DNV·GL

MARITIME

ASSESSMENT OF SELECTED ALTERNATIVE FUELS AND TECHNOLOGIES

June 2019

SAFER, SMARTER, GREENER

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1 SUMMARY

The shipping industry is under increasing pressure to act upon the Paris Agreement and reduce greenhouse gas (GHG) emissions. The substantial emission reductions which must be achieved over the next decades are expected to drive technology development and, in particular, the introduction of low-carbon fuels. Furthermore, authorities are increasingly paying attention to the consequences of hazardous NO_X, SO_X and particle emissions at the local level.

Around the world, air pollution is causing serious health problems and premature death, and local air pollution will be subject to tougher regulations over the coming years.

Reducing emissions to air and introducing new propulsion technologies are key challenges for the worldwide transport sector, including shipping. The world's future fleet will have to rely on a broader range of fuels, propulsion solutions and energy efficiency measures.

All alternative fuel options have benefits and challenges. This guidance paper provides an introduction to alternative fuels and technology solutions. It includes an overview of selected alternative ship fuels – LNG, LPG, methanol, biofuel and hydrogen – as well as emerging technologies such as batteries, fuel cell systems and wind-assisted propulsion. Ammonia – especially when produced using hydrogen from renewable sources – has entered the debate as an additional potential future fuel and will be discussed in greater detail in future DNV GL publications, including potential follow-up editions of this document.

The objective of this guidance paper is to provide decision support for investments in ships over the coming 5 to 10-year period. The paper focuses on technical parameters and limitations without accounting for local market conditions, considerations and incentive schemes which may have a significant impact on competitiveness and the uptake of alternative fuels and technologies.

2 BACKGROUND

Marine fuel currently contributes approximately 3 per cent to global man-made CO_2 emissions. Most seagoing ships are still using heavy fuel oil (HFO) or marine gas oil (MGO), with a maximum sulphur limit of 3.5 per cent (mass) in force for HFO and 0.1 per cent (mass) for low-sulphur MGO.

Looking at the future with the IMO 2020 low-sulphur standards and upcoming CO_2 emission regulation regime in mind, the share of conventional oil-based ship fuels will drop and the share of alternative fuels will grow.

Prerequisites for introducing a new fuel include availability of sufficient production and distribution facilities as well as an adequate bunkering infrastructure. In addition, new fuels in many cases require extensive on-board modifications and a reversal to a conventional system is complex and costly.

Based on current technology, a distinction should be made between short-sea and deep-sea shipping regarding the applicability of, and barriers to, various fuels. Deep-sea vessels have fewer options compared to the short-sea segment.

3 INTRODUCTION TO ALTERNATIVE FUELS

International initiatives towards reducing CO_2 and other emissions are driving the research into alternatives to conventional petroleum-based ship fuels. A wide range of alternative fuels are being discussed, and technologies such as fuel cell systems and Combined Gas Turbine and Steam Turbine Integrated Electric Drive Systems (COGES), which can only be applied efficiently in conjunction with cleaner fuels, have appeared on the agenda.

An impressive number of restrictions aiming to improve the environmental footprint of shipping are in force or under preparation (refer to Figure 1).

In particular, the decision of the International Maritime Organization (IMO) to limit the sulphur content of ship fuel from 1 January 2020 to 0.5 per cent worldwide, and the recently adopted ambition to reduce GHG emission by 50 per cent by 2050 have the potential to become game changers. As illustrated in Figure 2, the combined amount of heavy fuel oil (HFO) and marine gas oil (MGO) consumed by ships accounts for no more than 25 per cent of the global diesel fuel and petrol production (2016 figures).

This is roughly equivalent to the amount of energy consumed using liquefied natural gas (LNG) (24 per cent); however, LNG represents only a small

FIGURE 1: SHIPPING BECOMES GREENER AND MORE COMPLEX

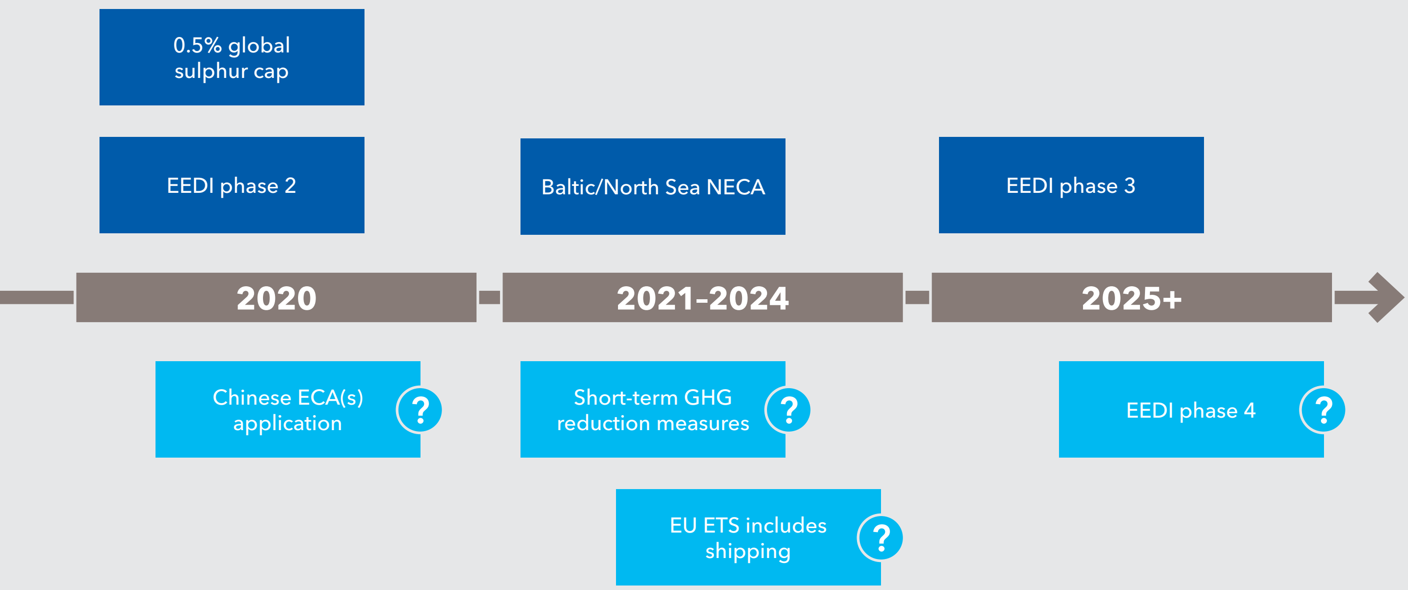
Selected items from the regulatory timeline towards 2030

AND TECHNOLOGIES

portion (approximately 10 per cent) of the overall gas market.

Once the global sulphur cap enters into force on 1 January 2020, up to 48 million tonnes of ship fuel containing 0.1 per cent or less of sulphur will be consumed annually from that time onwards. Most of the fuel consumed (70 to 88 per cent) will have a sulphur content between 0.1 and 0.5 per cent. This means that low-sulphur fuel will take the role of today's high-sulphur fuel. Assuming an installed base of about 3,000 scrubbers at that time, no more than 10 to 15 per cent of ship fuel usage will be high-sulphur fuel. Latest estimates assume that 2,000 to 2,800 scrubber systems will be installed by early 2020 (refer to scrubber overview on afi.dnvgl.com). This development suggests that HFO may only be available at major bunkering locations. It is difficult to predict a price level, but HFO is expected to be available at a significant discount compared to MGO or other compliant fuels.

These practical challenges related to sulphur reduction are knocking at the door. At the same time there is an accelerating worldwide trend towards pushing down CO_2, NO_X and particle emissions. All of these factors are reason enough to intensify the search for fuels and technologies that can help the industry meet the challenges ahead.

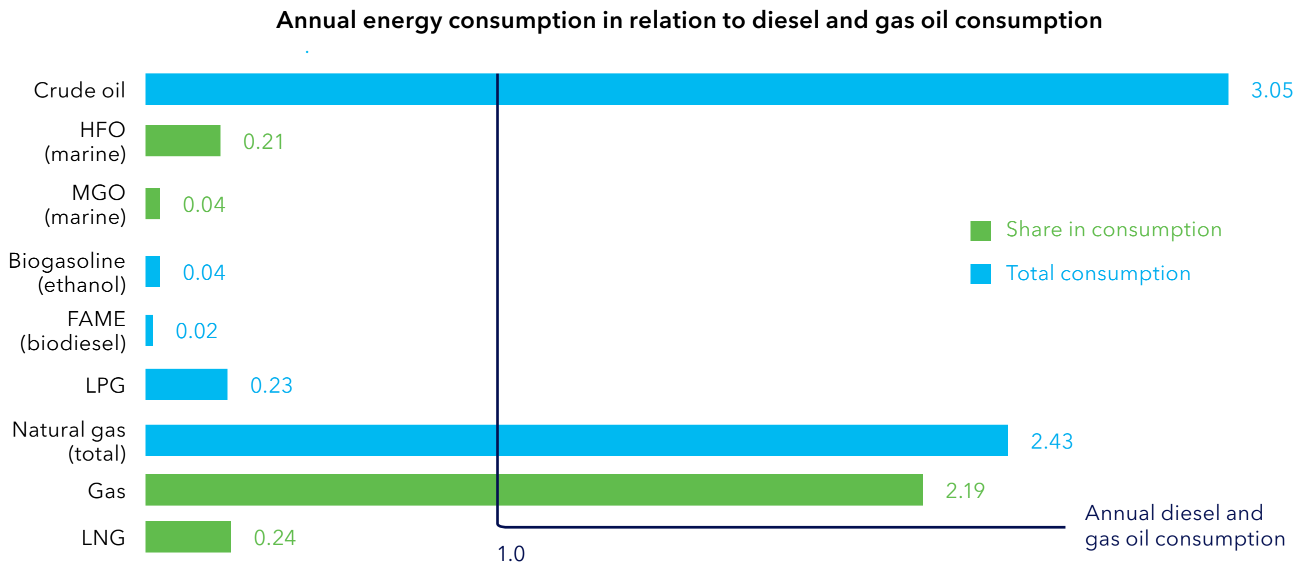


LNG-powered vessels[2] have been in operation since 2000. As of 1 December 2018, 137 LNG-fuelled ships were in operation and 136 newbuilding orders were confirmed. Biofuels (including renewables) and methanol[1],[2] are available at certain ports, and fully electrical/hybrid ships are emerging in the short-sea, offshore and passenger segments. Based on current technology, a distinction between short-sea and deep-sea shipping should be made with regards to applicability of various fuels:

- **Short-sea shipping:** Vessels typically operating in limited geographical areas on relatively short routes with frequent port calls. Due to their relatively low energy demand, these vessels are often ideal candidates for testing new fuels marked by high energy or fuel storage costs. The Norwegian ferry sector is in the process of being electrified, with about 50 battery-electric ferries to be phased in over the next few years. The use of hydrogen is also technically feasible, and the Norwegian national road authorities, supported by DNV GL, are working on the development of hydrogen applications and intend to put a new hydrogen-powered ferry into service by 2021[3].
- **Deep-sea shipping:** This includes large, ocean-going vessels covering long routes, often without a regular schedule. These vessels require fuel that is globally available. The energy source carried on board must have a sufficiently high energy density to maximize the available cargo space. For these vessels, LNG can be a viable option once an adequate bunkering infrastructure is available globally. Sustainable biofuels, methanol and LPG can also be a choice, provided that they can be made available in the required quantities and at an adequate quality level.

Based on current technology, batteries are viewed as impractical as a source of main propulsion energy for these vessels in the foreseeable future. Nuclear propulsion is technically feasible for large vessels, but there are political, societal and regulatory barriers to consider. Various sail arrangements (e.g. sail, kite, fixed-wing, Flettner rotors) have been tried on merchant vessels over the years. A new Delft study concludes that there is significant saving potential in wind-assisted propulsion on large tankers and bulk carriers (Delft, 2017).

FIGURE 2: SHIP FUEL CONSUMPTION IS MUCH LOWER THAN DIESEL AND GAS OIL CONSUMPTION



Source: Figures represent 2016 statistics. Compiled from "bp-statistical-review-of-world-energy-2017-underpinning-data.xlsx" and "BWK, Bd 69 (2017), No 5"

[2] Not including approx. 450 LNG carriers which also run on LNG.

[1] *Stena Germanica,* which bunkers at Gothenburg, is the only present example of a ship bunkering methanol: http://www.bunkerindex.com/news/article.php?article_id=18047

[2] Seven 50,000 tonne deadweight vessels are being built with the first-of-its-kind MAN B&W ME-LGI two-stroke dual-fuel engine that can run on methanol, fuel oil, marine diesel oil, or gas oil: https://www.methanex.com/about-methanol/methanol-marine-fuel#sthash.oW84bYPp.dpuf

[3] Breaking new ground in hydrogen ferry project: https://www.sjofartsdir.no/en/news/news-from-the-nma/breaking-new-ground-in-hydrogen-ferry-project/

3.1 WHICH FUELS ARE ALTERNATIVES?

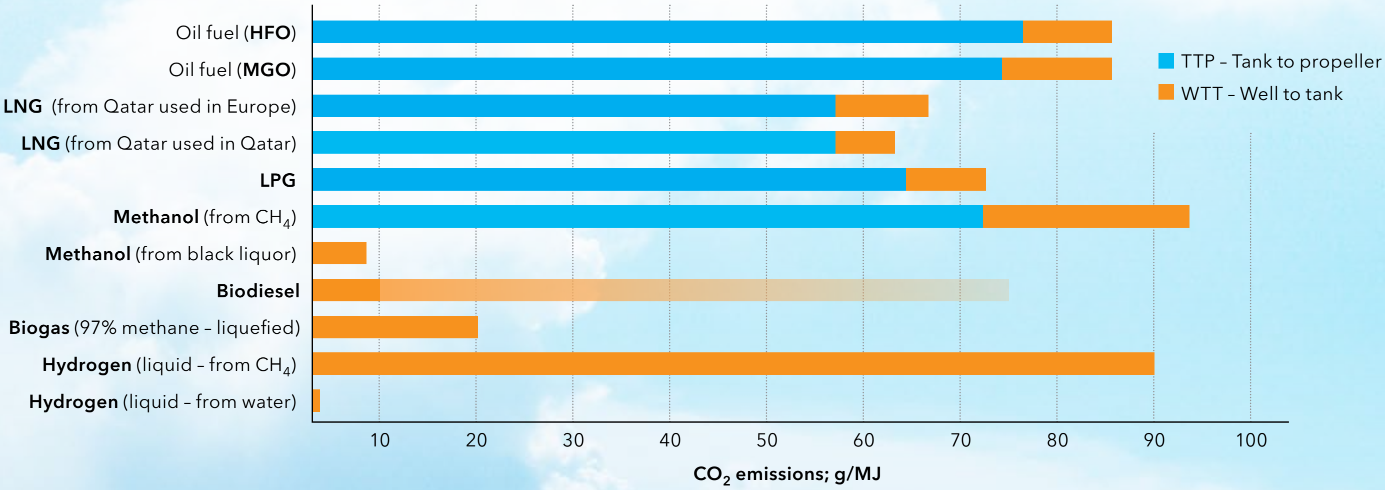
Among the proposed alternative fuels for shipping, DNV GL has identified LNG, LPG, methanol, biofuel and hydrogen as the most promising solutions. Among the new technologies we believe battery systems, fuel cell systems and wind-assisted propulsion to harbour reasonable potential for ship applications. As has been demonstrated by our PERFECt Ship concept study (refer to the PERFECt Ship video available on YouTube), the well-known combined cycle gas and steam turbine technology has potential for ships in the power range above 30 MW, provided that low-sulphur fuels are widely used in the shipping sector and/or high-sulphur fuels are required to undergo extensive treatment.

Fuel cell (FC) systems for ships are under development, but it will take time for them to reach a degree of maturity sufficient for substituting main engines. Battery systems are finding their way into shipping; however, on most seagoing ships their role is limited to efficiency and flexibility enhancement. Batteries cannot store the huge amounts of energy needed to power a large ship. Finally, wind-assisted propulsion, while not a new technology, will require some development work to make a meaningful difference for modern vessels.

The greatest challenges are related to environmental benefits, fuel compatibility, the availability of sufficient fuel for the requirements of shipping, fuel costs and the international rule setting by the IGF Code.

The IMO continues its work on the IGF Code for methanol and low-flashpoint diesel and the rules for FC systems. The other fuels named above are not on the current agenda for the IGF Code. This should be taken into consideration by owners contemplating LPG or hydrogen applications in the near future.

FIGURE 3: CO_2 EMISSIONS OF FUEL ALTERNATIVES IN SHIPPING



Source: DNV GL calculations; Bio diesel: emissions depend on the production method. Graphic uses data from the European Renewable Energy Directive (Council of the European Union, Interinstitutional File: 2016/0382 (COD), Brussels, 21 June 2018)

3.2 CO_2 EMISSIONS

Figure 3 illustrates the CO_2 footprint of various fuels. Greenhouse Gas (GHG) emissions are measured as CO_2-equivalent emissions. Of all relevant fossil fuels, LNG produces the lowest CO_2 emissions, as can be seen in Figure 3. However, the release of unburnt methane (so-called methane slip) could reduce the benefit over HFO and MGO because methane (CH_4) has 25 to 30 times the greenhouse gas effect compared to CO_2. Nevertheless, engine manufacturers claim that the tank-to-propeller (TTP) CO_2-equivalent emissions of Otto-cycle dual-fuel (DF) and pure-gas engines are 10 to 20 per cent below the emissions of oil-fuelled engines. Diesel-cycle gas DF engines have very low methane slip, and their TTP emissions are very close to those in the illustration*. This is also the case for the COGES system as proposed by the PERFECt Ship concept (refer to www.dnvgl.com/maritime/lng/perfect-2.html).

The comparison between the CO_2 emissions from LNG used in Qatar – close to the production site – versus LNG used in Europe reveals that the required transport of LNG does not increase the carbon footprint significantly.

The carbon footprints of methanol and hydrogen produced from natural gas are larger than those of HFO and MGO.

The key benefit of fuels produced using renewable energy is clearly a small carbon footprint. Among these fuels, first-generation biodiesel has a relatively low CO_2 reduction potential. However, liquefied methane produced from biomass (biogas) has extremely high CO_2 reduction potential. It should be noted that the main component of LNG is also methane; therefore both liquefied gases are equivalent.

The cleanest fuel is hydrogen produced using renewable energy. Liquefied hydrogen could be used in future shipping applications. Because of its very low energy density, its storage volume is large. This may prevent hydrogen from being used directly in international deep-sea shipping. In a sustainable energy world where the entire energy demand is covered by renewable, energy sources, hydrogen and CO_2 will be the basic ingredients for fuel production, most likely in the form of methane or diesel-like fuels produced in a Sabatier, Fischer Tropsch process.

