for retrofitting to existing ships, including roll-on, roll-off (Ro-Ro), container ships and car carriers. In 2008 *MS Beluga Skysails* was the world's first commercial container cargo ship partially powered by a 160-square-metre sail installation (Mofor *et al*., 2015).

Fixed-sails are essentially rigid 'wings' on a rotatable mast. Current proposals include use on large ships e.g. *UT Wind Challenger* and *EffShip's* project5 which includes using rigid sails capable of reefing down on telescoping masts for heavy weather or in-port situations. A UK company Oceanfoil, has revisited the 1986 Walker Wingsail design and has filed a new patent for a revised and improved design that was scheduled to be available for retrofitting from the beginning of 2015 (Mofor *et al*., 2015).

3 Life Cycle Analysis- LCA

To be able to comment on the environmental sustainability of fuels, quantitative data are required for Life Cycle Assessments (LCA). LCA permits comparison between different fuel pathways along the energy value chain. LCAs of alternative fuels for the automotive sector, Well-To-Wheel studies, are now well-established. LCAs of alternative fuels for the maritime transport sector, referred to as Well-To-Propeller studies, and are relatively new (Bengtsson *et al.*, 2011).

In LCA context, payback time and Global warming potential (GWP) have been widely discussed. The GWP of a greenhouse gas refers to an estimate of total contribution of the gas to global warming, over a particular time, that results from emission of one unit of the gas relative to one unit of CO_2 (reference gas), which is assigned a value of 1. The time frame usually used is 100 years. Greenhouse gases have different atmospheric impact lifespans and hence, the time frame is very important in describing the GWP.

Payback time is the amount of time required to recapture the carbon released during production and use of biofuel. For biofuels, the main concern is associated with the release of stored carbon from woody biomass (carbon sink) utilized for producing the fuel, or due to resulting land use change which can take many years to replenish (even for annual crops). It is important to know that this "debt" is repaid if the new system has net GHG emissions less than the emissions from the lifecycle of the fossil fuel counterpart. The more carbon intensive the fossil fuel replaced, the shorter is the payback time. Additionally, the less efficient the bioenergy system, longer are the payback times (Agostini, Giuntoli and Boulamanti 2013). For woody biomass, the balance between carbon capture and emission is strongly affected by the approach taken to forest management, for example which components of trees are used and the size of the forest landscape taken for accounting purposes (Cowie *et al.*, 2013).

