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ALTERNATIVE FUELS FOR SHIPPING



EXECUTIVE SUMMARY

This Position Paper provides an overview of the possible alternative fuels for marine propulsion. Maritime transport accounts for over 80% of world trade by volume and for approximately 3% of global greenhouse gas emissions, while it is also a contributor to air pollution close to coastal areas and ports. In order to reduce the impact maritime transport has on climate change and on the environment, a number of fuel efficiency measures, both on technical and on operational levels, have to be adopted, including the introduction of alternative fuels. The immediate effect of introducing alternative fuels will be a strong reduction in SO_x, NO_x, and PM, while greenhouse gas reductions will also be possible, depending on what types of fuel are used. Fossil-based fuels, such as LNG will have limited contribution to greenhouse gas reductions, while biofuels have the potential to lead to drastic reductions. On a technical level, the introduction of alternative 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. It is expected that a number of different fuels may become important in different markets around the world, depending on local availability of fuels, which will add to the complexity. In this environment, the role of Classification Societies will become increasingly important, in order to ensure the safe handling of fuels in shipping.

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CONTENT

EXECUTIVE SUMMARY	1
INTRODUCTION	2
DRIVERS AND CHALLENGES	4
Environmental Regulations and Environmental Concerns	4
Fuel Availability and Cost	8
Challenges and Barriers	9
OVERVIEW OF POTENTIAL ALTERNATIVES	10
LNG	11
Ship Electrification and Renewables	11
Biofuels	12
Hydrogen	13
Other Liquid or Gaseous Fuel Options	13
Nuclear Propulsion	14
WELL-TO-PROPELLER ASSESSMENT OF FUELS	15
The system boundaries and fuels studied	14
Uncertainties	20
Taking a Broader View	20
VISION FOR THE FUTURE	20
REFERENCES	22

INTRODUCTION

The global merchant fleet currently consumes approximately 330 million tonnes of fuel annually, 80-85% of which is residual fuel with high sulphur content, and the remaining are distillate fuels complying with stricter regulations. Upcoming regulations regarding the sulphur content of marine fuels, both in emission control areas and globally, are likely to create increased demand for low-sulphur fuels for shipping in the next five to ten years. The advent of new regulations in the next decade can lead to significantly increased fuel prices for distillate fuels, while refinery capacity for producing distillates can turn out to be insufficient for meeting the vastly increasing demand. In addition, climate change concerns will put increasingly more pressure on shipping for reducing its greenhouse gas (GHG) emissions. Both the demand for low sulphur fuels, as well as the need for reduced GHG emissions can be addressed by the introduction of alternative, low carbon fuels.

Alternative fuels have been used in the transportation sector in the past. In the 1920s a process to convert coal, biomass or natural gas into liquid fuels was invented by the Germans F. Fischer and H. Tropsch, and became known as the Fischer-Tropsch process. This process was heavily used in the 2nd World War in Germany to produce liquid fuels from coal, and also in South Africa during the

oil embargo in the 1970s and 1980s. Alternative fuels came into the picture again in the 1970s for reasons of security of energy supply. By the end of the 1980s and 1990s growing concern about the environmental impact of automobiles and of anthropogenic emissions in general stimulated the interest in alternative fuels.

There is a long list of fuels or energy carriers that can be used in shipping. The ones 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), Ethanol, Dimethyl Ether (DME), Biogas, Synthetic Fuels, Hydrogen (particularly for use in fuel cells), and Nuclear fuel. All these fuels are virtually sulphur free, and can be used for compliance with sulphur content regulations. They can be used either in combination with conventional, oil-based marine fuels, thus covering only part of a vessel's energy demand, or to completely replace conventional fuels. The type of alternative fuel selected and the proportion of conventional fuel substituted will have a direct impact on the vessel's emissions, including GHG, NO_x, and SO_x.

When considering the overall impact of a given fuel on the environment, it is important to take into account not only the direct emissions from using



the fuel on board a vessel, but also emissions related to the fuel's production and transport pathway. In addition, other effects, such as land and water usage can become important for certain types of fuels, especially for biofuels. Quantitative information for these impact areas can be collected and evaluated by performing a Life Cycle Assessment (LCA) of marine fuels. This allows for comparison between various pathways along the energy value chain, and therefore for the assessment of the potential impact compared to marine diesel fuels.

This Position Paper provides an overview of the possible alternative fuels for marine propulsion. A discussion of drivers and barriers is given, followed by a brief description of various fuels, including technological challenges and potential benefits from their use. The results of a lifecycle assessment (Well-To-Propeller Analysis) are also presented, focusing on GHG emissions. Finally, a discussion on future applications concludes this paper, indicating ways to overcome the challenges and make a transition towards a more sustainable future for shipping.

«This Position Paper provides an overview of the possible alternative fuels for marine propulsion.»

DRIVERS AND CHALLENGES

The merchant world fleet gradually shifted from sail to a full engine powered fleet from around 1870 to 1940. Steamships burning coal dominated up to 1920, and since then coal was gradually replaced by marine oils, due to shift to diesel engines and oil-fired steam boilers. The shift from wind to coal was driven by the developments in steam engines, and offered the opportunity for more reliable transit times, to a large extent independent of the weather conditions and prevailing wind directions. The following shift, from coal to oil, was driven by increased efficiency, ease of handling, and cleaner operations.