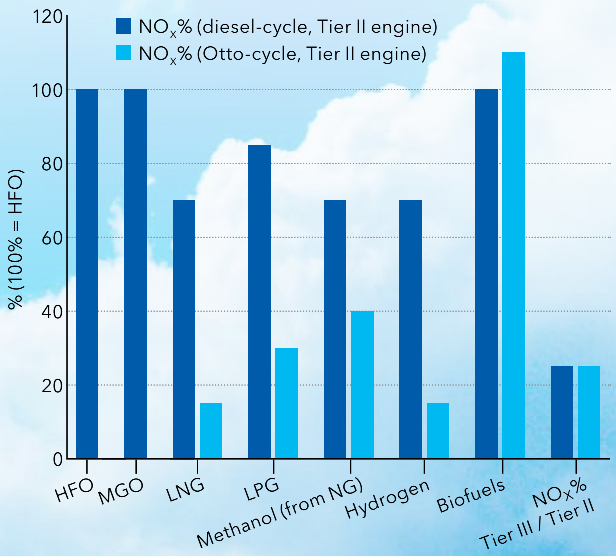
3.3 NO_X EMISSIONS

Figure 4 illustrates the influence of various ship engine technologies and fuels on NO_X emissions. The value for HFO-fuelled Tier II diesel engines is used as a baseline (100 per cent). The values are only comparable when assuming the same rotational speed.

The bars on the right-hand side of the diagram represent the potential emission reduction through switching from Tier II to Tier III (NO_X per cent).

It is obvious that for all fuels given in the below figure, diesel-cycle engines must be equipped with exhaust gas treatment systems to comply with the IMO Tier III limits. Only Otto-cycle engines burning LNG or hydrogen have the potential to remain within the Tier III limits without requiring exhaust gas treatment. This means that in most cases a switch of fuel is not sufficient to comply with the Tier III NO_X limits.

FIGURE 4: NO_X EMISSIONS OF ALTERNATIVE FUELS



Note that ship piston engines are not available in the market for all listed fuels; for instance, there are no ship piston engines available for hydrogen fuel.

Source: DNV GL calculations

* Regarding the working principle of DF and gas engines and the Otto-cycle/diesel-cycle principle, refer to Annex or e.g. Dag Stenersen, Ole Thonstad, "GHG and NOx emissions from gas fuelled engines", SINTEF Ocean AS Maritim, 2017-06-13, report no. OC2017-F-108

3.4 OVERALL EMISSION BEHAVIOUR

Ship propulsion concepts differ in their principal emission behaviour. This is illustrated in Figure 5 below for diesel-cycle and Otto-cycle engines as well as the gas steam turbine concept as applied in the PERFECt Ship project.

1. Diesel cycle: HFO
The IMO rules can be fulfilled when applying additional technical means, but at the cost of added fuel consumption and increased CO_2 emissions caused by the scrubber and exhaust gas recirculation (EGR) and selective catalytic reduction (SCR) equipment used to comply with NO_X Tier III standards.

2. Diesel cycle: LSHFO/MGO
SO_X compliance is ensured by the low sulphur content of the fuel. EGR/SCR equipment is required for NO_X Tier III compliance. However, both technologies can increase CO_2 emissions.

3. Diesel cycle: LNG
LNG is sulphur-free so there are no SO_X emissions. The effort required to achieve Tier III compliance is lower than for oil fuel, but EGR/SCR equipment is still needed. High-pressure, diesel-cycle LNG engines achieve near-zero methane slip.

4. Otto cycle: LNG
Otto-cycle medium and low-speed engines (pure gas and DF engines, refer also to Annex) can meet NO_X Tier III requirements without additional exhaust gas treatment. Methane slip compromises the benefit in terms of CO_2 reduction, so the maximum 28 to 30 per cent improvement cannot be achieved. Engine manufacturers indicate potential CO_2 reduction values of 10 to 20 per cent over similar oil-fuelled engines.

5. The COGES concept used in the PERFECt Ship project is illustrated for comparison. It should be noted that it can only achieve efficiency improvements and a CO_2 emission reduction similar to piston engines if the power demand is high enough (30 to 35 MW as an approximate lower limit). If this condition is met, Tier III NO_X compliance can be achieved with internal means (dry low NO_X burner) when operating on oil or gas. Methane slip does not occur. All things considered, the emissions of COGES systems as proposed in the PERFECt Ship project meet all foreseeable IMO limits. No external exhaust gas cleaning is needed.

It is obvious that all propulsion concepts have their pros and cons and that all of them are principally able to reach the emission limits with all fuel alternatives. The best concept for a given application needs to be determined on a case-by-case basis; it also depends on the owner's preferences. DNV GL is prepared to assist customers in the decision-making process.

FIGURE 5: OVERVIEW: FUEL – ENGINE SYSTEM – EMISSION

		HFO	LSHFO/MGO	LNG
Diesel	SO_X	Scrubber	Compliance	Future-proof
	NO_X	Tier III: EGR/SCR	Tier III: EGR/SCR	Tier III: EGR/SCR
	CO_2	High carbon	High carbon	Reduced CO_2*
Otto	SO_X			Future-proof
	NO_X			Future-proof
	CO_2			Reduced CO_2 (CH_4 slip)*
PERFECt (COGES)	SO_X		Compliance with 0.1 MGO	Future-proof
	NO_X		Future-proof	Future-proof
	CO_2		High carbon	Reduced CO_2 (No CH_4 slip)*

*Lowest CO_2 of all fossil fuels

3.5 SOME THOUGHTS ON FUEL PRICING

In most cases, the engine technology investment is not the dominant factor for the business case. The price of fuel over the lifetime of the ship, or the desired return on investment over a given period, is often the most relevant factor. Fuel pricing depends on a number of factors, including market conditions, which are difficult or impossible to predict. For international shipping it should be noted that subsidies for preferred fuels do not exist because ship fuels are tax-fee already. It remains to be seen whether this will change, for example through the introduction of a CO_2 fee scheme. The price ranges illustrated in Figure 6 reveal a qualitative trend based on price history.

The bars indicate the average minimum and maximum price differences to Brent crude oil. The value 1.0 represents the Brent baseline. Various internal and external sources were used to estimate the average pricing from 2005 to 2015/2016 for the different fuels. One of the main external sources is the BP Statistical Review of World Energy.

Hydrogen is not included. When hydrogen is produced using renewable energy, it can be assumed to be much more expensive than Brent crude oil. It would only be competitive under the assumption of massive subsidies, or of heavy taxes on conventional fuels. Today, nearly all hydrogen is produced from natural gas and therefore more expensive than natural gas. Historically, MGO has always been more expensive and HFO much cheaper than Brent crude oil.

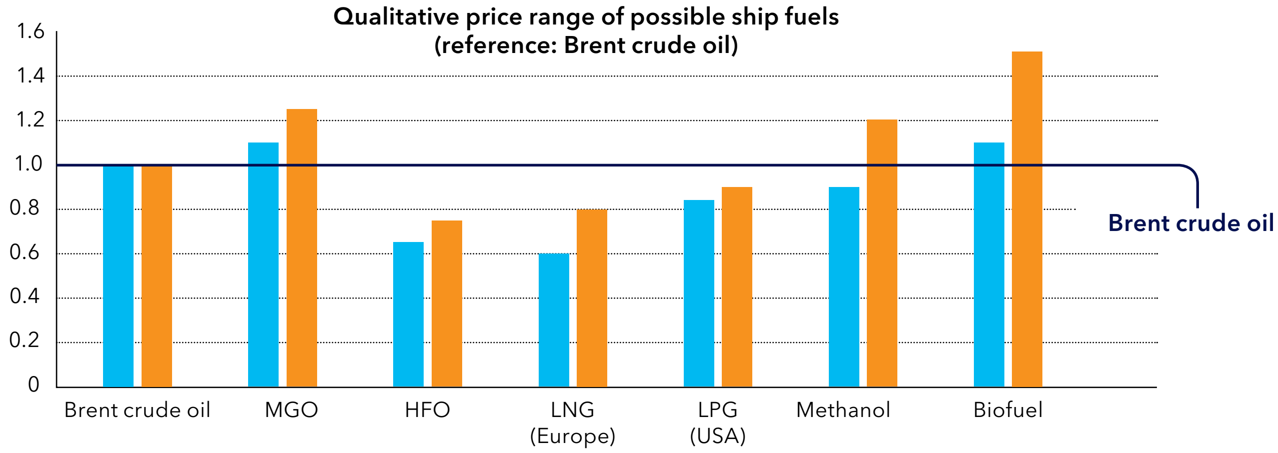
In Europe, LNG competes directly with the price of pipeline gas. LNG that is fed into the grid cannot be more expensive than pipeline gas. The calculations for the diagram use the gas price on the European spot market as a basis for LNG price predictions. The natural gas price in Japan is always an LNG price because the country imports all of its natural gas as LNG. Today, the gas prices in Japan and Europe are gradually aligning. The European and Japanese LNG price can be regarded as an indicator for the worldwide LNG prices regardless of major local deviations. It should be noted that these diagrams do not account for LNG distribution costs.

Most LPG is an oil refinery product. This is one of the reasons why LPG prices have aligned with the oil price in the past. However, LPG production in the USA as a byproduct of shale oil and gas production has increased since 2012, resulting in a drop of LPG prices. The LPG values in Figure 6 are based on US LPG prices from 2005 to 2016 and on European LPG prices between 2008 and 2015.

Today, methanol is mainly produced from natural gas. For this reason, the methanol price is typically above the gas price. The lower price in the diagram refers to methanol produced from gas, while the upper price reflects methanol produced from biomass. Biofuels are produced from biomass. While dependant upon the type of biofuel and the price of the biomass, the price is typically above that of Brent crude oil.

The diagram demonstrates that only LNG and, to some extent, LPG can currently compete with HFO in terms of market price. Methanol and biofuels may eventually be able to compete with MGO to some extent. Hydrogen is not price-competitive.

FIGURE 6: ARE ALTERNATIVE FUELS TOO EXPENSIVE?



	Brent crude oil	MGO	HFO	LNG (Europe)	LPG (USA)	Methanol	Biofuel
Min.	1	1.1	0.65	0.6	0.85	0.9	1.1
Max.	1	1.25	0.75	0.8	0.9	1.2	1.5

Source: DNV GL, IEA

3.6 FUEL AVAILABILITY

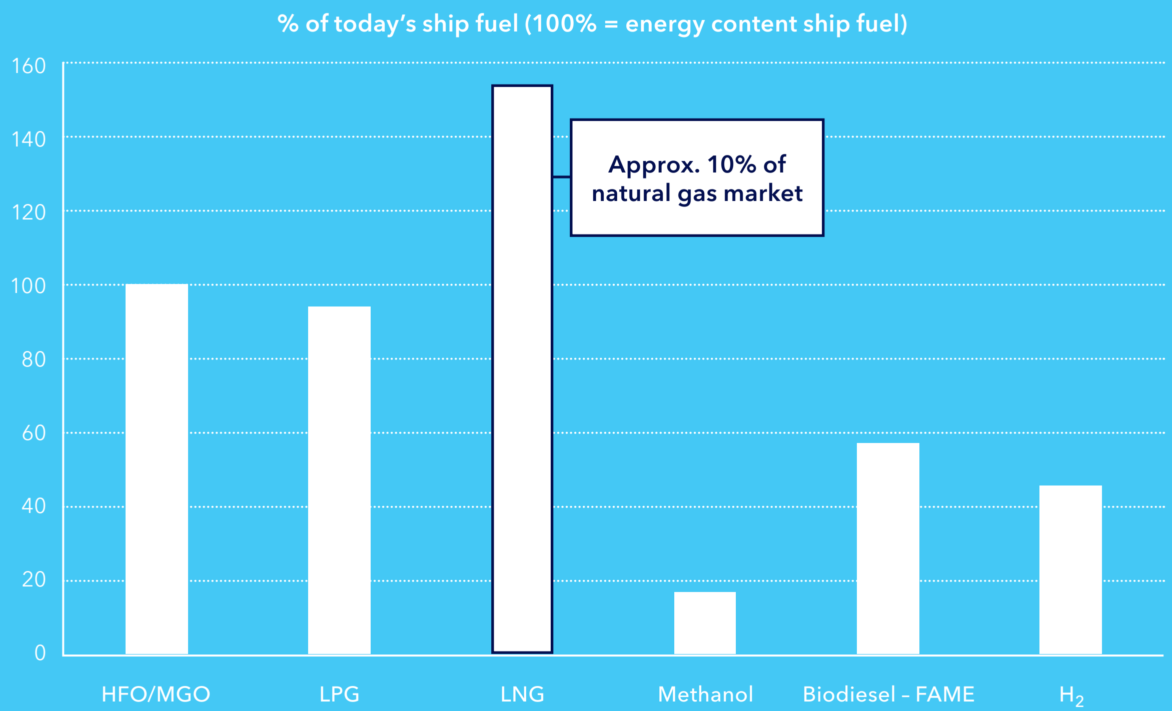
Apart from its price, a future fuel must be available to the market in sufficient quantity. All fuel alternatives discussed here could meet the requirements of the shipping industry for the next ten years, assuming only minor growth in shipping applications. The question is what would happen if a fuel alternative were to become so attractive that a large number of operators would want to adopt it for their ships within a short period of time.

Figure 7 gives an indication based on a comparison of the energy content of the worldwide production of specific alternative fuels with the energy need of the shipping industry.

The energy consumption of the global fleet serves as the 100 per cent baseline.

This comparison shows that for all alternative fuels, with the exception of LNG, a rapid rise in demand would require massive investments in production capacity. In theory, a switchover of the entire global fleet to LNG would be possible today since the current LNG production is higher than the shipping industry's energy requirement, and the share of LNG in the total gas market is only 10 per cent. Furthermore, LPG could likewise cover the energy need of the global fleet; however, in this case no LPG would be left for other users.

FIGURE 7: PRODUCTION OF POSSIBLE SHIP FUELS PER YEAR (RELATIVE ENERGY CONTENT)



Source: DNV GL internal evaluations and various other sources (e.g. "World LNG Report – 2015 Edition", International Gas Union)

3.7 CONCLUDING REMARKS

Environmental and price challenges are driving the interest in alternative ship fuels, but the number of realistic candidates is small. DNV GL believes LNG, LPG, methanol, biofuel and hydrogen to be the most promising candidates. Among them, LNG has already overcome the hurdles related to international legislation, and methanol and biofuels will follow suit very soon. It will be a while before LPG and hydrogen are covered by appropriate new regulations within the IMO IGF Code, as well.

The existing and upcoming environmental restrictions can be met by all alternative fuels using existing technology. However, the IMO target of 50 per cent GHG emissions reduction within 2050 is ambitious, and will likely call for wide-spread uptake of zero-carbon fuels, in addition to other energy efficiency measures. Fuel cells can use all available alternative fuels and achieve efficiencies comparable to, or better than those of current propulsion systems. However, fuel cell technology for ships is still in its infancy. The most advanced developments to date have been achieved by the projects running under the umbrella of the e4ships lighthouse project in Germany, with Meyer Werft and ThyssenKrupp Marine Systems heading the projects for seagoing ships. Wind-assisted propulsion could potentially reduce fuel consumption, especially when used for slow ships, but the business case remains difficult. Batteries as a means to store energy can be considered an alternative fuel source in the widest sense. They have major potential for ships running on short distances and can be used to boost the efficiency of the propulsion system in any ship. However, in deep-sea shipping, batteries alone cannot substitute fuel. With low-sulphur and alternative fuels becoming more widely available, the well-known gas and steam turbine combined cycle technology represents a viable alternative for high-power ship propulsion systems.

All fuel alternatives discussed here could meet the foreseeable volume requirements for shipping over the coming years. A major increase in consumption would require an appropriate increase in production capacity; the only exception is LNG, which is available in sufficient quantities today to meet the potential requirement of the shipping industry for many years.

Without taxation or subsidies, renewable fuels will find it difficult to compete with the prices of conventional fossil fuels. LNG and LPG are the only fossil fuels capable of achieving a CO_2 reduction. CO_2-neutral shipping seems possible only with fuels produced from renewable sources. If the shipping sector resorts to synthetic fuels produced from hydrogen and CO_2 using renewable energy, the available alternatives will be liquefied methane (which is very similar to LNG) and diesel-like fuels.

SUMMARY OF KEY FINDINGS

1. In particular, the decision of the International Maritime Organization (IMO) to limit the sulphur content of ship fuels from 1 January 2020 to 0.5 per cent worldwide, and the recently-adopted ambition to reduce GHG emission by 50 per cent by 2050 have the potential to become game changers.

2. There is an accelerating worldwide trend towards lower emissions of CO_2, NO_X and particles.

3. DNV GL identified LNG, LPG, methanol, biofuel and hydrogen as the most promising alternative fuels for shipping.

4. DNV GL believes battery systems, fuel cell systems and wind-assisted propulsion have reasonable potential for ship applications.

5. As has been demonstrated by the DNV GL PERFECt Ship concept study (refer to PERFECt Ship video available on YouTube), the well-known combined cycle gas and steam turbine technology has good potential for ships in the power range above 30 MW, provided that low-sulphur fuels are widely used in shipping

6. The major challenges for alternative fuels are related to environmental benefits, fuel availability in the quantities needed for shipping, fuel costs and the international rules within the IGF Code.

7. Of all fossil fuels, LNG produces the lowest CO_2 emissions. However, it will not be sufficient in view of the IMO vision to de-carbonizing shipping.

8. In a sustainable energy world where all energy is produced by renewable CO_2-neutral sources, hydrogen and CO_2 will be the basis for fuel production.

9. All propulsion concepts are capable of meeting the emission limits using any of the fuel alternatives.

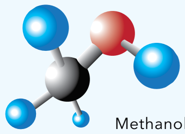
10. For international shipping, it should be noted that subsidies financed by taxes on fuel for preferred fuels do not exist because there is no taxation on ship fuels.

ALTERNATIVE FUELS

Biofuels

Biofuels are derived from primary biomass or biomass residues that are converted into liquid or gaseous fuels. A large variety of processes exist for the production of conventional (first-generation) and advanced (second and third-generation) biofuels, involving a variety of feedstocks and conversions. The most promising biofuels for ships are biodiesel (e.g. HVO – hydrotreated vegetable oil, BTL – biomass-to-liquids, FAME – fatty acid methyl ester) and LBG (liquid biogas, which primarily consist of methane).

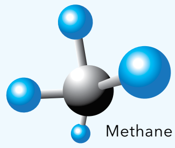
Biodiesel is most suitable for replacing MDO/MGO, LBG for replacing fossil LNG, and SVO (straight vegetable oil) for replacing HFO.



Methanol molecule

Methanol

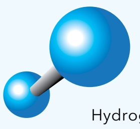
With its chemical structure CH_3OH, methanol is the simplest alcohol with the lowest carbon content and highest hydrogen content of any liquid fuel. Methanol is a basic building block for hundreds of essential chemical commodities and is also used as a fuel for transport. It can be produced from a number of different feedstock resources like natural gas or coal, or from renewable resources such as biomass or CO_2 and hydrogen.



Methane molecule

LNG

Liquefied natural gas (LNG) has more or less the same composition as natural gas used for households and power generation, and in the industry. Its main component is methane (CH_4), the hydrocarbon fuel with the lowest carbon content.