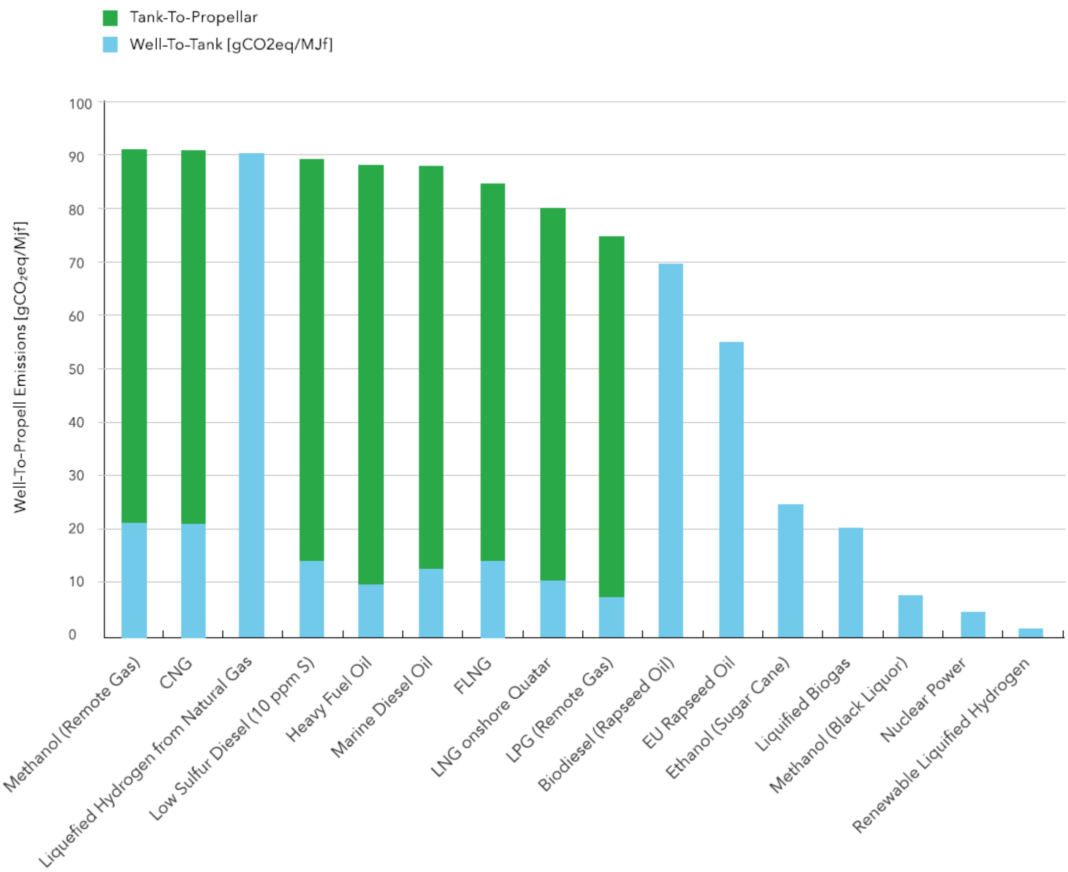

Figure 9. Emissions for different fuels

Designing policies to promote new alternative fuels require due diligence on the whole lifecycle. However, LCAs are complex and the chosen scenarios strongly influence the outcomes as shown in the three studies discussed below.

3.1 DNV 2014 LCA on different marine fuels

DNVGL (2014) made the following assumptions and set the systems boundaries in Table 9 for its LCA. The Well-To-Tank and Tank-To-Propeller results for the GHG emissions in gCO_2eq/MJ related to the different pathways for the maritime transport alternative fuels are shown in Figure 9.

It is noted that for LNG, the calculations have been performed assuming a 4-stroke dual-fuel engine, which results in a certain amount of methane slip, thus reducing the GHG savings. It is expected that when LNG is used in modern 2-stroke engines the methane slip is eliminated, leading to greater GHG reductions.

Table 9. System boundaries for LCA

Studied fuels	Scenarios and System boundaries [1]
HFO, MGO/ MDO, and low sulphur diesel	Crude oil transported from oil region to Europe (8,000 km), refined and distributed there
LNG	■ LNG produced onshore in Qatar and transported to Europe via LNG carrier ■ FLNG facility offshore Australia and transport of LNG to market via LNG carrier 10,000 km away
CNG	Natural gas is piped from Russia to Europe (7,000 km) where it is compressed using EU electricity mix
LPG	LPG as a by-product of remote natural gas production and shipped to Europe (10,000 km) via gas carrier
Methanol	■ Methanol produced near a remote natural gas field and transported to Europe via methanol tanker (10,000 km) ■ Methanol produced from black liquor and transported to Europe
Ethanol	Ethanol produced from sugar cane in Brazil and shipped to Europe (10,000 km)
DME	■ DME produced close to a remote natural gas field and shipped to Europe via gas carrier ■ DME produced via black liquor gasification close to a pulp-mill and transported to Europe
FT diesel	FT diesel plant close to a remote natural gas field and diesel transported to the market via product tanker
Biodiesel	European production of rapeseed oil and biodiesel production in the area
Raw Vegetable Oil	Production of rapeseed oil in Europe and used directly as fuel
Liquefied Biogas	Biogas produced in Europe from municipal waste and liquefied onsite
Nuclear propulsion	Nuclear fuel (Uranium) provision and its use on-board
Liquid Hydrogen	■ Liquid hydrogen produced from renewables and distributed in the area ■ Liquid hydrogen from reforming of Russian natural gas

[1] Most of the shipping routes in this study are assuming a distance of about 10,000 km, unless otherwise indicated.

Some of the fuels considered appear to be very attractive from a GHG emissions point of view. However, it is important to remember that all fuels are not equal when it comes to how much they cost at current market prices. Many alternative fuels can be competitive in terms of prices with low sulphur diesel (LSD). LNG seems to be the most attractive price-wise, but the costs of retrofitting or buying new LNG tanks and engines are not negligible and should be taken into account.

A more complete comparison can be performed by including in the lifecycle assessment of the equipment required for producing *and using* the fuels under consideration. An example could be the environmental footprint of producing and disposing of fuel cells, as compared to an internal combustion engine.