The main drivers leading to the advent of alternative fuels in the future can be classified in two broad categories:

- a. Regulatory requirements and environmental concerns
- b. Availability of fossil fuels, cost and energy security

ENVIRONMENTAL REGULATIONS AND ENVIRONMENTAL CONCERNS

The International Maritime Organization (IMO) has adopted a set of regulations for the prevention of air pollution by ships, outlined in Annex VI of the MARPOL Convention. MARPOL Annex VI sets limits on the emissions of sulphur oxides (SOx) and

nitrogen oxides (NOx) (IMO, 2008) from ship exhaust gases and contains provisions for setting up special SOx Emission Control Areas (ECAs), characterized by more stringent controls on emissions as illustrated in Figure 1. The ECAs currently include the North Sea and the Baltic, and a zone extending 200 nautical miles from the coastline of North America, see Figure 2. Other parts of the world can be included in ECAs in the future. The most likely candidates today are the Bosphorus Straits/Sea of Marmara, Hong Kong, and parts of the coastline of Guangdong, in China. In addition to this, the EU will mandate 0.5% in EU waters from 2020, irrespective of potential IMO delay elsewhere, and it has already imposed a 0.1% requirement in ports and inland waterways. Finally, California also has special, stricter requirements in place.

Ships operating in the ECAs have to use low sulphur fuel, or alternatively implement measures to reduce sulphur emissions, such as through the use of scrubbers.

In addition, the Marine Environment Protection Committee has agreed on a three-tier structure, which would set progressively tighter NOx emission standards for new marine engines, depending on the date of their installation. The Tier III standards will be enforced in the North American ECA only in 2016. There is currently uncertainty with a potential Tier III delay until 2021, which will be resolved at MEPC66 in the spring of 2014.