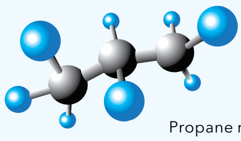


Hydrogen molecule

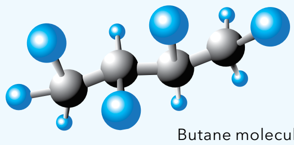
Hydrogen

Hydrogen (H_2) can be produced in several different ways, for example by electrolysis of renewable matter or by reforming natural gas. The production of hydrogen through electrolysis could be combined with the growing renewable energy sector which delivers, by its nature, intermittent power only. Conversion to hydrogen could facilitate storage and transport of this renewable energy.

Hydrogen is used in a variety of industrial processes and is currently being considered as a potential fuel for land-based transport, in particular in cars, buses, trucks and trains.



Propane molecule



Butane molecule

LPG

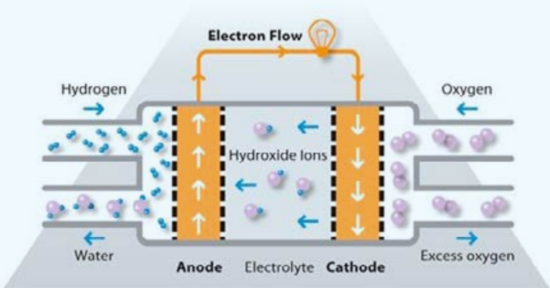
Liquefied petroleum gas (LPG) is by definition any mixture of propane and butane in liquid form. For instance, in the USA, the term LPG is generally associated with propane. Mixing butane and propane enables specific saturation pressure and temperature characteristics.

ALTERNATIVE TECHNOLOGIES

Battery stack

Batteries

Batteries provide the ability to directly store electrical energy for propulsion, opening up many other opportunities to optimize the power system. Recent advancements in battery technology and falling costs thanks to the growing worldwide demand for batteries make this technology attractive to shipping.



Functional principle of a fuel cell

Fuel cell (FC) systems

Fuel cells convert the chemical energy contained in a fuel directly into electrical and thermal energy through electrochemical oxidation. This direct conversion process enables electrical efficiencies of up to 60 per cent, depending on the type of fuel cell and fuel used. It also minimizes vibration and noise emissions, a major setback of combustion engines.

Sail propulsion

Wind-assisted propulsion

For thousands of years, wind was the primary energy source used to propel ships, apart from human muscles. Today, wind-assisted propulsion is understood to be a potential method of reducing the fossil energy consumption of ships. Wind is an inexhaustible source of energy.

4 INTERNATIONAL REGULATIONS AND CLASS RULES

Shipping is an international industry, and international environmental and safety standards for shipping are developed by the International Maritime Organization (IMO), a United Nations specialized agency. The International Code of Safety for Ships using Gases or other Low-Flashpoint Fuels (IGF Code) is the mandatory IMO instrument that applies to all gaseous and other low-flashpoint fuels in shipping, and to all gas-powered ships other than gas carriers. The use of low-flashpoint fuels in gas carriers is covered by the International Code for the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk (IMO IGC Code).

The IGF Code was adopted by the IMO in June 2015 (MSC.391[95]) and came into force on 1 January 2017. It is compulsory for all gaseous and other low-flashpoint-fuel ships and currently has detailed provisions for natural gas in liquid or compressed form (LNG, CNG). Regulations for methanol and low-flashpoint diesel fuels as well as for maritime fuel cells are under development.

The IGF Code contains mandatory provisions for the arrangement, installation, control and monitoring of machinery, equipment and systems using low-flashpoint fuels. It addresses all areas that need special consideration for the use of these fuels, taking a goal-based approach, with goals and functional requirements specified for each, the design, construction and operation of ships using this type of fuel.

Technical provisions for low-flashpoint fuels other than natural gas, and other energy arrangements such as fuel cell systems will eventually be added to the code as new chapters. For the time being, ships installing fuel systems designed to operate on other types of low-flash-point fuels will need to demonstrate individually that their design meets the IGF Code's general requirements. The alternative design approach as outlined in IMO MSC.1/Circ.1455 (guidelines for the approval of alternatives and equivalence as provided for in various IMO instruments) has to be followed, and be accepted by the flag administration of the vessel. This individual, and in some cases complex process will likely have a slowing effect on the introduction of alternative fuels not yet explicitly covered by the IGF Code. The presence of relevant class rules may, however, ease this situation significantly since a simplified process may be applied if the flag accepts the class rules as providing a safety level equivalent to that of the IGF Code.

DNV GL rules addressing the requirements of the IGF Code include:

- Mandatory Class Notation "GAS FUELLED": Rules for classification of ships, Part 6, Chapter 2, Section 5, Gas fuelled ship installations – Gas fuelled
- Voluntary Class Notation "GAS READY" for ships prepared for later gas fuel retrofit: Rules for classification of ships, Part 6, Chapter 2, Section 8, Gas ready ships – Gas ready
- DNV GL rules for ships using low-flashpoint liquid fuels (e.g. methanol) and for fuel cell installations:
  - Mandatory Class Notation "LFL FUELLED": Rules for classification of ships, Part 6, Chapter 2, Section 6, Low flashpoint liquid fuelled engines – LFL fuelled
  - Mandatory Class Notation "FC(Power)" or "FC(Safety): Rules for classification of ships, Part 6, Chapter 2, Section 3, Fuel cell installations – FC
  - DNV GL is currently also developing rules for the use of LPG as a fuel.

In addition, DNV GL was the first classification society to develop rules for lithium-ion battery installations on board ships:

- Mandatory Class Notation(s) "BATTERY (SAFETY)" and "BATTERY (POWER)": Rules for classification of ships, Part 6, Chapter 2, Section 1, Battery power

For further information regarding rules and regulations for alternative fuels and the IGF Code, please contact LNG, Cargo Handling & Piping Systems (mcano385@dnvgl.com). For further information about the rules for fuel cell installations, please contact Machinery Systems & Marine Products (mcade343@dnvgl.com). Questions about battery rules and systems can be sent to Electrical Systems (mcano381@dnvgl.com). Further details can also be found in a recent DNV GL report to the European Maritime Safety Agency (EMSA).

5 ALTERNATIVE FUELS AND TECHNOLOGIES – A BRIEF OVERVIEW

5.1 PRINCIPLES

To assess all fuels or technologies in a comparable manner, the information is categorized as follows:

1. Price: Accounts for production process, raw materials, market price and the reasoning behind it, current/foreseeable (five years) price or expected price (beyond five years)

2. Infrastructure: Current/future distribution network, bunkering, availability

3. Regulation: Existing/expected regulations, consequences

4. Scalability: Current/possible future production as related to the requirement in shipping

5. Environmental impact: CO_2, NO_X, SO_X, particulate matter (PM) and others

6. Technology: Availability of current/future technology, foreseeable changes

7. CAPEX: Engines, storage, processing, retrofitting

8. OPEX: Exhaust cleaning, scrubber, additional costs for fuel change

Please note that the following gives a brief overview only. For additional information, please refer to our Web platform on alternative fuels (www.dnvgl.com/afi).

5.2 REFERENCE FUELS – HFO AND MGO

5.2.1 General

The shipping industry currently uses heavy fuel oil (HFO) and marine gas oil (MGO) as fuels; HFO has a maximum sulphur limit of 3.5 per cent (mass), while low-sulphur MGO contains 0.1 per cent (mass) or less. Ship fuel currently contributes approximately 3 per cent to global man-made CO_2 emissions. The energy demand of the shipping sector is projected to be approximately 314 million tonnes per year in 2020 (base case, MEPC 70-5.3, p. 26). With the year 2012 fuel mix, this would equate to 245 million tonnes of HFO (78 per cent) with an average sulphur content of 2.5 per cent (m/m; MEPC 70-5.3, Tab 5) and 69 million tonnes of MGO (22 per cent).

When the decision of IMO MEPC 70 to limit the sulphur content in ship fuel to 0.5 per cent takes effect in 2020, only vessels equipped with SO_X scrubbers or equivalent technology will be allowed to consume HFO (containing more than 0.5 per cent sulphur). This will significantly reduce the global demand for high-sulphur HFO.

The fuel availability study prepared by the independent research and consultancy organization CE Delft, which served as a basis for the IMO decision, estimates that by 2020 around 4,000 vessels will operate with scrubbers installed. According to that study, this would result in HFO representing 6 per cent of the fuel mix once the sulphur cap takes effect. In January 2019, approximately 2,800 vessels were known to have installed or ordered scrubbers for installation before 2020, while more than 100 vessels will have scrubbers installed in 2020 or later. Based on the size of these vessels, HFO consumption can be expected to reach 10 to 15 per cent of marine fuel consumption.

There is currently much uncertainty regarding the fuel mix in early 2020 and the type of 0.5 per cent sulphur fuel that will be available in the market. In practical terms, these fuels can be assumed to be blends of HFO and MGO and will eventually replace the current high-sulphur HFO.

5.2.2 Details on specific subjects

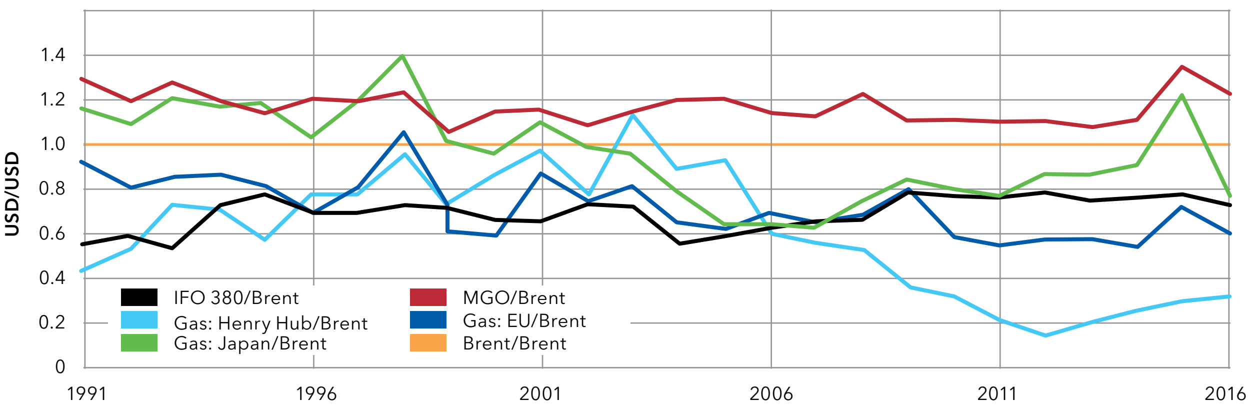
Price

For decades, the HFO price has been below and the MGO price above the crude oil price, as shown in Figure 8 below. Since global demand for HFO will drop significantly after 2020, its price is assumed to fall as well. However, there might be local variations depending on the actual HFO availability in certain geographical locations. At the same time, the price of MGO and of 0.5 per cent sulphur fuels is expected to rise significantly, leading to a high initial spread between HFO and compliant fuels, which is expected to close eventually. This spread may temporarily accelerate the uptake of scrubbers, while the high MGO prices may increase interest in alternative fuels.

Infrastructure

A well-developed worldwide MGO and HFO supply infrastructure is in place. Ships are supplied by bunker barges when in port, in most cases during cargo operations. The International Maritime Organization

FIGURE 8: YEARLY AVERAGE OIL AND GAS PRICES RELATIVE TO THE PRICE OF BRENT CRUDE OIL (SAME ENERGY CONTENT)



Source: DNV GL, BP

(IMO) expects oil-based, fuel-cap-compliant fuels to be available worldwide as of 2020, a notion challenged by other parties. However, it is not clear as yet what fuel products will be available to cover the demand.

Regulations

The IMO Marine Environment Protection Committee (MEPC) limited the sulphur content of ship fuel to 0.5 per cent from 2020 onward. This regulation applies worldwide.

Emission control areas (ECAs) for SO_X were introduced along the North American coasts as well as in the North Sea and Baltic Sea in 2015. In these areas, the sulphur content of fuel is limited to 0.1 per cent. It is allowed to continue burning HFO and use scrubbers to clean the exhaust gas to achieve an equivalent level of sulphur emissions.

In 2016, the North American coastlines were additionally declared NO_X-restricted areas. This means that ships keel-laid after 31 December 2015 must comply with Tier III NO_X requirements. The same restrictions will apply in the North Sea and Baltic Sea from 2021 onward.

Scalability

While there have been different views across the industry regarding the expected availability of sulphur-cap-compliant fuel by 2020, the IMO based its decision to implement the sulphur cap as of 2020 on an availability study performed by CE Delft. However, the reality about the availability of compliant fuels and its potential impact on prices will not be known until the industry starts consuming compliant fuel after the sulphur cap takes effect.

Environmental impact

Oil-based ship fuel has a greater environmental impact than the alternative fuels discussed in this guidance paper. The sulphur content of low-sulphur ship fuel is much higher than that of the other fuel types. Even low-sulphur fuel will produce higher particle emissions than alternative fuels. Furthermore, without selective catalytic reduction (SCR) NO_X emissions will be higher, as well, and CO_2 emissions will be higher than those of most of the alternative fuels discussed here. For a quantitative comparison, please refer to chapter 3.

Technology

All ships intended to operate on high-sulphur fuel from 2020 onward will be required to clean their exhaust gases by using scrubbers or equivalent technology. Scrubber technology is readily available. Even if the low expectations of IMO MEPC 70-5.3 regarding high-sulphur HFO consumption turn out to be true, thousands of scrubbers will have to be installed by 2020. In ECAs, the NO_X emission limits will require SCRs or exhaust gas recirculation (EGR) systems, in addition to scrubbers (depending on the keel-laying date). This technology is likewise readily available.

CAPEX

Depending on the size of the engine, the investment costs for scrubbers range between USD per kilowatt (5,000 kilowatt engine) and 150 to 100 USD per kilowatt (40,000 kilowatt and larger engines).

OPEX

An exhaust gas cleaning system requires energy to operate the pumps and scrubbing units to remove the SO_X from the exhaust gas. This energy use is estimated to be approximately 1 to 2 per cent of the power used by the engine(s) installed on the ship. This electrical energy is generated by auxiliary diesel generator sets burning either MDO/MGO or HFO (IMO MEPC 70–INF.9, Sec 3.6.1). The OPEX without maintenance and spare parts is approximately equivalent to 0.6 to 0.7 per cent of the hypothetical fuel costs without the presence of scrubber technology (according to MEPC 70-INF.9). The operational costs of scrubbers are composed of the cost of maintenance and energy consumption. According to IMO MEPC 70/5/3, these amount to approximately 0.7 per cent of the total fuel costs (ships with more than 25 MW of shaft power).

5.3 LNG

5.3.1 General

The main component of liquefied natural gas (LNG) is methane (CH_4), the hydrocarbon fuel with the lowest carbon content and therefore with the highest potential to reduce CO_2 emissions (maximum reduction: roughly 26 per cent compared to HFO). LNG has more or less the same composition as natural gas used in households, for power generation and by the industry. The LNG production process ensures that it is practically sulphur-free. Using LNG as fuel consequently does not produce any SO_X emissions. Since the boiling point of LNG is approximately –163°C at 1 bar of absolute pressure, LNG must be stored in insulated tanks.

The energy density per mass (LHV in MJ/kg) is approximately 18 per cent higher than that of HFO, but the volumetric density is only 43 per cent of HFO (kg/m³). This results in roughly twice the volume compared to the same energy stored in the form of HFO. Factoring in the shape-related space requirements, cylindrical LNG tanks typically occupy three to four times the volume of an equivalent amount of energy stored in the form of fuel oil.

LNG has been used as a fuel by LNG carriers since the 1950s. Today, approximately 500 LNG carriers using LNG fuel are in operation. Since the early 2000s, LNG has also been adopted by other ships. In December 2018, 137 of these LNG-fuelled ships were in operation, 136 were on order, and 135 were prepared for conversion to LNG as fuel (refer to afi.dnvgl.com).

5.3.2 Details on specific subjects

Price

Natural gas hub prices worldwide (except in certain parts of East Asia) have been below the price of crude oil and HFO for the last ten years. The delivered price of LNG fuel to ships must also account for the liquefaction or break-bulk cost, distribution cost and applicable profit margins. Compared to other alternative fuels, LNG seems to have reached the most competitive feedstock price level historically among all alternatives fuels. Currently, the price level is competitive with MGO, but direct competition with HFO may be difficult (refer to Chapter 3, Figure 6 and Figure 9).

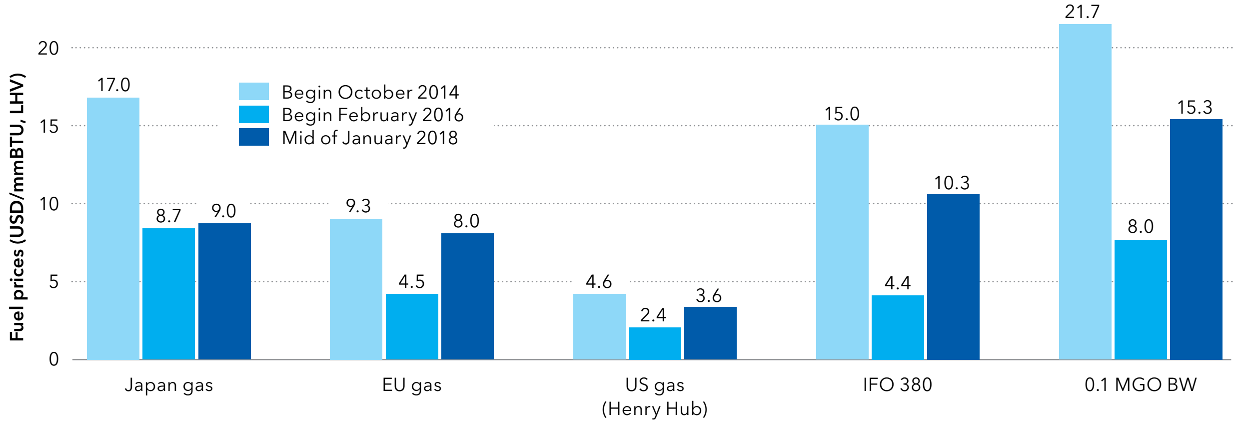
From 2020, high-sulphur HFO will not be permitted without a scrubber system installed, and the price of the new LSFO reference fuel is expected to be higher than HFO. Furthermore, the price of LNG is expected to be competitive with low-sulphur HFO. LNG also has the potential to compete with high-sulphur HFO and scrubbers.

Infrastructure

While still limited, the dedicated LNG bunkering infrastructure for ships is improving quite rapidly. A large share of LNG bunkering as well as LNG distribution to bunkering locations is still taking place by road. Delivery by rail would also be possible but is currently not practised. In 2017 and 2018, several LNG bunker vessels where delivered for operation in key locations such as the Amsterdam, Rotterdam and Antwerp (ARA) region, the North Sea, the Baltic Sea and at the Florida coast. Bunker vessels for other key locations such as the western Mediterranean, the Gulf of Mexico, the Middle East, Singapore, China, South Korea and Japan have been ordered recently or are under development and will likely materialize in parallel with significant orders for LNG-fuelled deep-sea ships within the next years.