3.2 ECOSYS 2012 LCA on different biofuels

This report covers a sustainability analysis which includes greenhouse gas balance and emissions to air for selected biofuels including biodiesel, DME, pure vegetable oil, biomethane, bioethanol and pyrolysis oil compared with LNG and liquid fossil fuel emissions (Florentinus *et al*., 2012).

Greenhouse gas balance
The GHG balance was determined for the different biomass resources which could lead to the selected type of biofuel. The highest and lowest greenhouse gas values per biofuel type are presented in comparison with the fossil reference fuel (grey) in Figure 10. In the case of biodiesel, the GHG emission depends strongly on the type of feedstock used in the production processes.

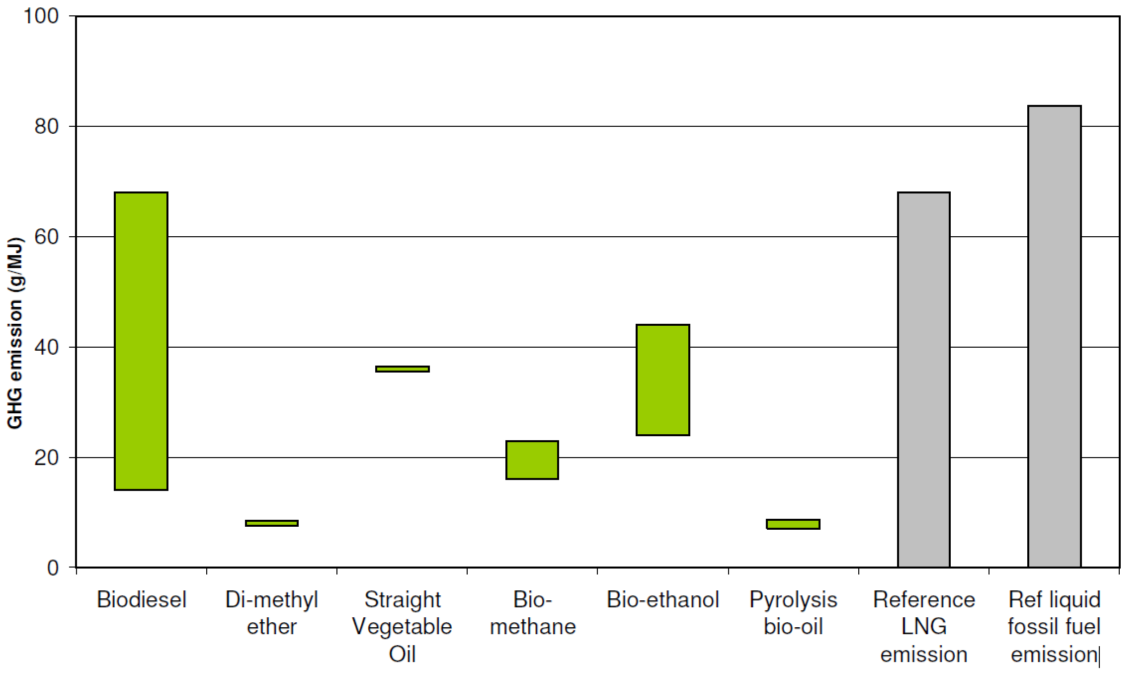

Figure 10. GHG emissions comparison (Source: Florentinus *et al*., 2012)

Emissions to air
Table 10 shows the typical change in emissions for the selected biofuels. Note that for ethanol, there is very limited information about its performance in diesel engines.

Therefore, for comparison, the relative performance of bioethanol in an Otto engine is given at the bottom of the table.

Since the biofuels do not contain sulphur, there are no emissions of sulphur-containing compounds such as sulphuric acid.

Table 10. Changes in emissions when fossil fuels are replaced by biofuels in diesel engines and gasoline engines (Source: Florentinus *et al*., 2012)

Blends	NOx	PM10	SOx	HC
Diesel engines				
B100	+10%	-50%	-100%	-65%
B20	+2%	-12%	-20%	-20%
DME	-	-	-	+
BTL	-	-		
Gasoline/ otto engines[1)]				
E85	-60%	-		+30%
M85	-30%	-		+25%
CNG	-33-97%	-95%	-100%	+

1) Gasoline is the reference fuel for ethanol and methanol (E85 and M85) in Otto engines, Otto engines are generally speaking much cleaner than diesel engines. Although the CNG is technically used in a Otto engine, this concerns a modified diesel engine and the reference fuel is diesel.