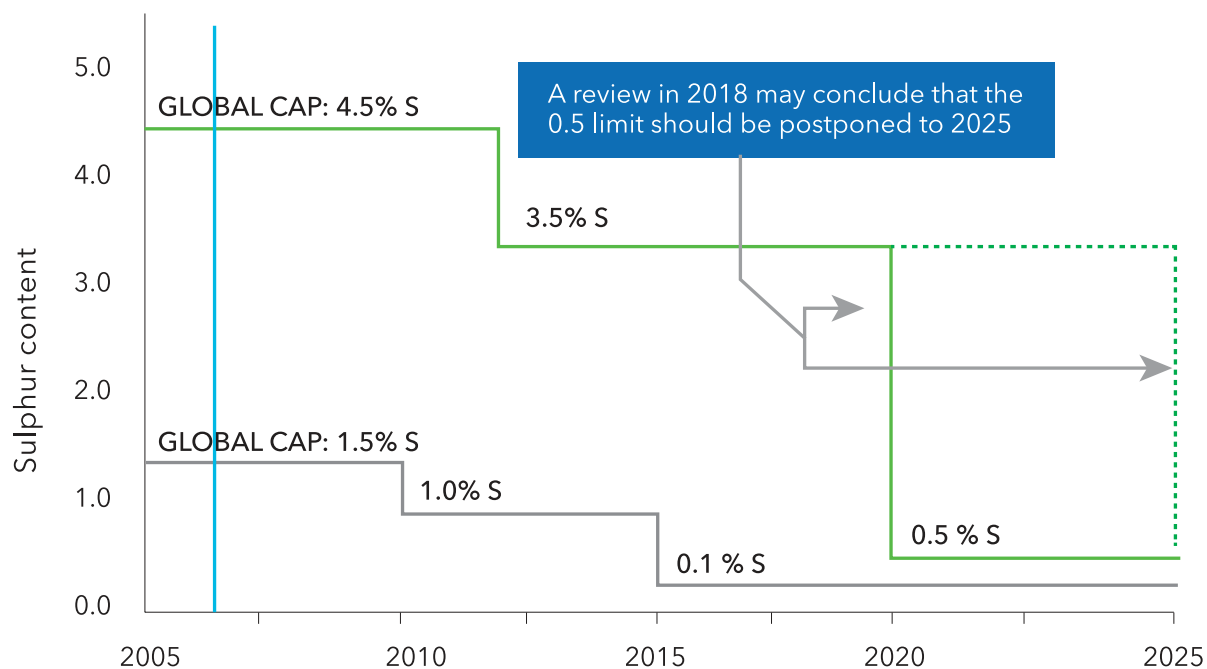


Figure 1. MARPOL Annex VI fuel sulphur content limits

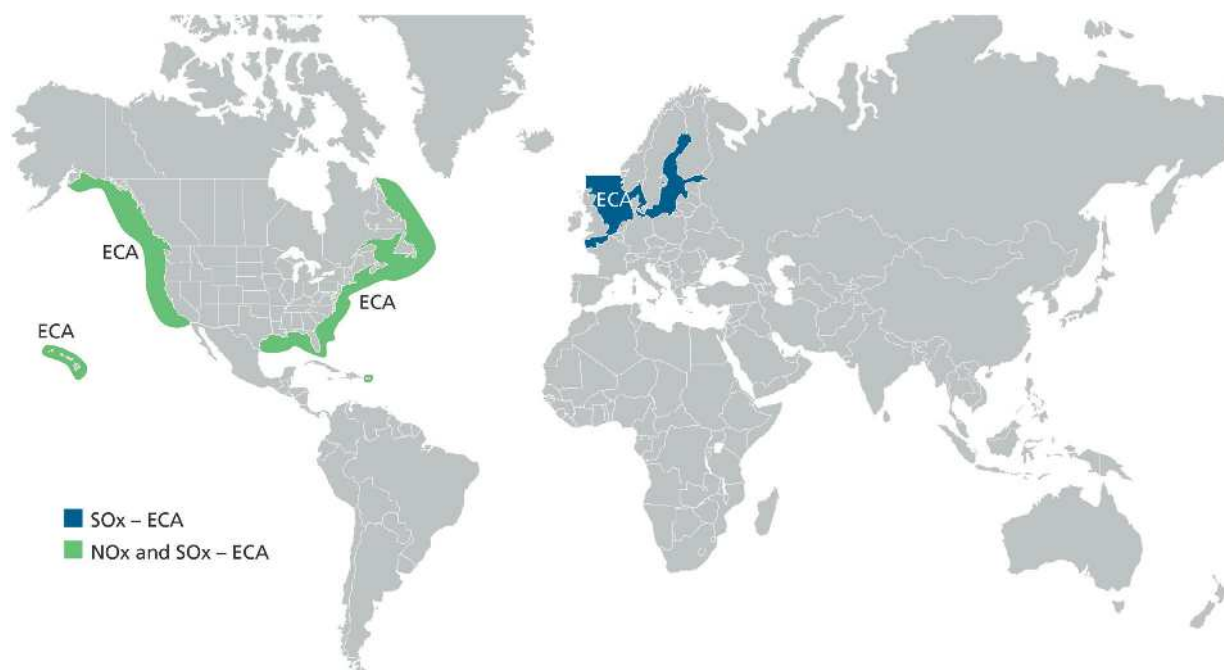


Figure 2. Emissions Control Areas map



Regarding GHG emissions, two mandatory mechanisms have been introduced, intended to ensure an energy efficiency standard for ships:

1. The Energy Efficiency Design Index (EEDI), for new ships
2. The Ship Energy Efficiency Management Plan (SEEMP) for all ships

The EEDI is a performance-based mechanism that requires newbuildings to fulfil a certain minimum design energy efficiency rating pertaining to the size of the vessels. Ship designers and builders are free to choose the technologies to satisfy the EEDI requirements for a specific ship design. The SEEMP establishes a mechanism for operators to improve the operational energy efficiency of ships.

The regulations apply to all ships of and above 400 gross tonnage and entered into force from January 2013. Further regulations, such as emissions monitoring, reporting and verification, are under discussion, but no decisions have been taken yet. Carbon pricing through e.g. emissions trading remains a distant prospect.

Meeting the NO_x and SO_x regulations is technically feasible, but can prove to be very costly. Introducing exhaust gas aftertreatment systems, such as SO_x scrubbers and urea-based catalysts, can add

significantly to the cost of a ship. These systems are both space-demanding and costly, while they can increase the fuel consumption by 2-3%. On the other hand, they allow for the use of less expensive, high sulphur fuels. Thus, 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).

Moreover, the requirement for reduced sulphur content in the fuel will also increase the cost of the fuel. This effect will be more pronounced after 2020 (or 2025, depending on when the new regulations will be enforced), when the sulphur content globally will be at 0.5% (or 5,000 ppm), which is lower than current levels for the ECAs. Introducing new, sulphur-free fuels can be a viable solution for this problem, provided that these fuels and the necessary technology are offered at competitive price levels.

The fuel consumption in the ECAs is estimated at approximately 30-50 million tonnes of fuel per year and it is going to increase if more areas are included in the ECAs in the future (Acciaro, 2012), (Sterling, 2012), (Wilson, 2012). These figures are important for evaluating the potential of each one of the alternative fuels presented in this report for replacing oil-based fuels.

FUEL AVAILABILITY AND COST

Estimates of future oil production vary and are controversial. Advanced methods of oil extraction



start becoming economically feasible, due to high oil prices in the last few years. The use of unconventional resources, such as shale oil and tar sands is gaining ground, while in the future there may be enhanced pressure to expand oil and gas activities in the Arctic. In the USA, the shale oil production of recent years has reshaped the North American energy market. Despite the potential of the Arctic for future oil and gas production, it is not clear how much the global production could increase in the future. This is mainly due to high costs and difficult conditions even with reduced sea-ice. The potential consequences of an accident in the Arctic could also be very severe.

Precise information regarding the location and quantity of global oil reserves is difficult to obtain, because many oil producing nations often make public claims that cannot be easily verified. In addition, the world largely depends on oil supplies from potentially politically unstable regions, which can have an adverse effect on fuel security. For some countries, this is a major driver for developing technology for exploitation of local unconventional resources, such as shale oil and gas in USA, and for investing in the development of biofuels, such as ethanol in Brazil and in USA, and biodiesel in Europe.

CHALLENGES AND BARRIERS

So far, the shipping industry has not acted decisively to realise its potential to reduce emissions via low carbon energy. For some owners, finding

capital to fund proven fuel savings technologies can be a challenge – even for technologies that pay for themselves in a matter of years. When introducing a new fuel, existing ships may have to be retrofitted because of incompatible machinery. This makes changes a long term investment. For pioneers – owners who take the risk to invest in new technologies solutions – unforeseen technical issues often result in significant delays, requiring additional capital.

At the same time, bunker costs for certain shipping segments are paid for by the charterer, removing incentives for owners to explore alternative fuels or even fuel efficiency measures. Patchwork regulations, enforced by different government bodies, and lack of standards, have also slowed coordinated actions.

Lack of appropriate infrastructure, such as bunkering facilities and supply chain, and uncertainty regarding long-term availability of fuel are additional barriers for the introduction of any new fuel. That is, owners will not start using new fuels if infrastructure is not available, and energy providers will not finance expensive infrastructure without first securing customers. Breaking this deadlock will require a coordinated, industry-wide effort and the political will to invest in the development of new infrastructure.