For information on LNG bunkering infrastructure, please visit DNV GL's Alternative Fuel Insight (AFI)

FIGURE 9: FUEL PRICES



Source: DNV GL

online portal (afi.dnvgl.com). AFI is free to access and gives detailed and continuously updated information on all worldwide bunkering points for alternative fuels, including LNG, that are in operation or under development. LNG is essentially available worldwide (at large-scale import and export terminals), and investments are underway in many of these locations to make LNG available to ships. DNV GL expects to see an increased focus on developing LNG bunker vessels for seagoing ships in the near future. Bunkering by truck and from permanent local depots will also continue to grow for certain trades and segments. Dual-fuel engine technology may offer some flexibility and redundancy as the LNG bunkering network for the deep-sea fleet evolves.

Regulations

The IMO IGF Code for LNG and CNG came into force on 1 January 2017, establishing an international regulatory basis for the design and construction of LNG-fuelled ships.

Other aspects, such as bunkering of LNG-fuelled ships, are subject to national regulations and therefore need to be evaluated on a case-by-case basis. For example, only a limited number of ports have established local rules for LNG bunkering. In addition, LNG bunkering requirements and guidelines have been developed by SGMF, IACS and ISO. While further harmonization and development of standards and tools for LNG bunkering operations would be highly beneficial, the current regulatory basis should not be considered as a barrier to further widespread use of LNG.

Scalability

For the foreseeable future, there are no principal limitations to production capacities that could limit the availability of LNG as ship fuel. LNG has a share of approximately 10 per cent in the overall natural gas market. LNG production capacity is set to increase significantly over the next five years. In 2016, the global LNG production capacity was approximately 320 m t/a. This figure will increase by almost 40 per cent to about 450 m t/a by 2020 (2017 World LNG report; International Gas Union [IGU]).

Environmental impact

Natural gas from LNG is the cleanest fossil fuel available today. There are no SO_X emissions related to it, particle emissions are very low, the NO_X emissions are lower than those of MGO or HFO, and other emissions such as HC, CO or formaldehyde from gas engines are low and can be mitigated by exhaust gas after-treatment if necessary. Nevertheless, methane release (slip) must be considered when evaluating the CO_2 reduction potential of LNG as ship fuel (maximum value is roughly 26 per cent compared to HFO). Low-pressure Otto-cycle gas engines (i.e. all four-stroke as well as all low-pressure two-stroke engines) burning LNG comply with the IMO Tier III NO_x limit without requiring exhaust gas treatment. For more details on engines, refer to the section "Engines for gas-fuelled ships" in the Annex.

In the case of Otto-cycle gas engines, the methane slip from the combustion process has a significant impact on the overall GHG reduction potential. High-pressure two-stroke engines require EGR or SCR technology to achieve NO_x Tier III compliance, both in diesel and gas mode. At the same time, the combustion principle eliminates the methane slip issue more or less entirely. Methane leakage along the value chain is also an issue which needs to be considered, as just a small fraction of leakage will cancel out the positive GHG effect achieved during

FIGURE 10: LNG-FUELLED SHIPS, BASED ON AIS POSITIONS OF THE LNG-FUELLED FLEET

(FROM 15 TO 25 MAY 2017)

Source: DNV GL, AFI web portal

combustion. Today, most of the energy consumption of ships occurs in two-stroke engines, especially on board deep-sea ships where alternative fuel and technology options are limited. Based on engine makers' data, methane slip is less of an issue in two-stroke engines than in four-stroke engines.

From a GHG abatement perspective, it is also worth noting that engine makers have successfully tested hydrogen mixed with natural gas in existing marine dual-fuel engines. The combined benefits of substituting a certain share of the fossil methane with renewable hydrogen, and of the positive secondary effect this may have on the combustion process with respect to methane slip, are significant.

Methane is the main component of LNG – and of biogas. Therefore liquefied biogas or methane produced from hydrogen and carbon in a power-to-fuel process (refer to Section 5.8) can be used in LNG fuel systems and gas engines without requiring any modifications. None of these liquefied methane-based gases cause any tank-to-propeller carbon dioxide emissions (TTP emissions), provided that carbon from renewable sources is used; if carbon from carbon capture and storage (CCS) is used, the TTP emissions will still be quite low. However, potential methane slip must be accounted for.

In discussions about the long-term viability of LNG as a marine fuel, decision-makers must keep in mind that, similar to diesel fuel and diesel engines, there are technically feasible low and zero-emission sources of liquid methane which can be used as drop-in fuels. At this stage, it is difficult to conclude whether the more cost competitive energy carriers from a combined ship-CAPEX-and-price perspective will be renewable diesel or renewable liquid methane, or something entirely different, for instance hydrogen or methanol. For most ship types and trades, dual-fuel technology is currently the best hedging option considering this particular uncertainty and in view of stricter GHG regulations in general.

Technology

Gas engines, gas turbines and LNG storage and processing systems have been available for land installations for decades. LNG sea transport by LNG carrier also has a history going back to the middle of the last century. Developments to use LNG fuel in general shipping began early in the current century. Today, the technology required for using LNG as ship fuel is readily available. Piston engines and gas turbines, several LNG storage tank types as well as process equipment are also commercially available.

$ CAPEX

LNG as ship fuel is rapidly approaching the status of a fully developed technology, with various technology suppliers active in the market. As applications increase and competition between suppliers heats up, we can observe the CAPEX decreasing. CAPEX costs for LNG systems are and will continue to be higher than the expenditures associated with using a scrubber system with HFO.

$$ OPEX

The OPEX costs for LNG systems on board ships are comparable with the operational costs of oil-fuelled systems without scrubber technology or an SCR. Gas-fuelled engine systems have about the same efficiency as conventionally-fuelled systems. For this reason, the energy consumption of an LNG-fuelled ship is roughly the same as that of an oil-fuelled ship. Maintenance of a gas-burning engine may be less expensive thanks to cleaner fuel. Currently, the maintenance intervals of conventional and gas-fuelled engines are typically the same, but with more operational experience to draw on, they may be extended for gas engines. The maintenance costs for the high-pressure gas supply system on board ships with high-pressure engines should be considered. A number of ports offer discounts to LNG-fuelled ships.

5.4 LPG

5.4.1 General

Liquefied petroleum gas (LPG) is by definition any mixture of propane and butane in liquid form. In the USA, the term LPG is generally associated with propane. Specific mixtures of butane and propane are used to achieve desired saturation, pressure and temperature characteristics.

Propane is gaseous under ambient conditions, with a boiling point of –42°C. It can be handled as a liquid by applying moderate pressure (8.4 bar at 20°C). Butane can be found in two forms: n-butane or iso-butane, which have a boiling point of –0.5°C and –12°C, respectively. Since both isomers have higher boiling points than propane, they can be liquefied at lower pressure. Regarding land-based storage, propane tanks are equipped with safety valves to keep the pressure below 25 bar. LPG fuel tanks are larger than oil tanks due to the lower density of LPG.

There are two main sources of LPG: it occurs as a byproduct of oil and gas production or as a byproduct of oil refinery. It is also possible to produce LPG from renewable sources, for example as a byproduct of renewable diesel production.

There are currently three newbuilding orders for Very Large Gas Carriers (VLGC) to be powered by LPG, while four existing LPG carriers will be converted to run on LPG in 2019.

5.4.2 Details on specific subjects

Price

Up until 2010, propane prices in the USA were very close to those of Brent crude oil, as shown in Figure 11.

Since 2011, prices have decoupled due to increased LPG production as a byproduct of shale oil and shale gas. The USA became a net exporter of LPG in 2012. Currently, LPG is more expensive than LNG but cheaper than low-sulphur oil.

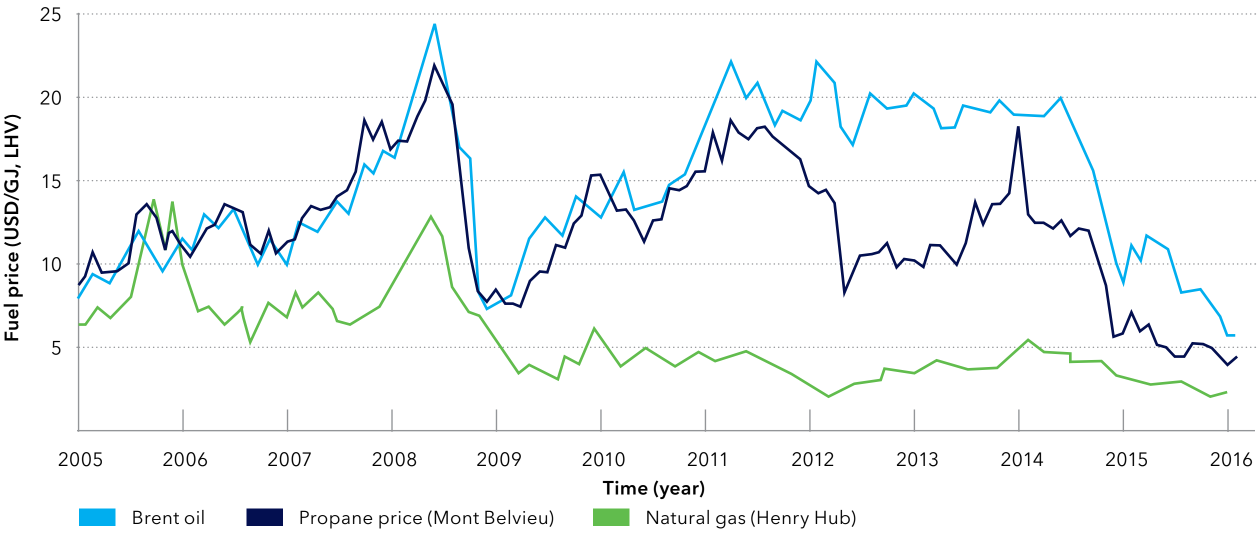
Infrastructure

Figure 12 shows the extensive network of LPG import and export terminals in Europe. It is relatively easy to develop bunkering infrastructure at existing LPG storage locations or terminals by simply adding distribution installations. Distribution to ships can occur either from dedicated facilities or from special bunker vessels.

FIGURE 12: OVERVIEW OF EUROPEAN IMPORT AND EXPORT LPG TERMINALS

Source: DNV GL

FIGURE 11: PROPANE PRICES



Source: DNV GL

Regulations

The IMO IGF Code is mandatory for all gas and other low-flashpoint-fuel ships (see above). LPG is currently not included and is not on the agenda for the near future.

Technical provisions will be needed to cover particular aspects of LPG fuel. The main safety concern that must be covered is related to the density of LPG vapours, which are heavier than air. Therefore leak detectors and special ventilation systems should be used. Transport of LPG by sea is subject to the IMO IGC Code, which also permits the use of LPG as fuel for gas carriers.

Scalability

According to the World LPG Association, global LPG production in 2015 was 284 million tonnes, or 310 million tonnes of oil equivalent. This is slightly higher than the global demand for marine fuel. Production has been increasing by approximately 2 per cent annually over the last decade.

The production increase has been most profound in North America and the Middle East. Only 9 per cent of LPG is used as transportation fuel for road vehicles, half of it in South Korea. Other uses of LPG include homes (cooking and heating), the chemical and other industries, and refineries.

In regional terms, Asia accounts for the largest share of LPG consumption. It is expected that at the current production level, the demand for shipping can be safely covered until 2030, provided that demand for LPG as ship fuel will grow slowly initially and remain at a moderate level.

Environmental impact

LPG combustion results in CO_2 emissions that are approximately 16 per cent lower than those of HFO. When accounting for the complete life cycle, including fuel production, the CO_2 savings amount to roughly 17 per cent.

The global warming potential of propane and butane as greenhouse gases is three to four times higher than that of CO_2. This has to be taken into consideration when addressing the issue of unburned LPG potentially escaping into the atmosphere (LPG slip). At the same time, using LPG virtually eliminates sulphur emissions. LPG is also expected to reduce particulate matter (PM) emissions significantly. The reduction of NO_X emissions depends on the technology applied.

For a two-stroke diesel engine, the NO_X emissions can be expected to be reduced by 10 to 20 per cent compared to HFO, whereas for a four-stroke Otto-cycle engine, the expected reduction is more significant and may be below Tier III NO_X limits. To comply with these standards, a two-stroke diesel-cycle engine would have to be equipped with EGR or SCR systems. Both solutions are commercially available.

Technology

There are three main options for using LPG as ship fuel: in a two-stroke diesel-cycle engine; in an four-stroke, lean-burn Otto-cycle engine; or in a gas turbine. Currently, only a single two-stroke diesel engine model is commercially available, the MAN ME-LGI series. In 2017, a Wärtsilä four-stroke engine was commissioned for stationary power generation (34SG series). This engine had to be derated to maintain a safe knock margin. An alternative technology offered by Wärtsilä consists in the installation of a gas reformer to turn LPG and steam into methane by mixing them with CO_2 and hydrogen. This mixture can then be used in a regular gas or dual-fuel engine without derating.

LPG can be stored under pressure or refrigerated. It will not always be available in the temperature and pressure range a ship can handle. Therefore the bunkering vessel and the ship to be bunkered must carry the necessary equipment and installations for safe bunkering. A pressurized LPG fuel tank is the preferred solution due to its simplicity, and because the vessel can bunker more easily using either pressurized tanks or semi-refrigerated tanks without major modifications.

$ CAPEX

The cost of installing LPG systems on board a vessel (e.g. internal combustion engine, fuel tanks, process system) is roughly half that of an LNG system if pressurized type C tanks are used in both cases. This is because there is no need for special materials that are able to handle cryogenic temperatures.

On large ships, the cost difference between LNG and LPG systems is lower if the LPG is stored in pressurized type C tanks, which are more expensive than large prismatic tanks. Alternatively, LPG can be stored at low temperatures in low-pressure tanks, which require thermal insulation.

$$ OPEX

The operational costs for LPG systems, excluding fuel costs, are expected to be comparable to those of oil-fuelled vessels without a scrubber system. Practical experiences are currently not available.

5.5 METHANOL

5.5.1 General

Methanol, with the chemical structure CH_3OH, is the simplest alcohol with the lowest carbon content and highest hydrogen content of any liquid fuel. Methanol is a liquid between 176 and 338 Kelvin (–93°C to +65°C) at atmospheric pressure.

It is a basic building block for hundreds of essential chemical commodities that contribute to our daily lives, such as building materials, plastic packaging, paints and coatings. It is also a transport fuel and a hydrogen carrier for fuel cells.

Methanol can be produced from several different feedstock resources, mainly natural gas or coal, but also from renewable resources like black liquor from pulp and paper mills, forest thinning or agricultural waste, and even directly from CO_2 that is captured from power plants.

When produced from natural gas, a combination of steam reforming and partial oxidation is typically applied, with an energy efficiency up to about 70 per cent (defined as energy stored in the methanol versus energy provided by natural gas).

Methanol produced from gasification of coal relies on a cheap, widely available resource, but the greenhouse gas (GHG) emissions are about twice as high as from natural gas. Due to its density and lower heating value (19.5 MJ/kg), methanol fuel tanks have a size approximately 2.5 larger than oil tanks for the same energy content. Methanol has a flashpoint of 11°C to 12°C and is considered a low-flashpoint fuel. It can also be converted to dimethyl ether (DME), which can be used as a fuel for diesel engines.

5.5.2 Details on specific subjects

Price

From 2010 to 2013, methanol prices per unit of energy content were between European HFO and MGO prices. Since then, methanol prices have slightly increased (and are now back to 2013 levels) and, at the same time, the drop in oil prices has made methanol more expensive than distillate marine fuels.

Since methanol is typically produced from natural gas, its price per mass unit is usually coupled to natural gas prices and is higher in relation to energy content.

Producing methanol from coal may bring the price down, but it increases GHG emissions drastically. Methanol is easy to produce from hydrogen and CO_2. Therefore the production of methanol from renewable energy makes it a green ship fuel. The costs are currently higher than the costs of methanol synthesis from methane.

Infrastructure

Distribution to ships can be accomplished either by truck or by bunker vessel. In the port of Gothenburg, Stena Lines has created a dedicated area for bunkering the vessel *Stena Germanica*, which includes a few simple safety barriers to avoid problems in case of a leak.

In Germany, the first methanol infrastructure chain, from production using renewable energy to trucking and ship bunkering through to consumption in a fuel cell system on board the inland passenger vessel *MS Innogy*, was launched in August 2017.

Regulations

For shipping, the main applicable guideline is the IGF Code, which is compulsory for all gas and other low-flashpoint-fuel ships. The chapter for methanol is currently under development. However, the IGF Code provides a means to approve a methanol fuel system by following the alternative-design approach. In addition, DNV GL has published rules for low-flashpoint fuels that address methanol.

Scalability

The global methanol demand was approximately 80 million tonnes in 2016, twice the 2006 amount. The production capacity is more than 110 million tonnes. The energy content of these 110 million tonnes is equal to approximately 55 million tonnes of oil. Most of the methanol is currently consumed in Asia (more than 60 per cent of global demand), where demand has been increasing for the last few years.

Approximately 30 per cent is used in North America, Western Europe and the Middle East, and this figure has been largely stable over the past decade. It is expected that the current production can safely cover the demand for shipping until 2030, assuming that the demand for methanol as ship fuel will grow slowly initially and remain at a moderate level.

Environmental impact

Methanol combustion in an internal combustion engine reduces CO_2 emissions (tank-to-propeller [TTP] value) by approximately 10 per cent compared to oil.

The exact value may differ depending on whether methanol is compared with HFO or distillate fuel. When considering the complete life cycle (well-to-tank [WTT] and TTP) including the production of the fuel from natural gas, the total CO_2 emissions are equivalent to or slightly higher (in the order of 5 per cent) than the corresponding emissions of oil-based fuels.

The WTT emissions of methanol from renewable sources (biomass) are significantly lower compared to production from natural gas. Using methanol virtually eliminates sulphur emissions and meets the sulphur emission cap.

It is also expected that particulate matter (PM) emissions will be significantly lower. The reduction of NO_X emissions depends on the technology used. In the case of a two-stroke diesel engine, the NO_X emissions can be expected to be approximately 30 per cent lower than those of HFO, whereas in the case of a four-stroke Otto-cycle engine, the expected reduction is in the order of 60 per cent, but not below Tier III NO_X limits. To comply with these standards, EGR or SCR systems should be used. Both solutions are commercially available.

Technology

There are two main options for using methanol as fuel in conventional ship engines: in a two-stroke diesel-cycle engine or in a four-stroke, lean-burn Otto-cycle engine.

Similar to LPG, only a single two-stroke diesel engine is currently commercially available, the MAN ME-LGI series, which is now in operation on methanol tankers. Wärtsilä four-stroke engines are in operation on board the passenger ferry *Stena Germanica*. Another possibility would be to use methanol in fuel cells (refer to Section 5.10). A test installation has been running on the Viking Line ferry *MS Mariella* since 2017.

Methanol is a liquid fuel and can be stored in standard fuel tanks for liquid fuels, with certain modifications to accommodate its low-flashpoint properties and the requirements currently under development for the IGF Code at the IMO. Fuel tanks should be provided with an arrangement for safe inert gas purging and gas freeing.

There are currently three newbuilding orders for Very Large Gas Carriers (VLGC) to be powered by LPG, while four existing LPG carriers will be converted to run on LPG in 2019.