When diesel is replaced by pure biodiesel (B100 in Table 7 above), the NOx emission generally increases by about 10%. This increase is linear, so that the use of a 20% biodiesel blend results in an increase in NOx emission of about 2%. NOx emissions do not depend on the chemical composition, but rather on the combustion conditions. The combustion of biofuels in ship engines will be slightly different from marine fuels, but actual performance for large quantities of biofuels is unknown at this point in time. This issue needs further research before biofuels are used in large quantities. In road transport, NOx emissions are reduced by post-treatment or injection of urea (e.g. adblue). Reduction of PM10 and hydrocarbon emissions was measured in a test with biodiesel in Amsterdam tourist boats.

A study of dimethyl ether (DME) as an alternative fuel for diesel engine applications showed a reduction in regulated exhaust emissions with the exception of total hydrocarbons (THC), which were primarily in the form of unburned DME. Tests on the application of synthetic diesel (BTL, GTL) generally show reductions of both NOx and particulate matter. Use of CNG in heavy duty vehicles leads to 65% to 85% lower emission of NOx compared to the fossil reference. Note that these vehicles use a modified diesel engine with spark ignition, so that it effectively operates as a gasoline engine. Wärtsilä dual-fuel engines in gas (from LNG) mode produce roughly 80% less NOx compared to IMO Tier I level and practically zero SOx and particulates.

3.3 LNG (Thomson *et al.*, 2015)

An in-depth analysis of LNG as a marine fuel was provided by Thomson, Corbett and Winebrake (2015). Three vessels types were studied: large ocean-going vessel (OGV), coastal OGV and a tug/towing vessel. For all cases, new natural gas engines were compared with new diesel engines; 45% efficiency for new and emerging LNG marine engines as well as current diesel engines were used. Emissions of NOx, SOx and PM10 for each of the 3 vessels were studied along with quantifying and comparing the GHG emissions (CO_2, CH_4, N_20) for each case. The results were represented as Technology Warming Potential (TWP) and takes into account both CO_2 and methane emissions. TWP is a ratio of the new technology (LNG vessels) to the existing (both high and low sulphur vessels), with TWP=1 indicating that the new technology is climate neutral with the old technology under the assumed operating conditions.

Figure 11 shows the immediate GHG benefit for the best case of switching to natural gas from high-sulphur marine fuel to LNG, shown by the corresponding lines reaching TWP 1 within a short time frame. Most transitions from low-sulphur marine fuel (LS) to LNG show a climate benefit within 30 years from conversion, though reaching climate parity will take longer (130−-190 years) for spark ignited natural gas engines. The specific pathway chosen can also have a large effect on the time needed to reach climate parity, with variations of over 50 years. The gap between the low-sulphur and high-sulphur fuels in the service vessel (Norway case) is different than the cargo transport vessel cases because the differences in CO_2 emissions among the service vessel cases is not as large, due to different operating conditions for a service tug/towing vessel and a cargo-carrying OGV.