OVERVIEW OF POTENTIAL ALTERNATIVES

DNV GL is studying a number of alternative fuels or energy carriers that are already used or could be potentially used in shipping in the future. These fuels are:

- Liquefied Natural Gas (LNG)
- Liquefied Petroleum Gas (LPG)
- Methanol and Ethanol
- Di-Methyl Ether (DME)
- Synthetic Fuels (Fischer-Tropsch)
- Biodiesel
- Biogas
- Use of electricity for charging batteries and cold ironing
- Hydrogen
- Nuclear Fuel

For each one of these fuels the following information is being collected in order to enhance our

understanding of these fuels and their potential impact in the future:

- Physical and chemical characteristics
- Production, availability and cost: information on production methods, current production volumes and prices, infrastructure, and future forecast, where available
- Applications and current status: applications in the maritime and in other sectors. Overview of technology including engines and storage tanks
- Safety considerations
- Emissions and environmental considerations

While renewable energy (solar, wind) –may have some potential to mitigate carbon emissions, this is not seen as a viable alternative for commercial shipping. Certainly, vessels equipped with sails, wind kites or solar panels may be able to supplement existing power generating systems, but the relative unreliability of these energy sources make them ill-suited for deep sea transport or operations in some latitudes with seasonal weather conditions. Likewise, nuclear power also remains problematic.

While a proven solution that produces no GHGs, the perceived risks are considered too high for nuclear power to be considered as a viable alternative for ships.

Over the next four decades, it is likely that the energy mix will be characterised by a high degree of diversification. LNG has the potential to become the fuel of choice for all shipping segments, provided the infrastructure is in place, while liquid biofuels could gradually also replace oil-based fuels. Electricity from the grid will most likely be used more and more to charge batteries for ship operations in ports, but also for propulsion. Renewable electricity could also be used to produce hydrogen, which in turn can be used to power fuel cells, providing auxiliary or propulsion power. If drastic reduction of GHG emissions is required and appropriate alternative fuels are not readily available, carbon capture systems could provide a radical solution for substantial reduction of CO₂.

In this section, the fuels that will most likely be part of the future energy mix for shipping are briefly presented.

LNG

Using LNG as fuel offers clear environmental benefits: elimination of SO_x emissions, significant reduction of NO_x and particulate matter, and a reduction of GHG emissions. It is an attractive option as to meeting current emission requirements, but it does not contribute to reducing CO₂ emissions to the levels that would be required for addressing climate change. There are currently around 40 LNG fuelled ships (excluding LNG carriers) in operation worldwide, while another 40 new buildings are now confirmed. 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 developing. The number of ships is increasing fast and infrastructure projects are planned or proposed along the main shipping lanes of the world. One barrier for the introduction of LNG is the increased demand for fuel tanks, leading to a decrease in payload capacity. The relatively high capital cost of the system installation is another issue.

Technology and Future Developments

LNG as fuel is now a proven and available solution, with gas engines being produced covering a broad range of power outputs. Engine concepts include gas-only engines, dual fuel 4-stroke and 2-stroke. Methane slip (contributing to GHG) during

combustion is practically eliminated in modern 2-stroke engines, and further reductions should be expected from 4-stroke engines. On the production side, the recent boom in non-traditional gas (shale) has had a dramatic effect on the market for gas, particularly in North America. Exploitation of shale gas in other parts of the world could also prove to be significant for LNG. However, the extraction process (hydraulic fracturing or "fracking") remains a controversial technology, due to growing public concerns on its impact on public health and the environment, regarding both air and water quality.

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 HFO prices. They will then be followed by larger ocean-going vessels when bunkering infrastructure becomes available around the world.

SHIP ELECTRIFICATION AND RENEWABLES

Recent developments in ship electrification hold significant promise for more efficient use of energy. Renewable power production can be exploited to produce electricity, in order to power ships at berth (cold ironing), and to charge batteries for fully electric and hybrid ships. Enhancing the role of electricity on ships will contribute towards improved energy management and fuel efficiency on larger vessels. For example, shifting from AC to on board DC grids would allow engines to operate at variable speeds, helping to reduce energy losses. Additional benefits include power redundancy and noise and vibration reduction.

If renewable energy from the sun or wind is not readily available for electricity production on shore, conventional power plants can be used. In this case GHG and other pollutants will still be emitted, but they can be reduced through exhaust gas cleaning systems or carbon capture and storage. Alternatively, nuclear power on shore could be used for emissions-free electricity production, to be used for charging of batteries on board.

Technology and Future Developments

Energy storage devices are critical for the use of electricity for ship propulsion, while they are also important for optimization of the use of energy on board in hybrid ships. There are several energy storage technologies currently available. Battery powered propulsion systems are already being engineered for smaller ships, while for larger vessels,

engine manufacturers are focussed on hybrid battery solutions. Challenges related to safety, availability of materials used, and lifetime must be addressed to ensure that battery-driven vessels are competitive to conventional ones, but the pace of technology is advancing rapidly. Other energy storage technologies that can find application in shipping in the future include flywheels, supercapacitors, and thermal energy storage devices.

Electrification has generated strong interest, particularly for ship types with frequent load variations (Vartdal, 2013). Significant growth in hybrid ships, such as harbour tugs, offshore service vessels, and ferries should be expected after 2020, and further applications for technology may be applied to power cranes for bulk carriers or even in ports. After 2030, improvements in energy storage technology will enable some degree of hybridization for most ships. For large, deep sea vessels, the hybrid architecture will be utilised for powering auxiliary systems, manoeuvring and port operations, to reduce local emissions when in populated areas.