$ CAPEX

The additional costs of installing methanol systems on board a vessel (e.g. internal combustion engine, fuel tanks, piping) is roughly one third that of the additional costs associated with LNG systems. This is because there is no need for special materials able to handle cryogenic temperatures or for pressurized fuel tanks.

$$ OPEX

The operational costs for methanol systems are expected to be comparable with those for oil-fuelled vessels without scrubber technology. Due to the small number of ships running on methanol, practical experiences are limited.

Methanol tanker *Lindanger*

5.6 BIOFUELS

5.6.1 General

Biofuel is a collective term for a range of energy carriers produced by converting primary biomass or biomass residues into liquid or gaseous fuels. The most promising biofuels for ships are hydrotreated vegetable oil (HVO), fatty acid methyl ester (FAME) and liquefied biogas (LBG), although other options are available, as well.

The use of biofuels is largely motivated by the goal to reduce greenhouse gases (GHG). A number of studies point to sustainable biofuels as one of few options available for deep-sea shipping to achieve the IMO target of reducing GHG emissions by at least 50 per cent by the year 2050 compared to 2008 levels. The effective GHG reduction varies greatly depending on feedstock and production process. Other aspects of biofuel production are also controversial, including land use and socio-economic issues. Several standards and initiatives address these aspects. Biofuels from advanced processes utilising sustainable feedstocks can achieve substantial GHG reductions while minimizing other effects. The potential for GHG reduction when using biofuels is illustrated in Figure 3 (Section 3.1).

5.6.2 Details on specific subjects

Price

Currently, HVO, FAME and LBG are more expensive than their fossil counterparts. The market for these fuels is immature and information on prices is very limited. There are also great local and regional variations in price and availability. However, the biofuel market is expected to grow, and there is significant potential for cost reduction. The potential for reducing production costs is expected to be higher for HVO than for FAME. The reduction will be driven by continuous process improvements, technological developments and scaling of production.

Infrastructure

There is a lack of global infrastructure and bunkering facilities for biofuels. Biofuel is available in certain ports, for example in the Netherlands, Australia or Norway.

HVO can in most cases be distributed using the existing MGO and HFO distribution systems, although modifications are sometimes required.

Using existing distribution systems for FAME is more challenging. Due to potential oxidation of FAME and potential sedimentation FAME storage for more than six months should be avoided. What is more, FAME is hygroscopic, and tanks containing MGO blended with FAME should have efficient drainage systems to regularly drain water from the bottom of the tank.

Liquefied methane produced from biomass (LBG) can use LNG infrastructure, which is expanding. Since methane is the main component of liquefied natural gas (LNG), LBG should easily blend with LNG.

Regulations

There are several standards covering biofuels addressing either technical or sustainability aspects. Among the former is ISO 8217:2017, a commercial quality standard for marine fuels which defines requirements for fuel used in marine diesel engines and boilers and their conventional treatment on board (sedimentation, centrifuging, filtering) before use. While this standard did not allow FAME to be blended with regular marine distillate or residual fuels in the past, its sixth edition introduces the DF (Distillate FAME) grades DFA, DFZ and DFB. These grades allow up to 7 per cent of FAME content by volume and are also covered by the European standard EN590. Apart from this aspect, all other parameters of these grades are identical to those of traditional grades. The limitations mentioned above do not apply to HVO, which is classified as a DM (distillate) under the ISO standard, provided that certain conditions are met.

The International Council on Combustion Engines (CIMAC) provides ship owners and operators with a guideline for managing marine distillate fuels containing up to 7 per cent of FAME.

Among the standards addressing sustainability of biofuels are the EU Renewable Energy Directive as well as ISO 13065, which specifies principles, criteria and indicators for the bio-energy supply chain to facilitate the assessment of environmental, social and economic sustainability aspects.

The Roundtable on Sustainable Biofuels (RSB) has addressed the many sustainability questions associated with growing crops for liquid fuel production. Furthermore, it has created tools and solutions for sustainability, such as the global certification standards for sustainable biomaterials, biofuels and biomass production. The Global Bioenergy Partnership (GBEP) defines sustainability indicators for bioenergy based on three pillars: environmental, social and economic feasibility.

While standards do exist, there is a lack of globally accepted biofuel standards specifically for the maritime industry. IMO currently only makes reference to technical ISO standards governing fuels. In the recently adopted IMO GHG reduction strategy, carbon intensity guidelines are one measure that is being considered. Details are still to be discussed, but these efforts could entail looking at sustainability aspects of biofuels.

Scalability

Global production data indicate that 81 million tonnes of conventional transport fuel (which includes sugar- and starch-based ethanol, oil crop biodiesel and HVO) were produced in 2017 (IEA, 2018). Over the next five years, this volume is anticipated to grow by 3 per cent annually. To achieve the UN's Sustainability Development Goals for 2030, the use of biofuels would have to triple. Drivers of this development include falling costs, widespread sustainability governance, and increasing adoption by various industries such as shipping. The use of biofuels in shipping is currently very limited.

Environmental impact

Biofuels are considered as a solution for GHG reduction although the use of these fuels does not directly reduce carbon emissions: CO_2 from the combustion of biological materials adds CO_2 to the atmosphere similar to combustion of fossil fuels. However, CO_2 emitted from combustion of biofuels is considered as part of the natural CO_2 cycle in which an equivalent amount of CO_2 is captured from the atmosphere by the feedstock plants as they grow. For this reason, bio fuels are regarded as CO_2-neutral fuels.

The actual GHG emissions from a given biofuel will depend strongly on the type of feedstock used and the fuel production process. GHG reductions ranging between 19 and 88 per cent have been reported for various biofuels, based on life-cycle assessments. The extent to which biofuels ultimately enable true GHG reductions is being debated. To establish a reliable data basis, it would be necessary to define a classification system for biofuels that can be used in shipping. The Renewable Energy Directive (RED) specifies that biofuels should lower GHG emissions by at least 50 per cent compared to fossil fuels; from 1 January 2018, the GHG emissions of biofuels produced in installations which began production on or after 1 January 2017 are to be at least 60 per cent lower than those of fossil fuels.

HVO has higher reduction potential than FAME, with a life-cycle emission reduction potential of about 50 per cent compared to diesel (IEA 2011, 2017). FAME

typically has lower energy content and lower GHG emissions than conventional marine fuels. The GHG reduction achieved by LBG is significantly better compared to LNG (refer to Figure 3, Section 3.1).

The NO_x emissions from HVO may be somewhat lower (about 10 per cent) while those from FAME are considered to be higher compared to conventional marine fuels (about 10 per cent). The values for LBG are in the same range as those for LNG, which reduces NO_x output by about 90 per cent. This means that only LBG can satisfy the IMO's Tier III NO_x requirements without using additional NO_x abatement technology. In general HVO, FAME and LBG all produce very low SO_x emissions. The particulate matter (PM) emissions of biofuels are likewise lower than those of conventional marine fuels.

Technology

Biofuels can be blended with conventional fuels or used as drop-in fuels as full substitutes of conventional fossil fuels. A drop-in fuel can directly be used in existing installations without major technical modifications. For this reason, biofuels are well suited to substitute petroleum-based fuels in the fleet in service.

HVO is a high-quality fuel from which the oxygen has been removed using hydrogen, which results in long-term stability. The characteristics of HVO make it suitable as drop-in fuel substituting fossil fuels. In general, HVO is compatible with existing infrastructure and engine systems, subject to approval by the manufacturer. In some cases, modifications may be required. Overall, there is limited operational experience with HVO as a ship fuel. HVO is currently used on board three ferries operating in Norway, and no negative effects have been reported to date.

FAME is not a drop-in fuel. Blending with conventional fuel in concentrations of up to 7 per cent is permissible only as specified by ISO 8217:2017 for DF (Distillate FAME) grades DFA, DFZ and DFB. The technical feasibility of various FAME biodiesel blends in shipping has been tested in a number of demonstration projects. FAME differs from MGO/MDO in terms of fuel stability, cold flow properties, compatibility with materials (e.g. in packs), durability and lubrication properties. In general, FAME performs poorly in cold temperatures, is less stabile when blended, and has a short shelf life. Some tests have experienced increased corrosion and susceptibility to microbial growth. Knowledge regarding other potential effects of FAME is limited, as most of the tests performed to date studied the use of FAME for shorter time periods only.

LBG can in essence be used as a fuel by LNG-powered ships and is unlikely to require any engine, tank and pipeline upgrading. Reliability is not expected to change when replacing LNG with LBG. It is also possible to blend LBG with LNG.

$ CAPEX

Additional costs related to modifications of ship engines and infrastructure for FAME are estimated by engine manufacturers to be less than 5 per cent of engine costs. There are no additional costs reported when switching to HVO.

Any additional costs associated with the use of LBG would be the same as for LNG. If a vessel is already running on LNG, there are no additional costs reported when mixing LBG and LNG.

$$ OPEX

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

Furthermore, there are reports that using FAME increases maintenance costs, such as costs of cleaning tanks, clogged filters and similar items.

Biofuels are currently more expensive than fossil fuels. The associated fuel costs are therefore expected to be higher than those of conventional marine fuels.

5.7 HYDROGEN

5.7.1 General

Hydrogen (H_2) is a colourless, odourless and non-toxic gas. For use on ships, it can either be stored as a cryogenic liquid, as compressed gas, or chemically bound.

The boiling point of hydrogen is very low: 20 Kelvin (–253°C) at 1 bar. It is possible to liquefy hydrogen at temperatures up to 33 Kelvin (–240°C) by increasing the pressure towards the "critical pressure" for hydrogen, which is 13 bar. The energy density per mass (LHV of 120 MJ/kg) is approximately three times the energy density of HFO. The volumetric density of liquefied H_2 (LH_2) (71 kg/m^3) is only 7 per cent that of HFO. This results in approximately five times the volume compared to the same energy stored in the form of HFO. When stored as a compressed gas, its volume is roughly 10 to 15 times (depending on the pressure [700 to 300 bar]) the volume of the same amount of energy when stored as HFO.

Hydrogen is an energy carrier and a widely used chemical commodity. It can be produced from various energy sources, such as by electrolysis of renewables, or by reforming natural gas. Today, 95 per cent of hydrogen is produced from fossil fuels, mainly natural gas (68 per cent), but also oil (16 per cent) and coal (11 per cent). Five per cent of current hydrogen production uses electrolysis. For applications in the transport sector, production from natural gas by reforming is currently the most common method. If the resulting CO_2 were captured, a zero-emission value chain for shipping could be achieved.

Production of hydrogen by electrolysis is viewed as an opportunity to store and transport surplus renewable energy, thereby stabilizing the energy output of solar or wind power plants.

When used in combination with marine fuel cells, the emissions to air associated with other marine fuels could be minimized or eliminated entirely. If H_2 is generated using renewable energy, nuclear power or natural gas with carbon capture and storage, zero-emission ships are possible.

5.7.2 Details on specific subjects

Price

The cost of H_2 production varies greatly depending on the price of electricity (in the case of electrolysis) or natural gas (in the case of reformation), and the scale of the production plant. The need for transport and compression or liquefaction also influences the purchasing price on the consumer's side.

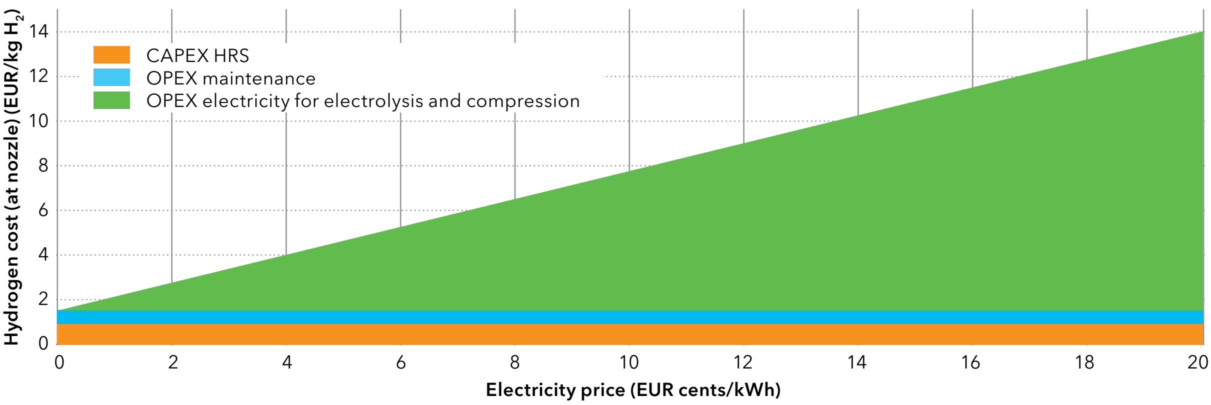
Cost estimates from relevant literature for H_2 produced by electrolysis range from about 3.5 to 8.3 USD per kilogramme (1,170 to 2,770 USD per tonne of crude oil equivalent).

The cost of hydrogen production by reforming natural gas or biogas varies greatly across a range from around 1.5[1] to 6.5 USD per kilogramme (800 to 2,170 USD per tonne of fuel oil equivalent), averaging around 4.1 USD per kilogramme (1,370 USD per tonne of crude oil equivalent). These cost estimates include production, compression, storage and transport. The impact of electricity prices on the cost of hydrogen is illustrated in Figure 13.

For reference: a price of 70 USD per barrel of oil approximately corresponds to 510 USD per tonne of fuel oil equivalent.

According to forecasts, the price of electrolysers will fall in the near future, reducing the CAPEX and

FIGURE 13: EXAMPLE OF HYDROGEN COST AT REFUELLING NOZZLE AS A FUNCTION OF THE ELECTRICITY PRICE FOR A HYDROGEN REFUELLING STATION WITH A CAPACITY OF 6,000 KG H_2/D



Source: EC "Guidance document on large scale hydrogen bus refuelling", March 2017 consequently the production cost of hydrogen. The location of production facilities may also play a role in the cost of H_2. For example, electrolysis in areas in Norway with low electricity prices has the potential to drive the production costs down to between 3.5 and 4.1 USD per kilogramme by 2020 (1,170 to 1,370 USD per tonne of crude oil equivalent).

Infrastructure

Today, most hydrogen is produced from natural gas using a related, mainly industrial, land-based infrastructure. Since there is currently no demand for H_2 fuel, there is no distribution or bunkering infrastructure for ships. Liquefied hydrogen (LH) could be distributed in a similar manner as LNG.

Standard 40-foot containers for LH with a typical tank capacity of around 3,600 kilogrammes of hydrogen per tank are available in the market, and a liquid tank can be filled up to approximately 94 per cent of its total volume. Due to the very low boiling point of hydrogen, super-insulated pressure vessels are used for storage in liquid (cryogenic) form. Boil-off is unavoidable, and the boil-off rate, which depends on the relationship between tank surface area and volume, can be 0.3 to 0.5 per cent per day depending on technology and conditions. For stationary use, the capacity range of current LH tanks is about 400 to 6,700 kilogrammes.

Once LH storage technology for liquid hydrogen tankers (under development at Kawasaki[12]) is available, it will be possible to store up to 88,500 kilogrammes of hydrogen per tank. A demonstration tank system will be commissioned in 2020.

Hydrogen production from electrolysis is a well-known and commercially available technology suitable for local production, for instance in port, as long as adequate electrical energy is available. Electrolysis would eliminate the need for a long-distance distribution infrastructure.

In future, liquefied hydrogen (LH) might be transported to ports from storage sites where hydrogen is produced using surplus renewable energy, such as wind power, whenever energy production exceeds grid demand. The hydrogen produced could be stored in compressed – not liquefied – form in salt caverns and at other suitable sites. Transport could be by road, ship, or pipeline depending on the site, volume and distance.

Regulations

Hydrogen is a low-flashpoint fuel subject to the International Code for Safety of Ships using Gases or Other Low-flashpoint Fuels (IGF Code). The current edition of the IGF Code does not cover hydrogen storage. Rules for the use of hydrogen in fuel cells are under development and will be included in a future amendment to the IGF Code. For the time being, hydrogen storage and use must follow the alternative design approach in accordance with SOLAS Regulation II-1/55 to demonstrate an equivalent level of safety.

Other regulations, such as the DNV GL class rules for fuel cell (FC) installations (DNV GL rules for classification of ships Part 6, Chapter 2, Section 3), cover design principles, material requirements, arrangement and system design, safety systems and other aspects.

Regarding the use of hydrogen, the ISO/TR 15961 "Basic considerations for the safety of hydrogen systems" provide an overview of safety-relevant considerations for H_2.

The IGC and IGF Codes cover the storage of liquefied gas on board ships, and the C-tank rules will in principle cover liquid hydrogen, but additional considerations will be necessary due to the properties of hydrogen and its very low storage temperature.

Bunkering of hydrogen-fuelled ships is subject to national regulations and therefore needs to be evaluated on a case-by-case basis. Bunkering and port regulations for bunkering H_2 fuel do not exist at this time. However, several ports do have LNG rules, and bunkering is subject to SGMF guidelines and ISO/TS 18683. It is assumed that there will be a significant overlap with future standards for hydrogen.

Scalability

More than 50 million tonnes of H_2 are produced per year globally. This is about equal to the energy content of 150 million tonnes of ship fuel. Nearly all hydrogen is produced from natural gas. As hydrogen can be produced from water using electrolysis, there are no principal limitations to production capacity that could restrict the amount of available H_2 to the shipping industry.

[1] DNV GL GTR ETO 2018 Hydrogen value chain assessment.

Environmental impact

There are energy losses associated with H_2 production and possible compression or liquefaction. When H_2 is generated from renewable or nuclear power using an efficient supply chain, it can be a low-emission alternative fuel for shipping. Current development initiatives explore hydrogen production from natural gas while safely capturing and storing the resulting CO_2 (CCS).

Hydrogen used in fuel cells as energy converters does not produce any CO_2 emissions and could eliminate NO_X, SO_X and particulate matter (PM) emissions from ships. Hydrogen-fuelled internal combustion engines for marine applications could also minimize greenhouse gas (GHG) emissions, while NO_X emissions cannot be avoided when using combustion engines.

Technology

Power generation systems based on H_2 may eventually be an alternative to today's fossil-fuel-based systems. While fuel cells are considered the key technology for hydrogen, other applications are also under consideration, including gas turbines or internal combustion engines in stand-alone operation or in arrangements incorporating fuel cells.

Hydrogen-fuelled internal combustion engines for marine applications are said to be less efficient than diesel engines. Hydrogen fuelled piston engines for ships are not available in the market. On land, development is ongoing*. Possibly larger-scale industrial and maritime applications combined with waste heat recovery solutions might be better suited for high-temperature technologies such as solid oxide fuel cells (SOFC) or even industrial systems using molten carbonate fuel cells.

Fuel cells combined with batteries (and possibly super capacitors) adding peak-shaving effects are a promising option. Even proton exchange membrane fuel cells (PEMFC), thanks to their flexible materials, could improve fuel cell lifetime significantly when protected against the harshest load gradients. SOFC must be applied in a hybrid environment using peak-shaving technology to be a realistic alternative for shipping.