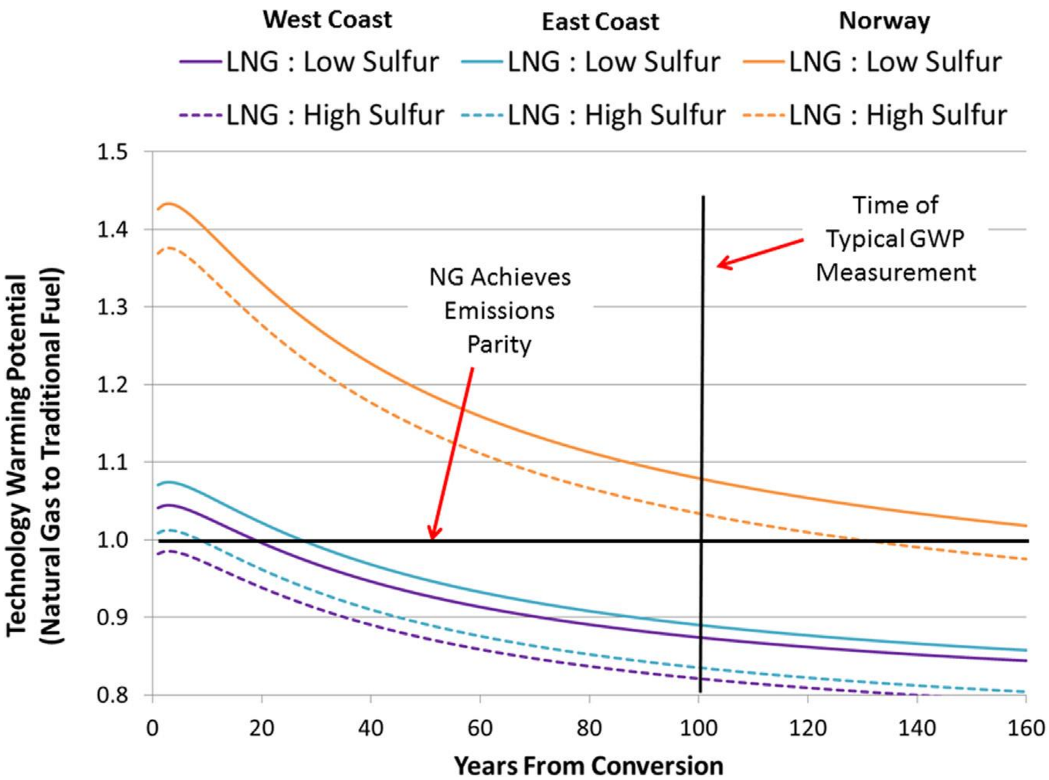

Figure 11. Technology Warming Potential (TWP) of replacing marine fuels with LNG. Source: Thomson *et al*., 2015)

A technology transition to natural gas marine technology is not immediately climate neutral without continued requirements for substantial improvements in both upstream and downstream methane leakage control. However, prioritizing high-sulphur transition to LNG can achieve GHG parity soonest in either global warming potential (GWP) or TWP contexts.

4 General Comments

Strict regulation on emissions and reports on harmful effects associated with the use of traditional marine fuels are driving the marine industry to adopt alternatives fuels. Towards this objective, techniques to reduce emissions using current fuels and introduction of alternative fuels have also been considered, as they form a simple alternative solution. The viability of using alternative fuels in the shipping industry has been proven with ships running on new fuels either as drop-in fuel or as dual fuel. Use of low-sulphur fuels such as ULSD can help in complying with the regulations. This however, does not reduce reliance on fossil fuels, and the availability of ULSD is currently being assessed. Hence, introduction of new fuels would be a better step in future development in this area.

With new bunkering facilities being built and support being provided from the Governments towards this infrastructure, LNG represents the first and most likely alternative fuel, at least for Europe. While LNG is a fossil fuel, it nevertheless affords reduced GHG emissions. However, the cost and long times needed to refit ships with gas engines must also be taken in to account. In the future it could be that ships would be built with dedicated gas engine if the LNG becomes a fully accepted fuel. Methanol is also considered to be a preferred fuel and Stena is leading the industry with its Stena Germanica ferry. The cost associated with retrofitting the engine for methanol has been reported to be less compared to retrofitting to a LNG engine.

From a long term perspective, moving to LNG and methanol as near-future alternative fuels is also a strategically attractive move. This is because each of the two fuels has a biofuel counterpart biomethane (Bio-LNG) and biomethanol. This means that ships and infrastructure built for LNG and methanol can be used to supply biomethane and methanol without much complication. This could equate to using LNG and methanol as transition fuels before making a major shift to biofuels. Technical problems associated with biofuels such as instability of on board stored fuels, corrosion and bio-fouling have been reported to be readily surmountable (Ecofys, 2012). However, their potential use will depend on a number of factors including the global availability of sustainable feedstock for their production and their eventual availability in the market. Market availability will depend on the availability of cost effective production technologies and environmentally sustainable biomass feedstocks.

5 Conclusions and Recommendations

JRC plays an important role in the introduction of renewable fuel sustainability standards for road transport. It is only natural that JRC could extend the same level of commitment towards marine transport as multiple stake holders are already showing initiative in this area.

There are already initiatives towards this from the EU as well:

- The EU has plans to move 30% of road freight travelling over 300 km to other modes such as rail or waterborne transport by 2030, and more than 50% by 2050. Another goal is to reduce the EU CO_2 emissions from maritime transport by 40% (if feasible 50%) by 2050 compared to 2005 levels, as the environmental record of shipping can and must be improved by both technology and better fuels and operations (COM 2011).
- The EU LeaderSHIP initiative aims at ensuring the future of European shipbuilding. Because decarbonising the shipping sector would involve not only introduction of greener marine fuels, but also innovative green and energy-efficient ship designs.