BIOFUELS

Biofuels can be derived from three primary sources: edible crops, non-edible crops (waste, or crops harvested on marginal land) and algae, which can grow on water and does not compete with food production. In addition to having the potential

to contribute to a substantial reduction in overall GHG emissions, biofuels derived from plants or organisms also biodegrade rapidly, posing far less of a risk to the marine environment in the event of a spill. Biofuels are also flexible: they can be mixed with conventional fossil fuels to power conventional internal combustion engines, while biogas produced from waste can be used to replace LNG.

Technology and Future Developments

Biofuels derived from waste have many benefits, but securing the necessary production volume is a challenge. Consider that the land required for production of 300 M Tonnes of Oil Equivalent (TOE) biodiesel based on today's (first and second generation biofuels) technology is slightly larger than 5 % of the current agricultural land in the world. Algae-based biofuels seem to be the most efficient and the process has the added benefit of consuming significant quantities of CO₂, but more work needs to be done to identify alga strains that would be suitable for efficient large scale production. Concerns related to long-term storage stability of biofuels on board ships, and issues with corrosion also need to be addressed.

Experimentation with biofuels has already started on large vessels, and preliminary results are encouraging. However, advances in the development of biofuels derived from waste or algae will depend on the price of oil and gas. As a



result, biofuels will have only limited penetration in the marine fuels market in the next decade. However by 2030, biofuels are set to play a larger role, provided that significant quantities can be produced sustainably, and at an attractive price.

HYDROGEN

Renewable electricity can be employed to produce hydrogen, which can be utilized to power fuel cells on board ships. This solution will also help to deal with the challenges associated with the intermittent nature of many renewable energy sources. Hydrogen is the smallest and lightest of all gas molecules, thus offering the best energy-to-weight storage ratio of all fuels. However, hydrogen as fuel can be difficult and costly to produce, transport, and store. Compressed hydrogen has a very low energy density by volume requiring six to seven times more space than HFO. Liquid hydrogen on the other hand, requires cryogenic storage at very low temperatures (-253°C or 20K), associated with large energy losses, and very well insulated fuel tanks.

Technology and Future Developments

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. 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. Challenges include high investment costs, the dimensions and weight of fuel cell installations, and their expected lifetime. Special consideration has to be given to storage of hydrogen on board ships, to ensure safe operations.

Significant improvements in technology, accompanied by cost reductions are required if fuel cells are to become competitive for ships. With the recent commercialisation of certain land-based fuel cell applications, there is reason to believe that costs will fall. For ship applications, reductions in size and weight are also of immense importance, while response at transient loads also remains a big issue. Fuel cells can become a part of the future power production on ships, and in the near future it might be possible to see successful niche applications for some specialised ships, particularly in combination with hybrid battery systems.

OTHER LIQUID OR GASEOUS FUEL OPTIONS

A number of liquid fuels can be used in dual fuel engines, as substitute for oil. 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. Some of the fuels that can be used are Liquefied Petroleum Gas (LPG – a



mixture of propane and butane), Methanol, Ethanol, and Di-Methyl Ether (DME). Most of these fuels offer significant reductions of NO_x and Particulate Matter emissions, while they are sulphur free and can be used for compliance with ECAs regulations.

Technology and Future Developments

Marine engine manufacturers offer dual fuel engines that can be operated with the fuel options mentioned above. Depending on the type of fuel, special designs for fuel tanks and piping are required.

In July 2013 DNV released rules for using low flashpoint liquid (LFL) fuels, such as methanol, as bunker fuel (DNV, 2013). Interest in methanol as ship fuel is growing in Sweden in response to the need to reduce NO_x and SO_x emissions. 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. As a result of these properties, additional safety barriers are required by DNV GL.

The new mandatory notation LFL FUELLED covers aspects such as materials, arrangement, fire safety, electrical systems, control and monitoring, machinery components and some ship segment specific considerations.

Due to the limited availability of all these fuels, it is not expected that they will penetrate deep sea shipping sectors in the near to medium term future. However, they can become important parts of the fuel mix in local markets.

NUCLEAR PROPULSION

Nuclear power is a rather controversial technology that can also be used in shipping, depending on technology developments and social acceptance. Nuclear material is defined by the International Atomic Energy Agency (IAEA) as uranium, plutonium and thorium. To avoid the possibility of making weapons out of the nuclear material, nuclear powered ships would need to run on low-enriched nuclear material. Even though not considered a truly sustainable energy alternative, due to the use of limited resources, it has an obvious advantage of not emitting any GHG's, with the exception of emissions related to handling of the nuclear materials.

Nuclear power can be used for propulsion on very large ships, or on vessels that need to be self-supporting for longer periods at a time. The Russian ice-breaker fleet, operating in the northern sea route,

is one example where nuclear power is fully adapted. In addition several nuclear powered navy vessels are in operation today. Still, very few nuclear powered merchant ships have ever been built, and all without commercial success.

Electricity produced from nuclear power plants onshore can also be used for cold ironing, for charging batteries of pure electric ships, or for providing the necessary energy for producing other fuels, such as biofuels or hydrogen.

Technology and Future Developments

There are several concepts for compact nuclear reactors being studied, ranging from 30MWe to 200MWe in power output, all with more than 10 years of service life. An important barrier that needs to be overcome is related to safe storage and recycling of spent fuel.