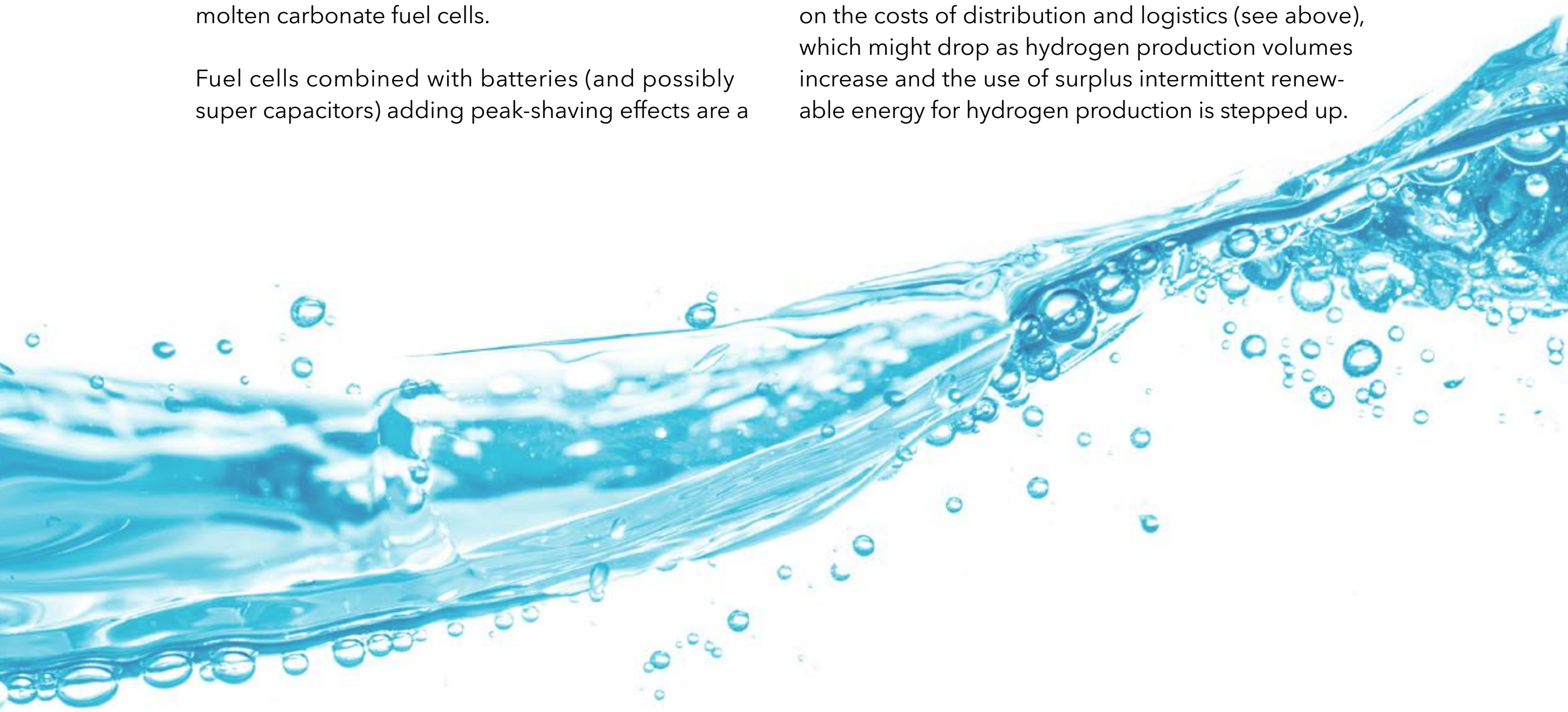
$ CAPEX

The added CAPEX of conventional energy converters such as piston engines is expected to be similar to that of LNG-fuelled engines. Storage tanks for liquefied hydrogen (LH_2) in ships are expected to be more expensive than LNG tanks because of the lower storage temperatures, higher insulation quality, as well as lack of experience with hydrogen in maritime applications. Costs of other equipment (e.g. piping, ventilation, heat exchangers, pumps) can be expected to be comparable to those of LNG systems. However, since the physical properties of hydrogen differ from those of natural gas, it may not be possible to use the same kind of system components.

$$ OPEX

It is anticipated that conventional systems like piston engines or turbines running on hydrogen will have OPEX comparable to those of oil-fuelled systems. As indicated above, the cost of hydrogen production varies depending on local conditions and because the current hydrogen market is dominated by the industrial gases market where individual contracts apply.

In addition, hydrogen fuel prices will vary depending on the costs of distribution and logistics (see above), which might drop as hydrogen production volumes increase and the use of surplus intermittent renewable energy for hydrogen production is stepped up.



*Compare, for instance, www.governmenteuropa.eu/hydrogen-powered-zero-emission-combustion-engine/86777/

When hydrogen is produced locally using electrolysis, the distribution costs are marginal. The lifetime of energy converters (e.g. fuel cells) is shorter than that of piston engines or turbines and depends on fuel quality and system operation management. A recent study estimates the annual balance of plant (BOP, all associated costs excluding the fuel cells themselves) cost for fuel cells to be 3 per cent of the fuel cell capital cost, and the fuel cell refurbishment cost after the end of the fuel cell unit's lifetime to be around 1,000 USD per kilowatt. The expected crew training requirements could be comparable to those of LNG/CNG but can be expected to be higher during the initial phase.

Others

One thing batteries and hydrogen have in common is that they represent potential game changers that become increasingly relevant when the cost of pollution (GHG or local pollutants) rises significantly and/or where strict emission limits apply.

In such a situation, the key parameters for fuel comparison might change. This has been experienced in the case of battery-powered ferries in Norway, for example, which can be very price competitive (OPEX) with conventional fuels. At the same time, they require a very different infrastructure, which is typically associated with innovative, fast-charging technology at every stop and conventional charging when the ferry is not in use (e.g. overnight).

The energy chain perspective is important. Two main production paths can be assumed for hydrogen:

- Hydrogen produced from natural gas, the most common production method today (in future possibly combined with CCS)
- Hydrogen produced by electrolysis using renewable energy

In both cases, conversion of the original energy source to hydrogen will mean that some energy is lost.

In an energy environment marked by a growing renewable energy sector, hydrogen and batteries complement each other. Batteries are a suitable means to store relatively small amounts of energy for a shorter duration, whereas energy conversion to hydrogen is better for long-term (e.g. seasonal) storage of larger volumes of energy (e.g. using underground caverns).

[2] Appendix B: SF-BREEZE Optimization Study, in Sandia Report SAND2018-0421, Jan 2018. Optimization of Zero Emission Hydrogen Fuel Cell Ferry Design, With Comparisons to the SF-BREEZE, by Pratt and Klebanoff.

5.8 POWER TO FUEL: SYNTHETIC FUELS FROM HYDROGEN AND CARBON OR NITROGEN

5.8.1 General

All efforts to substitute fossil fuels with carbon-free energy are related to the production of electricity, most of which is generated using wind, solar, hydro or nuclear power. The use of biomass is another way to decarbonize the energy supply (refer to Section 5.6). Electricity produced from renewables can be stored directly in batteries to provide a carbon-free energy carrier for ships (refer to Section 5.9). Electricity can also be used to produce gaseous or liquid energy carriers. A variety of names are common for fuels produced from water, carbon or nitrogen using electricity, such as power-to-gas/liquids/fuel, electrofuel, e-fuel or synthetic fuel. In the following discussion, power-to-fuel (PtoF) or electrofuels is used as an umbrella term for synthetic fuels from renewable sources such as diesel, methane, methanol, ammonia and hydrogen.

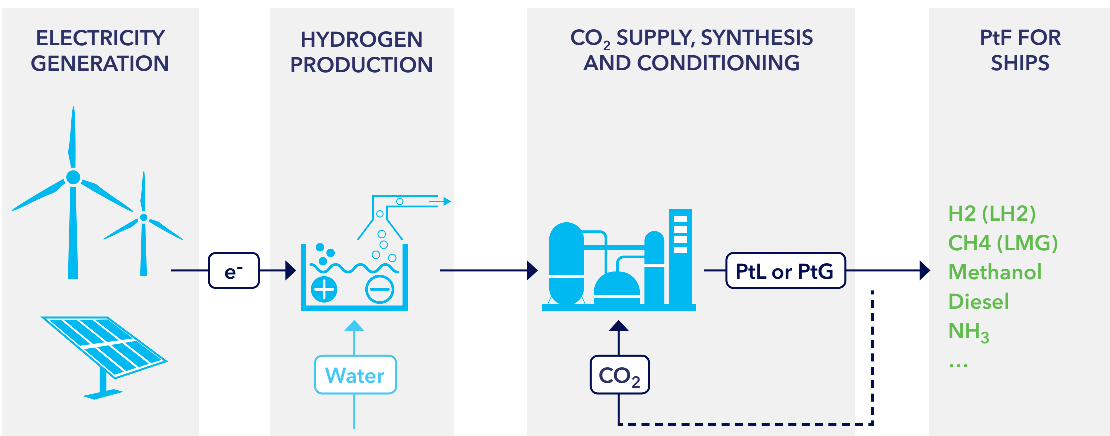
The principal pathway to produce hydrogen from renewable electricity, through electrolysis for further processing to produce various PtoF fuels, is illustrated in Figure 14 (for carbon-neutral fuels, also refer to Maritime Forecast to 2050, Section 5.1).

The fluctuating nature of wind and solar energy production requires an oversized production capacity to ensure a reliable supply to networks which largely depend on these renewable sources, such as the energy supply system envisioned by the German Energy Transition concept (Energiewende). At the same time, these energy systems are likely to encounter a supply shortfall in periods of high energy need and low wind conditions or sun irradiation, such as in wintertime in the northern hemisphere and – in the case of solar power – at night. To balance this supply-and-demand discrepancy, it is necessary to create substantial energy storage capacity.

Furthermore, it is widely assumed that highly industrialized and densely populated countries will be unable to cover their energy needs entirely with local renewable electricity from wind and solar power generation (refer to "Integrated Energy Transition – Impulses to shape the energy system up to 2050", German Energy Agency [dena], Berlin, October 2018). This means that these countries will have to supplement their energy mix with imported energy carriers from carbon-neutral or carbon-free sources. While land-based transport could conceivably be powered entirely by electricity using battery storage, the deep-sea shipping and aviation transport modes will always depend on fuels with a high energy density that can be carried along without taking too much space or adding too much weight. Therefore, renewable energy will have to be converted to carbon-free/carbon-neutral energy carriers for the purpose of trading as well as for use as fuel in aviation and deep-sea shipping.

Hydrogen produced using renewable electricity and electrolysis is the source component for any storage of carbon-free energy in liquid or gaseous form. Hydrogen can either be used directly as an energy carrier (refer to Section 5.7) or chemically processed together with carbon or nitrogen to produce gaseous or liquid fuel. Carbon-based synthetic fuels have properties similar to the fossil fuels used today. Using nitrogen instead of carbon results in ammonia (NH_3). These chemical synthetization processes are known as power-to-liquid (PtoL) and power-to-gas (PtoG), summarily referred to as power-to-fuel' (PtoF) processes.

FIGURE 14.: PRINCIPAL PRODUCTION PATHWAY FOR POWER-TO-FUEL
Power to Liquid (PtL), Power to Gas (PtG) = Power to Fuel (PtoF)



Source: DNV GL

Of course, the direct use of hydrogen from electrolysis is the preferable option (refer to Section 5.7) because synthesizing PtoF fuel from hydrogen and a carbon-neutral source consumes energy, which compromises the overall energy yield.

If the carbon input into the process stems from carbon-neutral sources or is taken directly out of the atmosphere, the resulting synthetic fuel will be carbon-neutral and no tank-to-propeller CO_2 emissions must be accounted for; the tank-to-propeller (TTP) emissions can be regarded to be zero. CO_2 emissions related to production (well-to-tank [WTT]) still need to be considered.

PtoF-based fuels play an important role in carbon reduction scenarios as the shipping industry moves towards 2050. As shown in Table 1, which is based on the DNV GL Maritime Forecast until 2050, about 102 million tonnes of fuel oil equivalent are expected to be carbon-neutral fuels, which includes both bio-fuels and carbon-free fuels (H_2, NH_3).

These carbon-neutral fuels will mainly be synthetic fuels from PtoF processes and biofuels in liquid or gaseous form (bio methane gas).

5.8.2 DETAILS ON SPECIFIC SUBJECTS

Price

Since PtoF processes require hydrogen produced through electrolysis using carbon-free energy as the basic energy carrier, the price of electricity is the most relevant cost factor for PtoF production, accounting for more than 50 per cent of production costs.

Depending on the assumed technical scenarios (with CAPEX for the electrolysis and PtoF process falling over time) and electricity prices, the values that can be derived from literature vary widely.

TABLE 1: PROJECTED FUEL MIX IN 2050 TO FULFIL THE IMO GHG STRATEGY (MARITIME FORECAST TO 2050)

	EJ/a	Million t (oil equivalent)
Carbon-neutral	4.3	102
LNG	2.5	60
Electricity	0.6	13
HFO/MGO	3.7	89
Total	**11.1**	**264**

Presumable price ranges for PtoF fuels have been estimated by various studies, such as dena (2018) and Brynolf et al. (2018). By 2030, renewable hydrogen is estimated to cost 1,000 to 2,000 USD per tonne of oil equivalent (toe), liquefied biogas (methane) 1,500 to 2,500 USD per toe, synthetic diesel 1,700 to 2,700 USD per toe, and synthetic methanol 1,700 to 2,500 USD per toe.

For comparison purposes, please note that the current cost of MGO ship fuel is approximately 650 to 700 USD per tonne (October/November 2018). Historically, the MGO price reached 1,200 USD per tonne in 2008 and ranged between 900 and 1,000 USD per tonne between 2011 and 2013.

Ammonia prices will likely be similar to those for methane gas. ISTP (2017) puts ammonia prices at 1,800 to 2,300 USD per tonne of fuel oil equivalent in a low versus high price scenario for 2030, assuming technology availability (ISPT, power to ammonia, March 2017, http://www.ee.co.za/wp-content/uploads/2017/06/Producing-ammonia-and-fertilizers-new-opportunities-from-renewables.pdf).

PtoF fuels with the same or a similar chemical composition as fossil fuels can be used in the same engines and may be directly mixed with their fossil counterparts. These alternative, interchangeable substitute fuels are referred to as "drop-in fuels". The costs of drop-in fuel blends will mainly depend on the cost of the respective fossil fuel and the added amount of PtoF synthetic fuel.

It is obvious that the introduction and long-term use of synthetic fuels from PtoF processes would lead to higher costs compared to today's and historic fuel prices. It can be assumed that the competition between different fuel options may lead to a mix of different marine fuels, depending on the given application and trading area.

Infrastructure

As the introduction of LNG as ship fuel has shown, it is costly and time-consuming to build up a new fuel supply infrastructure or to adapt existing infrastructure to a new fuel. Even methanol as a fuel will at the least require separate storage facilities and bunkering installations.

Ship fuels produced in PtoF processes, however, could potentially use existing infrastructure. Diesel fuels from Fischer Tropsch synthesis can use existing

HFO and MGO installations. Liquefied methane, which is nearly identical to LNG and that contains 70 to 90 per cent methane, can utilize existing LNG bunkering infrastructure. Similarly, diesel and methane can be blended with fossil diesel and LNG, reducing the carbon footprint compared to 100 per cent fossil diesel or LNG fuel.

Considering the international nature of deep-sea shipping, it is unlikely that a large number of different fuels with different infrastructure requirements will be used in the long run. In short-sea shipping and on fixed routes, the situation is different because a dedicated infrastructure may be commercially feasible (e.g. for liquid hydrogen or batteries).

Regulations

As explained above, the most relevant use of synthetic fuels from PtoF processes will be drop-in fuels with physical properties similar to those of their fossil "twins". From the current direction the IMO is taking in the development of the IGF Code, it can be concluded that regulations for low-flashpoint diesel, LNG and methanol will be included once fuels from PtoF process are made available (beyond 2030). Furthermore, LPG (propane/butane blends), hydrogen and ammonia may be covered by the IGF Code within roughly the same timeframe. All of these fuels can be produced in PtoF processes from hydrogen and carbon/nitrogen when the need arises. The regulatory hurdle from the IMO perspective in terms of safety is considered to be low.

Scalability

Apart from some test installations, no large-scale PtoF production facilities for synthetic fuels are currently in existence. The cost difference between conventional fossil fuels and carbon-free drop-in fuels is significant, and no measures have been taken so far to offset these costs.

The DNV GL Maritime Forecast to 2050 assumes that the IMO 2050 GHG targets will be met and carbon-neutral fuels will be made widely available after 2035. In this context, synthetic fuels from PtoF processes will likely play a role in shipping from 2030 onwards.

It is still an open question whether these fuels will be produced in the quantities needed by the shipping industry (provided that prices are competitive and an appropriate regulatory regime is in place). To date, there have been no political activities discernible towards making synthetic fuels from PtoF processes available. It is likely that significant amounts of synthetic fuels and/or biofuels will be needed to meet the IMO GHG targets.

Environmental impact

Looking at emissions from synthetic fuels, a distinction must be made between the opportunity to reduce CO_2 emissions and the handling of directly harmful emissions that can result from combustion processes, such as nitrous oxides (NO_X), sulphur oxide (SO_X) and particulate matter (PM). The amount of NO_X emissions a combustion process releases depends on the type of energy converter used, for instance Otto versus diesel-cycle piston engine, gas turbine or fuel cell.

For CO_2, the picture is different. While, for example, MGO from PtoF will be regarded as carbon-neutral with zero tank-to-propeller (TTP) emissions, conventional fossil MGO emits approximately 74 CO_2-equivalent grams per megajoule (refer to Figure 3 in Section 3).

To meet the IMO's GHG targets in the near future, synthetic, carbon-neutral PtoF fuels may be blended with conventional fossil fuels. In such a blend, a lower carbon content in the fossil fuel component will require a smaller amount of added synthetic fuel to meet the relevant carbon emission limit.

By definition, fuels from PtoF processes have zero TTP emissions if the used carbon is taken from CO_2-neutral sources. Note that some CO_2 emissions do occur during production of PtoF fuels (WTT). As Figure 3 in Section 3.1 shows, in the case of fossil fuels, WTT emissions are well below TTP emissions. The WTT emissions from PtoF processes can be expected to be even lower than those of fossil fuels because hydrogen production through electrolysis releases few emissions, and PtoF processes can be assumed to cover their own energy needs mainly from renewable sources.

Technology

Fuels from PtoF processes can be produced using a variety of technologies. The Sabatier process is the most common method to produce methane from hydrogen and carbon, while the Fischer Tropsch process is the standard method for production of diesel-like fuels from hydrogen and carbon. Ammonia is synthesized using the Haber Bosch process. All these processes are well known and have been used in large-scale applications.

Table 2 compares the energy efficiency of various PtoF processes. The overall efficiency ranges between 51 and 62 per cent. As these values are relatively similar and all processes may harbour some optimization potential, it is impossible to determine from today's perspective which PtoF fuel may become dominant in future. The easiest solution for shipping will be drop-in fuels which can use the existing infrastructure or even be mixed with their fossil equivalents.

From Table 2 it can be concluded that liquefied hydrogen does not offer any major advantages over other PtoF fuels because of the highly energy-intensive liquefaction process. This and the low volumetric energy density of liquefied hydrogen (21 per cent compared to HFO) make it difficult to use liquefied hydrogen in deep-sea shipping. The situation is different for compressed and liquid hydrogen in short-sea shipping (refer to Section 5.7) on fixed routes covering limited distances.