Apart from this, development of infrastructure and greening of the ports are in process.

However, introduction of alternative marine fuels will be accompanied by additional complexity in the areas of fuel supply infrastructure, rules for safe use of fuels on board and operation of new systems (DNV GL, 2015). Additionally, adoption or wide acceptance of these new fuels could possibly be a challenge for ship-owners. To ensure confidence that the technologies will work as intended, Technology Qualification from neutral third parties is needed, and JRC could play a part. This would also include developing safety standardisation techniques etc., equivalent to the tasks JRC performed for road transport.

Among the stakeholders, ship owners and shipping agents will also play a major role in this transition. Although marine fuel standards are set in ISO 8217, all responsibilities for the fuel quality and quantity lie with the ship owners, with little to no liability towards the fuel suppliers or bunker parties (Florentinus *et al*., 2012). Also, unlike the case for road transportation, fuels are not simply procured by the vessel owner according to engine manufacturer's specification (McGill *et al*., 2013). The choice of fuel lies primarily with the charterer (the shipping agent) who, in principle, rents the vessel from a ship owner (McGill *et al*., 2013). Hence, while considering new marine fuels, all these stakeholders must also be included.
It is evident from the life cycle assessments (LCA) that the sustainability of the fuels depends on the various parameters being considered for each study and the different process routes. JRC could also develop an in-depth comprehensive LCA analysis of these future fuels with respect to the marine sector. Additionally, with the resources of the Commission, JRC could also identify regional factors that could affect adoption of new fuels and take into account various challenges concerning them.

As mentioned above, the EU aims to shift some of the road transport load to the more efficient marine and inland waterway systems. Hence, implementation of a specific renewable fuel mandate for the marine sector could create a synergy with the already existing mandate for the road transport. The two can complement each other in areas such as technology development, implementation, government support and deployment.

With the results from the COP21 summit still fresh, this is the right time to invest in the decarbonisation of the marine sector. The new implementation or support could contribute towards the 5 yearly review of each country's contribution to cutting emissions and this will be reviewed again in 2018. Hence, renewable marine fuels can make it to this review. Another point of the summit was to extend support from rich countries to poorer countries to switch to renewable energy. Sharing such techniques and good practices could be more direct and strategic as international trade and transport links all countries.

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7 List of abbreviations and definitions

AMP	Alternative Maritime Power (also called cold ironing when electrical power is provided to ships while at berth to avoid engine emissions)
BTL	Biomass-To-Liquid (technology)
CNG	Compressed Natural Gas
DME	Dimethyl ether (gaseous biofuel mainly produced from pulp and paper residues)
dwt	deadweight tonnage (of a ship)
ECA	Emission Control Area
EPA	Environmental Protection Agency (USA)
EEDI	Energy Efficiency Design Index (for new ships)
EGR	Exhaust gas recirculation
FAME	Fatty acid methyl ester
FT	Fischer-Topsch (process for production of liquid hydrocarbon fuel from gasified feedstock
GTL	Gas-To-Liquid (technology)
HDRD	Hydrogenation Derived Renewable Diesel (similar terms used for specific fuels are HVO, hydrogenated vegetable oil, and HEFA, hydro-processed esters and fatty acids)
HFO	Heavy Fuel Oil
HVO	Hydrotreated Vegetable Oil
IFO	Intermediate Fuel Oil
IGF	Maritime Organization's draft International Code of Safety for Ships using Gases or Other Low-Flashpoint Fuels
IMO	International Marine Organisation
LCA	Life Cycle Assessment
LFL	Low Flashpoint Liquid (fuels)
LNG	Liquefied Natural Gas
LPG	Liquefied Petroleum Gas
LSD	Low-Sulphur Diesel
LSRF	Low-Sulphur Residual Fuel
MARPOL	The International Convention for the Prevention of Pollution from Ships, originally from 1973, later modified by the Protocol of 1978 and usually referred to as MARPOL 73/78
MGO	Marine Gas Oil

Mtoe	Million tonnes of oil equivalent
PM	Particulate Matter
SCR	Selective Catalytic Reduction
TRL	Technology Readiness Level
ULSD	Ultra-Low-Sulphur Diesel

8 List of Figures

9 List of Tables

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