The use of Thorium as nuclear fuel (instead of Uranium or Plutonium, utilized today), can also offer significant advantages: higher fuel availability, higher efficiency, and reduced nuclear waste production. Thorium oxide can be mixed with 10% plutonium oxide, which also offers a way to recycle plutonium. The mix of thorium and plutonium oxide increases the melting point and thermal conductivity, resulting in safer reactors. An experimental Thorium reactor is currently being tested in Norway, in order to evaluate the feasibility of this technology.

Nuclear power is one of the most controversial technologies for power generation and propulsion. While the safety standards are very high and the number of accidents very low, the consequences of an accident can be devastating. Recent history (the Three Mile Island, 1979, Chernobyl, 1986, and Fukushima, 2011, accidents) illustrates the impact of an accident in shaping public opinion and driving policy decisions. The most recent example of this is the abrupt change of direction in Germany with a drastic scaling down of nuclear power immediately after the accident in Fukushima in 2011.

Given the public opposition to nuclear power in most countries, and fears related to potential consequences from accidents, it seems very unlikely that nuclear propulsion will be adopted in shipping within the next 10-20 years. Nuclear power generation on land will stay at today's levels, mostly due to developments in China. This picture could change after 2030, provided that societal acceptance increases, and other efforts to reduce GHG's do not prove as effective as desired.



WELL-TO-PROPELLER ASSESSMENTS OF FUELS

Alternative fuels can contribute significantly to reducing the carbon footprint of shipping (Eide, et al., 2012). To be able to comment on the sustainability of fuels, quantitative data are required to put things in perspective. This can be done by performing Life Cycle Assessments (LCA) of marine fuels, which allow for the comparison between different fuel pathways along the energy value chain. The results of an LCA can be used to assess the environmental footprint of each fuel. These types of assessments are complex and the chosen scenarios highly influence the outcomes.

Whereas LCAs of alternative fuels for the automotive sector, or so called Well-To-Wheel studies have been performed for a long time now (Johannsson et al., 1998), LCAs of alternative fuels for the maritime transport sector, or so called Well-To-Propeller (WTP) studies are relatively new (Bengtsson et al., 2011). This is partly due to the recent focus on GHG emissions from maritime transport activities and the more restrictive upcoming regulations on both air quality and GHGs.

Among the recent WTP studies available are those performed at Chalmers University of Technology (Bengtsson et al., 2011), for HFO, MGO, GTL FT diesel, LNG and LBG, at TNO (Verbeek et al., 2011) for LNG, HFO, MGO/MDO and EN590, as well as the WTP Total Energy and Emissions Analysis for Marine Systems Model (TEAM) model from the Rochester Institute of technology (Winebrake et al., 2006) for Residual Oil, conventional diesel, low sulphur diesel, CNG, GTL FT diesel and biodiesel from soybeans. The results of these studies show that there are possibilities to reduce GHG emissions from a lifecycle perspective, depending on the fuel choice. Some fuels, such as CNG or FT-diesel, could, depending on their production methods, actually be worse than conventional diesel when it comes to GHG emissions.

The current Well-To-Propeller study of alternative fuels for the maritime transport assesses the potential climate impacts of alternative fuel systems at all stages in their life cycle – from oil & gas wells (or from farming) to the propeller (Chryssakis, 2013).

The system boundaries and fuels studied

The system boundaries include the fuel production cycle and the fuel use on-board the ship. The fuels considered in this report, as well as the scenarios for each fuel are summarized in Table 1. The following assumptions are made:

- The boundaries between the technological system and the natural world system begin at the extraction point of the hydrocarbons and raw materials. The final stage is combustion of the fuel.
- The geographical boundaries of the system vary depending on the fuel value chain. They typically include scenarios with fuel extracted and produced in remote locations and transported thousands of kilometres to the relevant market.
- Chronological boundaries are immediate to short-term ones, with technologies and scenarios feasible today or in the next 5 years. The Well-To-Propeller analysis is carried out to evaluate present impacts of existing alternative fuels. Speculative technologies and far-fetched scenarios have been avoided as much as possible.

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	<ul style="list-style-type: none"> ■ 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	<ul style="list-style-type: none"> ■ 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	<ul style="list-style-type: none"> ■ 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	<ul style="list-style-type: none"> ■ 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.

During the life cycle inventory the only product considered is GHG emissions (amount of CO₂ equivalent), normalized with the energy content of the fuel (Mega Joule of fuel - 1 MJf). The contribution of various GHG's, for different time horizons, can be taken into account by converting into emissions of CO₂ equivalent, here in grams (gCO₂eq), as presented in Table 2 (Foster et al., 2007). In this study the Life Cycle Assessment is limited to Global Warming Potential, with a 100 years horizon (GWP100).

Emissions	Global warming potential for given time horizon		
	20 years	100 years	500 years
CO ₂	1	1	1
CH ₄	72	25	7.6
N ₂ O	289	298	153

Table 2. Global Warming Potential of greenhouse gases considered in this report, relative to CO₂

The GHG emissions associated with the combustion of renewable fuels are not accounted in the total GHG balance. This is standard practice in similar published lifecycle assessments (Bengtsson et al., 2011, Winebrake et al., 2006). The Well-To-Tank and Tank-To-Propeller results for the GHG emissions in gCO₂eq/MJf related to the different pathways for the maritime transport alternative fuels considered here are displayed in Figure 3.