$ CAPEX

Fuels from PtoF processes are assumed to be primarily drop-in fuels which can either be mixed with similar fossil fuels or used to substitute the latter. For this reason, the additional ship-related CAPEX that is needed to switch over to PtoF fuels will be low or, in most cases, zero. This does not mean that no additional costs will be incurred compared with today's oil-based fuels. For example, LNG systems require more CAPEX than HFO, MGO, LPG or methanol systems.

Considering the higher prices of future ship fuels discussed here, it is obvious that possible additional CAPEX costs associated with some synthetic fuels can more easily be compensated by reduced OPEX.

$$ OPEX

The operational costs of synthetic fuels, excluding fuel costs, are expected to be comparable to those of oil or gas-fuelled vessels without a scrubber system. No practical experience is currently available.

TABLE 2: ENERGY EFFICIENCY OF PTOF PRODUCTION PROCESSES

	H_2	CH_4	Gasoline/ Diesel	Methanol	Ammonia
Electrolysis	0.71	0.71	0.71	0.71	0.71
PtoG process	–	0.75	–	–	0.87
Liquefaction	0.83	0.96	–	–	–
PtoL process	–	–	0.75	0.75	–
Production efficiency	0.59	0.51	0.53	0.53	0.62

Source: DNV GL (various sources)

5.9 WIND-ASSISTED PROPULSION

5.9.1 General

Wind-assisted propulsion is today considered a means to reduce a ship's consumption of fossil energy.

From the time man began travelling across large bodies of water until the advent of fossil fuels, sails were the primary means of ship propulsion. Today, the entire worldwide maritime trade relies on fossil fuels. As efforts to curb pollution and climate change intensify, the commercial shipping world is looking at wind as an inexhaustible power source, at least in a supporting role, with renewed interest.

Some of the sail technologies available today are the result of long-term development, driven in part by competitive racing such as the America's Cup (rigid wing sails), or by the need for short-handed automated sailing (DynaRig). Other, older developments were all but forgotten until rediscovered by the merchant shipping industry recently (Flettner rotor). Innovative approaches have been developed specifically for modern commercial ships (kites).

Practical experience exists with two of these methods, which are currently in use: kites, and the Flettner rotor. The DynaRig principle is being used by some large sailing yachts.

5.9.2 Details on specific subjects

Price

There are obviously no direct fuel costs involved in using wind to propel a ship. Most wind-assisted propulsion systems require a secondary source of energy to be operated:

- Flettner rotors need to be started up by motors to develop their aerodynamic thrust forces.
- Soft and solid sail systems require a certain amount of energy for hoisting and dropping as well as for position adjustments to achieve the optimum angle of attack.
- Kites need to be launched, inflated, controlled and retracted by external means.

In all of these cases, the amount of energy required for operation is very small in relation to the propulsion power these devices generate.

For calculating the business case, the availability of wind and therefore the operation area of wind-assisted vessels is the most relevant factor.

Flettner rotor

Wing sails

DynaRig

Kites

Infrastructure

There is no infrastructure required to make use of wind as an energy source. Specialized knowledge may be required for maintenance and repair work, most of which may not be possible on board. Depending on the size of an installed wind propulsion system, there may be restrictions for passing under bridges.

In addition, certain types of wind assistance systems may impede ship loading and unloading.

Regulations

The SOLAS Convention does not exclude the use of wind as a power source, provided a ship does not solely rely on it. In today's economic environment, cross-oceanic trade must adhere to strict schedules. Exclusive dependence on wind would not be feasible. Therefore a propulsion engine is required to compensate for or buffer time losses when wind conditions are inadequate.

Any evaluation of a potential wind application must account for the implications regarding the safety of seafarers and compliance with current international standards. Current energy efficiency regulations are not prescriptive.

The way the EEDI Index is determined leaves room for new technology developments and for the choice of means to achieve specific targets or objectives. This includes the potential use of wind as a power source, either in the form of wind propulsion systems or in hybrid systems.

There is no international rule for the design and construction of sail propulsion systems. However, DNV GL has issued Design Guidelines for Certification and Classification Procedures associated with:

- Flettner rotors (document MCADE0452-001)
- Wing rigs (document MCADE0452-003)
  installed on seagoing ships

A similar guideline for DynaRig systems is currently under development.

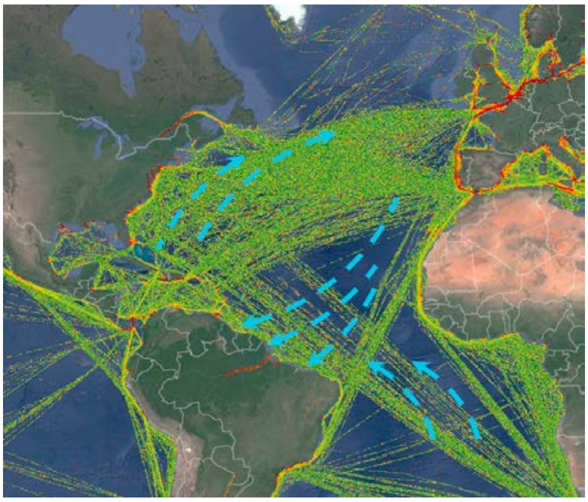
These technical standards may additionally serve as a means to satisfy statutory regulations and requirements, which may not necessarily in all aspects be prepared for wind-assisted propulsion.

A new DNV GL additional class notation "WAPS" (Wind Assisted Propulsion) for seagoing ships will soon be available.

Scalability

The availability of wind as a power source is unlimited. However, the quantity and quality of this energy source is not constant. As a meteorological phenomenon, the strength and direction of wind is subject to frequent change. Global trade routes with relatively constant, high wind conditions are best suited for profitable use of this energy source, especially when combined with weather routing based on global weather patterns and local forecasts.

FIGURE 15: HEATMAP OF VESSEL VOYAGES AUGUST 2015–2016 AND TRADE WINDS



Source: DNV GL

Environmental impact

A wind propulsion system can reduce fuel consumption. The energy savings achieved are directly proportionate to the reduction of fuel-related CO_2, NO_X, SO_X, particulate matter (PM) and other emissions.

Technology

After an absence of about 100 years, the rediscovery of wind propulsion for seagoing ships is tantamount to a relaunch of a forgotten technology.

Various technologies are currently in some kind of project or trial stage; some solutions are commercially available and can even be retrofitted. The following choice of technologies does not intend to exclude other, innovative or further developed approaches and does not claim to be comprehensive.

- The Flettner rotor, also called Flettner sail or rotor sail, is named after its German inventor Anton Flettner who developed the concept in the 1920s. Its physical principle consists in the generation of aerodynamic thrust using a rotating cylinder (Magnus effect). The technology is well developed, and Flettner rotors have been installed on eight ships since the time of their invention. A recent long-term test on board an MPV has produced very positive results in terms of fuel savings.
- Based on a design concept by German engineer Wilhelm Prölls in the 1960s, the DynaRig employs automated soft sails. It can serve as a ship's primary propulsion system when weather conditions allow, provided that the purpose and design of the ship are optimized accordingly. DynaRigs are currently commercially available for mega sailing yachts *(Maltese Falcon, Oceanco Y172)*, and there are projects to develop a DynaRig for seagoing ships.
- The rigid wing sail technology is based on the concept of using vertically-arranged, fixed symmetrical aerofoils on a ship to generate aerodynamic thrust. There have been numerous initiatives pursuing this concept but no full-scale installation on a commercial vessel.
- Kites use aerodynamic forces generated by producing an apparent wind speed higher than that experienced at a stationary position on board a sailing vessel, by causing the kite to enter a state of dynamic movement. Employment and deployment of a kite can be automated. The technology has been commercially available since the early 2010s.

$ CAPEX

Wind propulsion systems utilize renewable energy to assist primary propulsion units and save fossil fuel. The multitude of technologies and their varying dominance in connection with the drive to reduce energy consumption is too varied for this paper to provide detailed guidance regarding the costs involved, or a comparison thereof.

When conceptualizing a particular system, including all its parameters, ideally geared towards a pre-selected choice of trade routes, it is possible to estimate or determine investment expenditures as well as operational costs in addition to the fuel-saving potential.

$$ OPEX

OPEX are related to the maintenance of the wind-assisted propulsion system and the replacement of components at the end of their lifetime. Energy costs related to operation are small but need to be figured in nevertheless.

5.10 BATTERIES

5.10.1 General

Batteries and hybrid power plants represent a transformation in the way energy is used and distributed on board vessels. Electric power systems using batteries are more controllable, and easier to optimize in terms of performance, safety and fuel efficiency. As ship power systems become increasingly electrified, and as battery technology improves and becomes more affordable, new opportunities emerge.

Fully electric ships represent a leap forward in power system design, but at present they are only feasible in limited applications such as ferries and short-sea shipping. The feasibility of all-electric operation for other vessels is typically limited either by the size of the required battery system or its cost. Unsurprisingly, the same limitations apply to many other uses of battery systems, as well. Further research and development work is urgently needed to achieve significant improvements to this technology, and efforts are underway at many levels and in many industries.

5.10.2 Details on specific subjects

Price

Battery prices are decreasing rapidly – almost too fast for accurate characterization – while significant performance improvements can be observed at least in some market areas. These cost reductions are primarily driven by demand in the automotive and consumer electronics industries. Prices of market-leading lithium-ion battery cells have dropped by more than 50 per cent since 2016, but prices continue to range widely, dependent upon performance, technology and application. Total battery system prices for large-scale installations, such as in shipping, comprise both the lithium-ion battery cells themselves and the cost of system integration, including module construction, battery control hardware and software, power electronics, thermal management, and testing. The figure below indicates trends in battery cell pricing as well as potential trajectories for full maritime systems (AC, including power electronics).

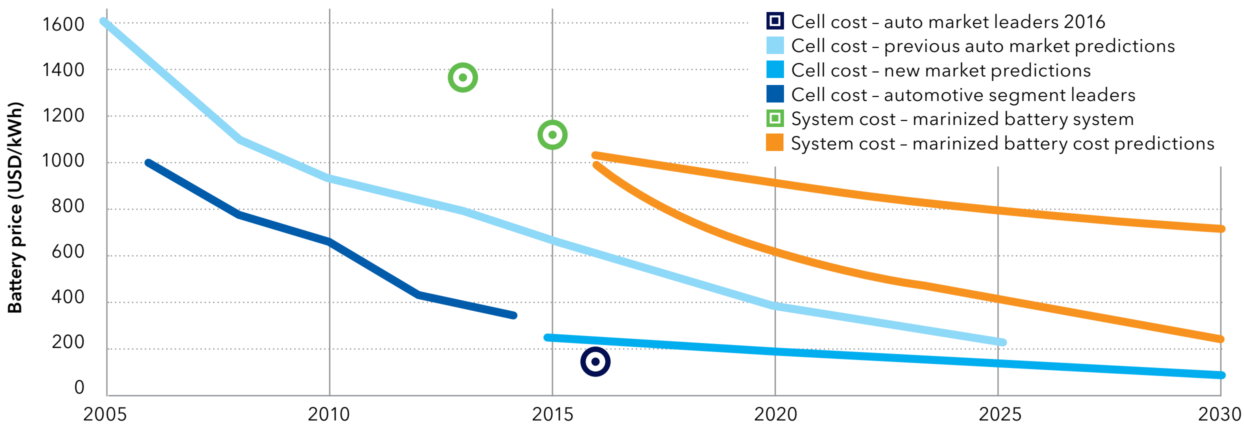
Carmakers have set a price goal of 100 USD per kilowatt hour, for lithium-ion cells by 2020, and based on market predictions this goal might be achieved. This development may correlate to maritime system costs as low as 200 USD/kWh, although additional cost margins may remain in place in this market segment. One primary objective for battery storage systems will be to further increase energy density for new applications, followed by a continued downward trend of prices, if at a lower rate.

Lithium-ion will likely remain the leading technology for many years. Other technologies may reach market maturity and supersede lithium-ion technology if they prove to be price competitive.

In terms of future price development, a closer look at the raw materials is instructive:

- Graphite is a widely-used material, with 70 to 80 per cent currently coming from China. Facing stricter environmental regulation, this may result in a price increase and the development of new mines.
- The cobalt market was previously small but is now growing rapidly. Over 50 per cent of the global cobalt supply currently comes from the Congo in Africa, with companies seeking more humanely-acquired alternatives.
- For lithium, large amounts exist but only one-third is considered economically accessible, primarily from salty, briny lakes, and the evaporation process can be lengthy. Still, based on total availability and underutilized sources in Chile, China and Australia, lithium supplies appear reliable for the long term.
- Nickel is a relatively expensive component in lithium-ion manufacture. It is a valuable metal used widely as a component of stainless steel. New demand from innovative technologies can cause price spikes, while an oversupply will cause prices to drop. Overall, the market is well-developed.

FIGURE 16: BATTERY PRICES



Source: DNV GL

Infrastructure

Given the absence of consumption costs, batteries do not face the same type of supply or infrastructure requirements as other, more traditional energy sources. The infrastructure required for battery systems on board ships mainly consists in providing an adequate charging grid. Depending on the application, the battery size and required charging times can increase power demand. For instance, charging 1,000 kilowatt hours (approximately equivalent to 100 litres of oil-based fuel) in 30 minutes requires 2,000 kilowatts of power; charging the same amount of energy in 10 minutes requires 6,000 kilowatts of shore power. This often puts a considerable load on the local electrical network and may require additional resources.

In general, the existing on-shore power supply infrastructure can be used to supply electricity to ships. Another key aspect is that a battery system is essentially a device that stores DC electricity and interfaces to the power grid with standardized power electronics hardware. This means that once the electrical system has been established for a given installation, it is nominally a straightforward process to replace the batteries with a new, updated or replacement technology. Therefore the electrical infrastructure for battery systems is easily reused and the nature of the technology enables a high degree of interchangeability.

Regulations

The primary focus of relevant regulations is the safety of battery systems and installations. DNV GL was the first classification society to develop such rules and is actively engaged in research programmes to continue refining and developing these requirements. Other classification societies have since developed rules of their own, but nothing noteworthy has been achieved at the IMO level so far. The year 2016 saw a significant increase in maritime-specific regulations, which have been very effective in producing systems capable of a high level of safety. It is likely that more economical ways of producing the same capabilities may be available in the future. Shore connections for charging are predominantly governed by regulations and requirements established for the electric grid.

Scalability

The consumer electronics and automotive industries are driving battery manufacture and cell development. For comparison, the entire accumulated megawatt hours of power of batteries currently deployed in the maritime industry represents less than 1 per cent of the amount of lithium-ion batteries produced in a single year. This means that the required volumes are readily available. However, getting manufacturers interested in the – currently rather small – maritime battery market could pose a challenge since systems typically utilize cells from vendors serving other large industries. However, the existence of many companies specifically serving the maritime sector seems to indicate a more than adequate manufacturing infrastructure.

Environmental impact

Batteries produce zero emissions during operation, but as with every production process, the manufacture of batteries is energy-intensive. Several studies have investigated the CO_2-equivalent emissions of both conventional and battery system life cycles. For the maritime case, as summarized below, the environmental benefit of batteries is overwhelming. In a study for the Norwegian NO_X fund, the environmental payback period compared to a traditional drive configuration was calculated for a hybrid platform supply vessel (PSV) and an electric ferry.

For the hybrid PSV, the environmental payback period for global warming potential (GWP) and NO_X is 1.5 and 0.3 months, respectively. For the fully electric ferry, the environmental payback period for GWP and NO_X is 1.4 and 0.3 months, respectively, when using the Norwegian electricity mix. For the EU electricity mix, the GWP payback time increased to 2.5 months, and for a global electricity mix to just under one year.

In addition, lithium-ion battery recycling has proven to be feasible, with several companies providing this service. The current focus is on aluminium and copper recovery, as this provides the greatest revenue stream, with the low price of mined lithium proving to be highly competitive. The full potential of such processes is limited primarily by the current low inflow of recycled, used or decommissioned batteries – refurbishment is presently a more common end-of-life service resulting in an even better environmental footprint.

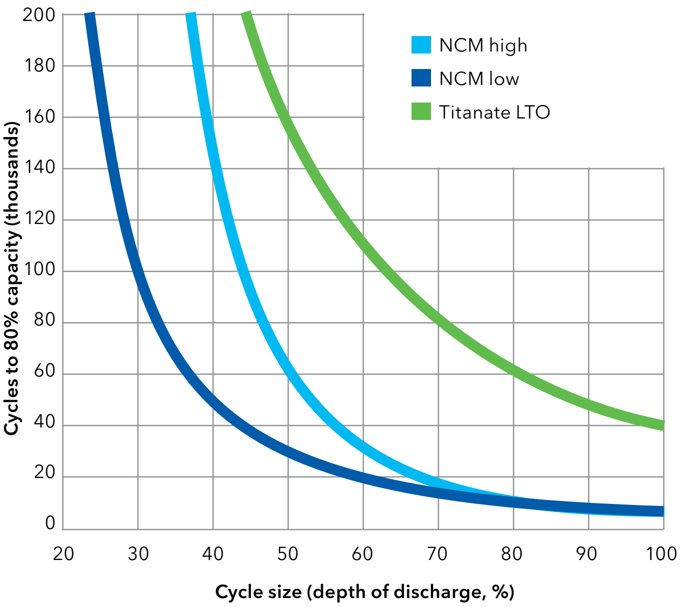
Technology

Developments during the past five years have occurred primarily as a result of improved manufacturing processes and quality control, as well as incremental improvements in existing (cathode) chemistries and combinations. It is important to note which there are many different types of chemistries that are considered "lithium-ion" and there can be significant differences in performance. In addition, depending on the vendor, even batteries with the same nameplate chemistry can have very different properties. Iron phosphate (LFP) and nickel cobalt manganese (NCM) have proven to lead the market. These developments have been paralleled with continually improving knowledge regarding the complex electrochemical processes of batteries, leading to optimized design and utilization. Additionally, new developments have now entered the market representing developments on the anode side – the use of silicon or titanium – representing the opposing objectives of more affordable energy density and high performance, respectively.

The stringent requirements of the maritime industry have greatly advanced the level of safety that lithium-ion battery systems can provide, particularly with regard to propagation and off-gas handling. Solid electrolyte technologies are among the most promising, pending advancements, and may present significant advantages with regard to safety. Although this advancement will need to prove capable of living up to the tough maritime performance requirements, the improved level of safety they may provide would certainly be an asset to the maritime industry.

Maritime applications are often much more demanding on lithium-ion battery performance than other industries such as consumer electronics or stationary/grid support. These needs depend on the application, but many maritime systems require much higher power levels and much longer life cycles than may be acceptable for other lithium-ion battery systems. These requirements represent a need in maritime systems that is a diversion from the pressure to improve cost and energy density, which drives much of the current technology development.

FIGURE 17: LIFETIME OF BATTERIES DEPENDS ON THE DEPTH OF DISCHARGE



Source: DNV GL

New technologies which may represent a large or disruptive change in the market may be as much as ten years away. The most evident technological advancements are expected to be the result of continued incremental improvements in terms of cost and performance of existing battery types. Furthermore, many of the technologies that appear to be on the horizon are likely to struggle with the maritime environment and application requirements, pushing their penetration of this market back further than others.