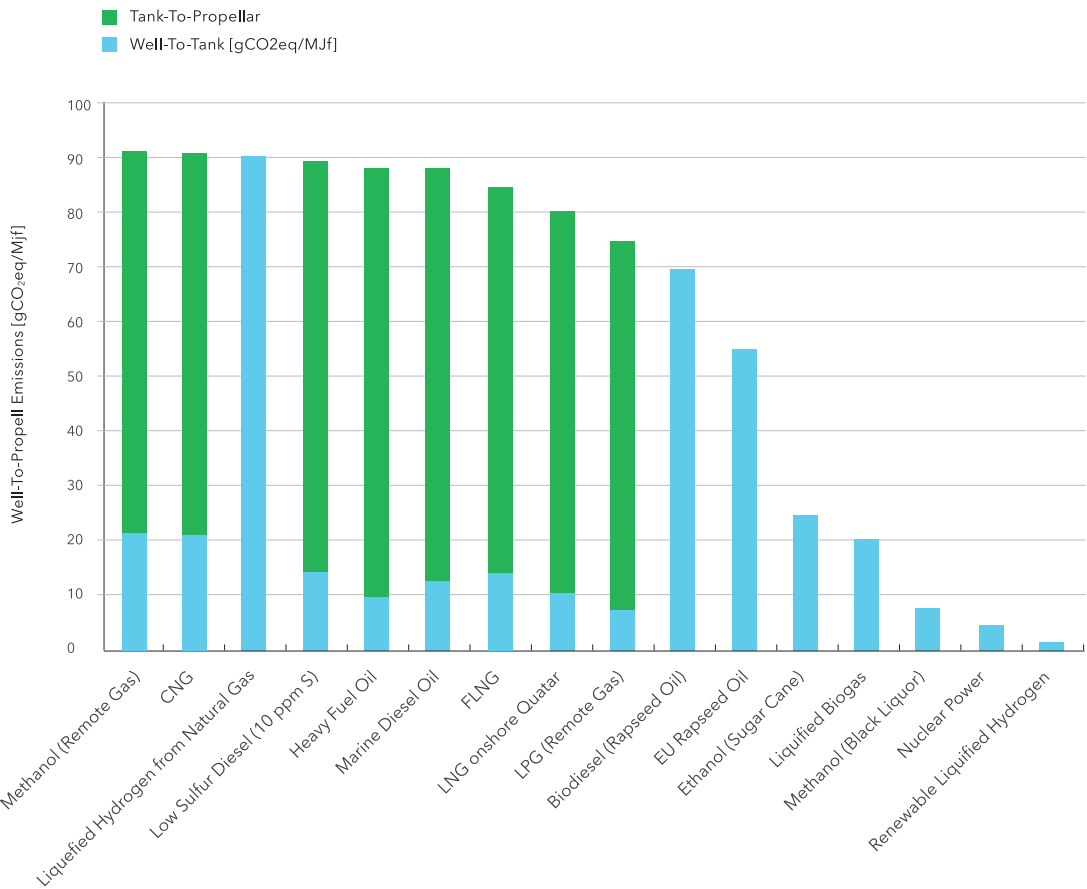


Figure 3. WTP GHG emissions results for marine alternative fuels.

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 its GHG benefits. It is expected that when LNG is used in modern 2-stroke engines the methane slip is eliminated, leading to stronger GHG reductions.

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. LNG seems to be the most attractive price-wise, but costs of retrofitting or buying new LNG tanks and engines are not negligible and should be taken into account. An expensive fuel may be more suitable for use in other sectors, such as in automotive, where the market conditions could make it more attractive.



«... it is very unlikely that any new fuels will be introduced in ocean going vessels, if a global supply infrastructure is not in place»

UNCERTAINTIES

There are many sources of uncertainty for each one of the fuels considered. These are related to differences in boundary limits (fuel production and fuel combustion/use on-board a ship) and to differences in the value chain (different production methods, transportation, and distribution). Some specific examples of uncertainties for WTT are provided here:

- For the rapeseed oil based fuels, the GHG emissions are dominated by the seed production step, mostly through N₂O emissions. This is largely due to the fact that rapeseed crops require a lot of nitrogen-based fertiliser, the related emissions of which are very uncertain. This can lead to variations of -7% to +43% in the WTT GHG emissions (Edwards, 2011).
- For wood-based feedstock, the fertiliser and energy needs are lower so the uncertainty is decreased to -5% variation in WTT emissions for DME from black liquor (Edwards, 2011).
- For oil and gas related processes, when electricity is produced onsite, as in the case of liquefaction, the process data are better documented and not subject to a large uncertainty.
- In the case of future or cutting edge process like GTL technology, the WTT uncertainty for total GHG emissions is in the range of -10% to + 15% (Edwards, 2011).

The uncertainty related to the combustion (Tank To Propeller) of the alternative fuels is low; however, different types of engines (2-stroke vs. 4-stroke) can lead to different final results. Further work utilizing different powertrains and operating profiles, including hybrid systems, could result into greater variations in results.

TAKING A BROADER VIEW

A more complete comparison can be performed by including in the lifecycle assessment the equipment required for producing and using the fuels under consideration. An example could be the environmental footprint of producing and disposing a fuel cell, as compared to an internal combustion engine. A few LCAs for marine fuel cell applications have been carried out, for example by (Reenaas 2005), and (Alkaner & Zhou, 2006). Even though the fuel cell technology is relatively new and production volumes are low, compared to internal combustion engines, the LCAs show that fuel cells can be competitive from a GHG emissions point of view (Ludvigsen & Ovrum, 2012).

Moreover, more pollutant emissions (NO_x, SO_x, PM) and other side-effects of the use of alternative fuels (such as land use and land use change, use of fertilizers, etc.), should be considered. A methodology for performing a LCA, including a number of indicators has been developed by (Vanem et al., 2012), and by (Roskilly et al., 2010). This methodology introduces the concept of an integrated LCA in order to facilitate the integration of risk-based design and ecodesign of ships. In order to make this efficient, it is proposed to monetize values for all relevant indicators from such assessments. The dimensioning indicators pertaining to ship design have been identified and actual values have been proposed in order to monetize the various indicators, i.e. to efficiently convert all indicators to the common denominator. One example of this methodology is shown in Figure 4.

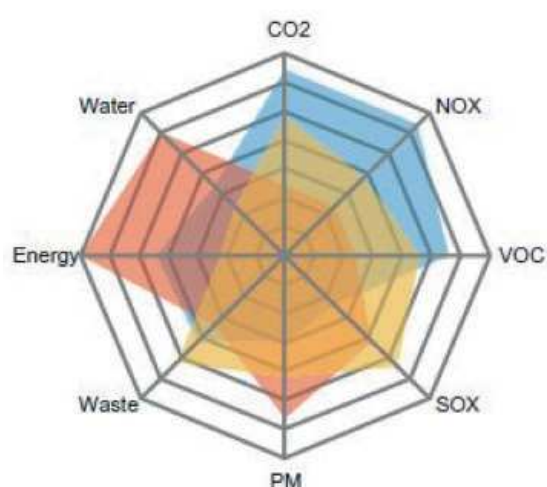


Figure 4. Spider diagrams are one way of presenting the results of an LCA, here an example from (Vanem et al., 2012)

An important concern when considering alternative fuels is related to fuel availability and security of supply. According to (US EIA International Energy Outlook, 2011), 2,500 million tonnes of oil are currently used in the transportation sector, and the rest is used for power generation and the petrochemicals industry. It is obvious from Table 3 that most alternative fuels are not produced in sufficient volumes for large scale application in shipping. This means that a number of different alternative fuels could initially be used for short sea shipping in local markets, where long term supply can be guaranteed. This also offers a relatively inexpensive way for testing these fuels in small vessels. A recent representative example is the plan of Stena Line for using methanol as a fuel for ferries operating close to Sweden. However, it is very unlikely that any new fuels will be introduced in ocean going vessels, if a global supply infrastructure is not in place.

Fuel	2010 total consumption (million TOE/year)	Consumption for maritime transportation (million TOE/year)
Oil	4,028	»330 HFO/MDO: »280/50
Natural Gas	2,858 of which LNG: 250-280	Very low (Approximately 40 vessels in 2013)
LPG	275	0
Methanol	23	0
Ethanol	58	0
DME	»3-5	0
Fischer-Tropsch	»15	0
Biodiesel	18-20	0
Liquefied Biogas	Very low	0
Nuclear (Uranium)	626	Very low
Hydrogen	Very low	0
Rapeseed Oil	5	0

Table 3. Global consumption volumes of various fuels in 2010. All figures in Tonnes of Oil Equivalent (TOE). Source: (BP, 2011)

VISION FOR THE FUTURE

The introduction of any alternative energy source will take place at a very slow pace initially as technologies mature and necessary infrastructure becomes available. In addition, introduction of any new fuel will most likely take place first in regions where the fuel supply will be secure in the long-term. Due to uncertainty related to the development of appropriate infrastructure, the new energy carriers will first be utilised in smaller short sea vessels. As technologies mature and the infrastructure starts to develop, each new fuel can be used in larger vessels, and eventually on ocean going ships, provided that global infrastructure becomes available.

At present, LNG represents the first and most likely alternative fuel to be seen as a genuine replacement for HFO for ships built after 2020. The adoption of LNG will be driven by fuel price developments, technology, regulation, increased availability of gas and the development of the appropriate infrastructure. The introduction of batteries in ships for assisting propulsion and auxiliary power demands is also a promising low carbon energy source. Ship types involved in frequent transient operations (such as dynamic positioning, frequent manoeuvring, etc.) can benefit most from the introduction of batteries

through a hybrid configuration. Moreover, energy storage devices can be used in combination with waste heat recovery systems to optimise the use of energy on board. Cold ironing could become a standard procedure in many ports around the world.

The pace of development for other alternative fuels, particularly biofuels produced from locally available waste biomass, will accelerate, and may soon compliment LNG and oil-based fuels. Indeed, it is likely that a number of different biofuels could become available in different parts of the world after 2030. However, acceptance of biofuels in deep-sea transportation can only take place if these fuels can be produced in large volumes and at a competitive price around the world.

Maritime applications for renewable energy (solar, wind) will certainly continue to be developed, but it is unclear if these would have a significant impact on carbon emissions. Nuclear power is not likely to be a preferred alternative fuel beyond a few niche segments, so is not expected to play a large role in reducing carbon emissions. However, in the event that the impact of climate change rises to a level where required reductions in GHG emissions become substantially larger, these technologies could play a role.

There are many possible solutions to improve sustainability for shipping in the future, but there are still significant technology barriers. It is very likely that in the future there will be a more diverse fuel mix where LNG, biofuels, renewable electricity and maybe hydrogen all play important roles. Electrification and energy storage enable a broader range of energy sources to be used. Renewable energy such as wind and solar can be produced and stored for use on ships either in batteries or as hydrogen.

Besides IMO rules and ISO standards, development of appropriate Rules and Recommended Practices is necessary for the safe implementation of any of these technologies in the future. To achieve this, the role of Class Societies will be crucial. Adopting new technologies is likely to be an uncomfortable position for ship-owners. To ensure confidence that technologies will work as intended, Technology Qualification from neutral third parties, such as classification societies, is also likely to be more widely used.







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