$ CAPEX

The lifetime of batteries is highly dependent on the duty cycle for which they are used, relative to the size of the battery. For instance, a smaller battery will have reduced CAPEX but will not last as long as a larger battery in a given application. Thus sizing is a key aspect of battery system procurement. DNV GL has performed testing and modelling using a verification tool called Battery XT to assess these complex interrelated aspects. The life cycle also depends on battery chemistry and varies significantly based on the manufacturer or vendor. Systems are most typically engineered and warrantied for ten years of operational life.

System integration costs for battery systems are often significant and should be taken into account at an early stage of adoption. Beyond the storage system purchase price (including power electronics), the total cost includes: purchase changes (PMS/IAS/DP), installation at yard (including electrical), FMEA, switchboard modification, commissioning and testing. All these collateral aspects combined can sum up to equal the cost of the full battery system itself.

For instance, a smaller battery will have reduced CAPEX but for a given application, will not last as long as a larger battery. Thus sizing is a key aspect of battery system procurement. DNV GL has performed testing and modelling using a verification tool called Battery XT to assess these complex interrelated aspects. The life cycle additionally depends on battery chemistry – there are many different types of lithium-ion batteries – and varies significantly based on manufacturer or vendor. Systems are most typically engineered and warrantied for ten years of operational life.

$$ OPEX

Apart from efficiency aspects, the OPEX costs are driven by electricity prices, which vary significantly from region to region. Norway prices are typically around 0.12 USD per kilowatt hour, while EU prices range from 0.09 to 0.30 USD per kilowatt hour. By comparison, marine diesel – assuming 11,800 kilowatt hours per tonne and an average price of

600 USD per tonne – comes at a cost of 0.05 USD per kilowatt hour. However, the efficiency of using electrical energy in a battery-driven ship is significantly higher than that of a conventionally-propelled ship, lowering energy consumption and cost. As a result, the OPEX of an electric ship can be lower than that of its conventionally-powered equivalent. The actual energy efficiency – or energy utilization – of an electrical propulsion system is approximately 76 to 85 per cent of the electrical energy provided from shore. In other words: the efficiency of battery systems ranges from 85 to 95 per cent (round trip), while power electronics often have a 95 per cent efficiency. Power taken from the shore will likely see losses of 15 to 24 per cent by the time it reaches the propulsion motors, depending on the associated components and operation. By comparison, diesel propulsion systems typically have an efficiency of 40 to 45 per cent, in part because of the redundancy requirements and low loading conditions. A battery system is consequently about twice as efficient as a diesel generator.

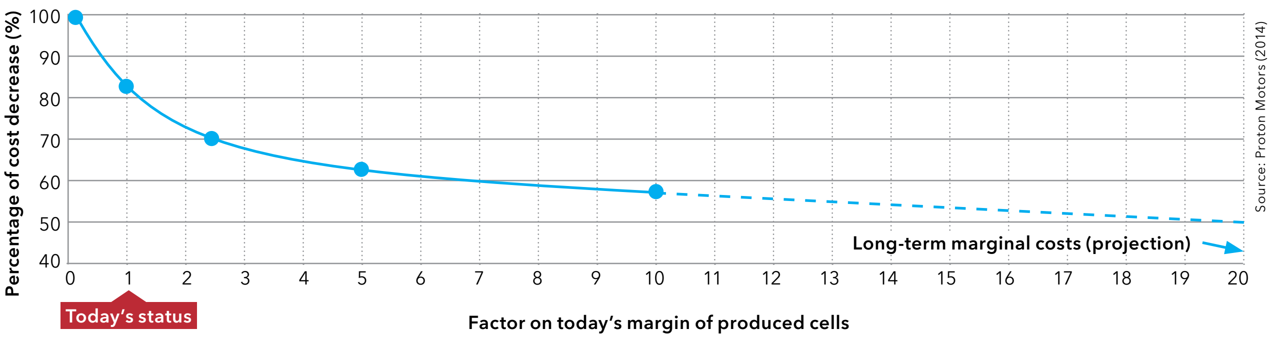
5.11 FUEL CELLS

5.11.1 General

Fuel cells offer high electrical efficiencies as well as lower noise and vibration emissions than conventional engines. The main components of a fuel cell power system are the fuel cells themselves, which convert the chemical energy stored in the fuel directly into electrical and thermal energy by electrochemical oxidation. This direct conversion enables electrical efficiencies of up to 60 per cent, depending on the fuel cell type and fuel used.

There are various fuel cell technologies under development. The chemical mechanism, working temperature, efficiency and fuel suitability depend on the material used in the fuel cell. Maritime development projects and feasibility studies[1] have shown that the three most promising fuel cell technologies for maritime use are the solid oxide fuel cell (SOFC), low-temperature proton exchange membrane fuel cell (LT-PEMFC), and high-temperature proton exchange membrane fuel cell (HT-PEMFC).

FIGURE 18: POTENTIAL SCALE EFFECTS OF MASS PRODUCTION ON FUEL CELL STACK COSTS



Source: Proton Motors

[1] DNV GL on behalf of EMSA: Study on the use of fuel cells in shipping
[2] DNV GL rules for classification, Part 6, Chapter 2, Section 3 "Fuel Cell Installations – FC"

All fuel cells need a hydrogen-rich fuel for the chemical process. Apart from the use of pure hydrogen, chemical reactors (fuel reformers) are used to convert other fuels such as natural gas, methanol or diesel to hydrogen-rich fuel for the cells.

The fuel reforming process can involve a small amount of fuel combustion. The greater part of the fuel is used in a combustion-free electrochemical process in the fuel cell. Consequently, fuel cell technology can reduce emissions to air significantly.

5.11.2 Details on specific subjects

Price

Mass production, which is expected to occur beyond 2022, should allow production costs to reach a competitive level, as shown in Figure 19 below. Development projects are underway, and the most promising project for maritime fuel cells, e4ships, is aiming for a market launch in 2022. With increased production, the impact of material costs will become a dominant factor in fuel cell prices. Maintenance and operational costs will reach a competitive level after fuel cell durability reaches the same level as the longevity of combustion engines.

Infrastructure

As for conventional maritime technologies, the provision of infrastructure for fuel cell power systems depends on the availability of maintenance and repair components and services. Relevant services are currently provided by the fuel cell manufacturers themselves. With the exception of fuel cell systems for military submarines, all present fuel cell systems in shipping are non-commercial prototype installations. Commercialization will include guarantee and lifetime technical support. A service network comparable to the existing network for diesel engines has yet to be established, but infrastructure development is expected to start at the time of the prospective market launch after the year 2022.

Regulations

The international rule base for the design and construction of maritime fuel cell applications is currently under development at the IMO as part of the International Code of Safety for Ships using Gases or other Low-flashpoint Fuels (IGF Code). Existing class rules form the basis of special permits. The current international regulatory framework is geared towards combustion engines. Apart from some class rules[2], there is no binding international regulatory framework for maritime fuel cell applications.

The requirements for fuel cell installations currently under development at the IMO might be integrated into the IGF Code in 2028 at the earliest. Fuel storage and fuel supply systems must comply with the related chapters of the IGF Code, which currently covers LNG and compressed natural gas (CNG). Regulations for methanol and low-flashpoint diesel are likewise under development and may be included in the 2028 revision of the IGF Code, as well. Interim guidelines will be published for fuel cells and methanol fuel to give temporary guidance for approval until the related IGF Code chapters are finalized.

Scalability

Fuel cell systems are currently available in small numbers from several manufacturers.

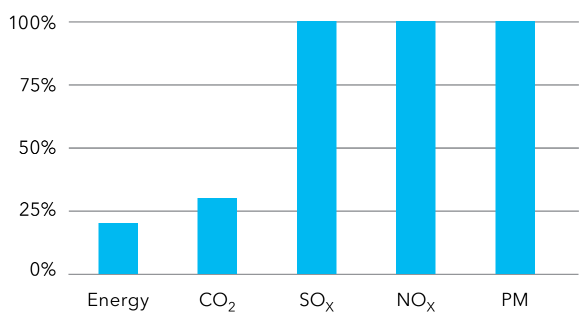
While the availability situation for materials for fuel cells themselves is not critical, the availability of suitable fuels in larger amounts will be essential for the technology to be adopted widely.

Environmental impact

The fuels typically used in fuel cells eliminate emissions of NO_X, SO_X and particulate matter (PM) nearly to zero. Due to the high efficiency of fuel cells, a reduction of CO_2 emissions by 30 per cent is possible when using hydrocarbon-based fuels like natural gas or methanol. An example is shown in Figure 19. When using pure hydrogen as a fuel, tank-to-propeller (TTP) emissions of CO_2, NO_X, SO_X and PM are zero.

FIGURE 19: ENERGY AND EMISSION REDUCTION POTENTIAL OF A TYPICAL CRUISE SHIP USING FUEL CELLS

Assumption: HT-PEMFC with methanol as fuel; exhaust gas energy of fuel cell used for processes on board



Source: e4ships lighthouse project

Technology

In the maritime industry, there are currently only small fuel cell applications in operation with an electrical power output of up to 100 kilowatts. Several development projects are underway, including a Norwegian fuel cell hydrogen ferry aiming to start operation in 2021, and e4ships, scheduled for market launch in 2022. It should be noted that the lifetime of fuel cell systems and reformer units has not yet been shown to be satisfactory. A methanol fuel cell system has been in operation on board the passenger ferry *MS Mariella* since 2016. The vessel, operated by Viking Line, runs between Helsinki and Stockholm.

Another methanol fuel cell system is installed on board *MS Innogy*, an inland passenger vessel operated by the White Fleet Baldeneysee and Innogy. Presumably the first commercial hydrogen fuel cell ferry, the Water-Go-Round in San Fransisco Bay, is expected to start operating in 2019.

Proton exchange membrane (PEM) technology in particular has reached a development level comparable with the dimension of automotive engines and capable of handling ship load changes well.

Fuel cells combined with batteries (and possibly super capacitors) adding peak-shaving effects are a promising option. Even proton exchange membrane fuel cells (PEMFC), thanks to their flexible materials, could improve fuel cell lifetime significantly when protected against the harshest load gradients. Solid oxide fuel cells (SOFC) must be applied in a hybrid environment using peak-shaving technology to be a realistic alternative for shipping.

CAPEX

Fuel cell technology is still under development. Current installation costs are between 2,200 and 5,600 USD per kilowatt of installed electrical power. Ongoing developments aim to reduce installation costs by up to 1,000 USD per kilowatt of installed electrical power by 2022 to be competitive with modern diesel engine installations. The reason PEM cells are dramatically cheaper than other fuel cell types is the automotive industry’s massive investments in this technology over the past 15 to 20 years. While still too expensive for the car market, the cost of PEM fuel cells has dropped to a level that is attractive for ship applications.

The expected cost of automotive PEM fuel cell systems based on current technology is approximately 280 USD per kilowatt when manufactured at a volume of 20,000 units per year. This number reflects the cost of the complete fuel cell system. To build a complete ship system that meets regulatory requirements it will be necessary to integrate additional safety and interface components. Similar strategic goals are being pursued in Europe: in its 2016 annual work plan and budget, the Fuel Cell and Hydrogen Joint Undertaking (FCH JU) aims to achieve a fuel cell system production cost of 100 USD per kilowatt at an annual production output of 50,000 units.

$$ OPEX

The overall efficiency from fuel to propeller is slightly higher for fuel cells than for combustion engines. The operational costs will be competitive when:

- fuel cells reach about the same durability as combustion engines before requiring a general overhaul,
- the cost and time of a fuel cell exchange are equal to those of a general engine overhaul, and
- the primary fuel prices will be competitive with MGO.

It should be noted that fuel cells may require less maintenance than conventional combustion engines and turbines.

6 WE SUPPORT YOU TO MAKE THE RIGHT

DNV GL ACADEMY

The DNV GL Academy offers a training course designed to help overcome the challenges the challenges of fuel switching in ECAs by discussing the issues related to the change-over in detail.

Air pollution from ships in practice
The course objective is to gain advanced knowledge about exhaust emission legislation, abatement technology and alternative fuels.

Low-sulphur fuel – basics and experience
Participants will gain detailed knowledge for managing the international requirements regarding sulphur reduction for ship newbuildings and ships in service.

Gas as ship fuel
The course will give participants an overview about the current developments in the field of gas as ship fuel.

SO_X Exhaust Gas Cleaning (EGC) – in practice
Become familiar with different SO_X EGCs technologies available on the market, and understand applicable requirements regarding SO_X EGCs according to MARPOL Annex VI and MEPC.259(68).

For more information, please visit our training web page: **www.dnvgl.com/maritime-academy**

ADVISORY SERVICES

DNV GL Advisory can support customers in a variety of services of services for assisting with the upcoming the upcoming fuel shift. For optimized compliance, we provide low sulphur decision-making support tailored to your specific conditions, operation and requirements.

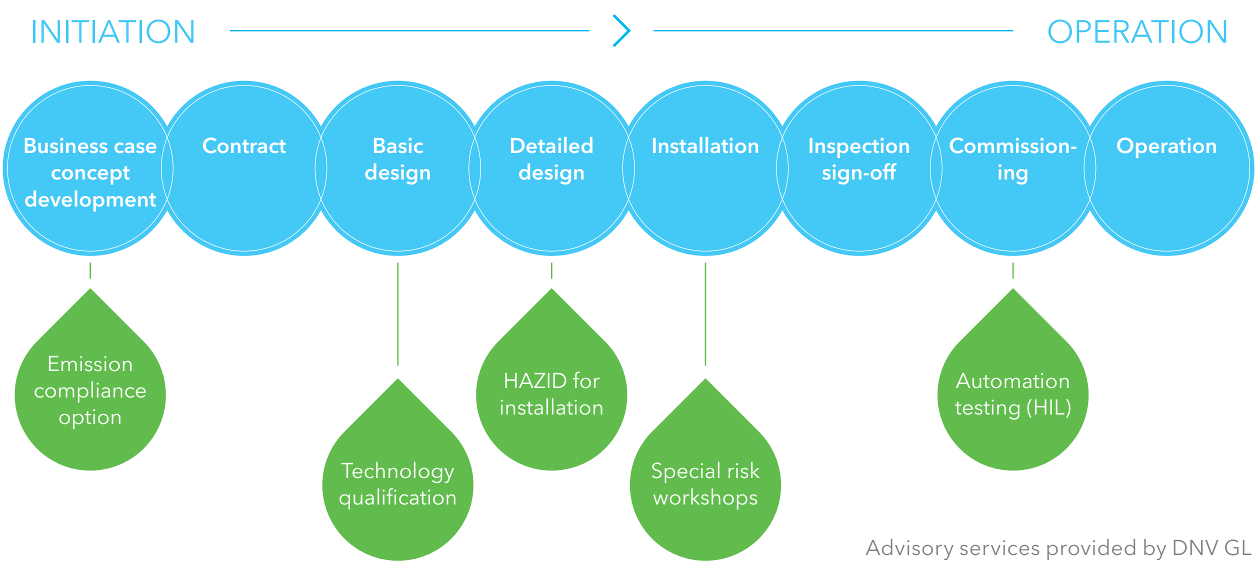
To comply with stricter environmental regulations and limit costs, shipowners need to evaluate alternatives to traditional fuels and technologies. But which option is best for a ship's actual operational setting?

As marine and industrial engineers, economists and environmental specialists, DNV GL has the deep knowledge across multiple disciplines to offer reliable solutions.

We advise the maritime sector on environmental regulations and compliance options, we measure and benchmark your environmental performance, support you in making the best business decisions on environmental technology, and help turn environmental performance into a marketing advantage.

As a designated technical advisor for various governmental initiatives to reduce ship emissions, we have deep knowledge of the regulatory policies and technical solutions.

If incidents damage the fuel systems and other related systems, we can help alleviate the problem. We have a wide range of experience with trouble- shooting, both on a design level and on board the ship. DNV GL



Advisory services provided by DNV GL

DECISION

engineers can help customers to find root causes for the problem and recommend modifications to reduce future damage in terms of costs and/or even off-hire.

For more information, please contact **environmentadvisory@dnvgl.com**

Our services in environmental technology and alternative fuels include:

Fuel changeover calculator (FCO)
DNV GL's ship-specific FCO plots a complex numerical simulation of the fuel changeover process from conventional HFO to ultra-low sulphur fuel oil, which is typically marine gas oil (MGO). It promises a very accurate calculation and potential cost savings compared to a linear model, and also takes into account recommended maximum temperature change per minute. The FCO also offers a comprehensive package to account for documentation requirements. Receive more information at: www.dnvgl.com/maritime/advisory/Fuel-change-over-calculator.html

Fuel strategy and decision support
The decision of the IMO to limit fuel sulphur content from 1 January 2020, the sulphur and NOX in ECAs, and the recently adopted ambition to halve GHG emissions by 2050 mean the world's future fleet must rely on a broader range of fuels and adopt novel propulsion solutions and energy efficiency measures. Based on the experience from hundreds of feasibility studies and independent research work DNV GL offers a well proven structured approach to benchmarking and selection of alternative fuels and technologies for newbuild and existing ships:

- Technical feasibility study with energy/fuel storage requirements, suitable tank locations and engines etc. based on client's operational profile.
- Financial benchmarking including CAPEX and OPEX estimates and fuel price scenarios

Emission analyses and assessments
We conduct tailor-made studies on fuels, technologies, regulations, emissions and environmental accounting, policy instruments and activity-based ship data (AIS).

Alternative Fuels Insight (AFI) platform
The AFI platform (https://afi.dnvgl.com) provides a 360-degree view on the uptake and infrastructure development of alternative fuels and technologies in shipping. The information is free and available to the public. AFI offers detailed insight in interactive map and statistics views, in addition to the information needed for improved decision-making regarding alternative fuels for vessels ordered today and in coming years.

Assessing robustness of newbuilding strategies – The Carbon Robustness framework
Moving forward the uncertainty facing the industry seem only to increase, with potential for big shifts. It is not clear which fuels and technologies will win in the short or long term. How to choose a robust design for ships ordered today? To help navigate this future, and manage the uncertainty, DNV GL has developed the Carbon Robustness framework to assist ship-owners in "future proofing" their vessels to secure long-term competitiveness and profitability. The framework test competitiveness for individual designs under different scenarios – taken into account: Fuel & technology, Regulations, and Risk related to market. The main idea is to assess the competitiveness of your designs, against a fleet of competing ships in the short or long term perspective. For more details, visit https://eto.dnvgl.com/2018/maritime.

Technology qualification
Determination of whether a solution is fit for its given purpose. Risk identification and risk reduction through failure mode, effect and criticality study (FMECA), hazard identification study (HAZID) or hazard and operability study (HAZOP).

Triple-E
Triple-E is an environmental and energy efficiency rating scheme for ships. As an independent verification tool, it measures a vessel's environmental performance, covering management, operation and design.

Control system software testing
The verification and testing of control system software using Hardware-in-the-Loop (HIL) technology will result in safer and more reliable automation systems and shorter commissioning times due to less software issues. Any control system can be tested, e.g. EGCS/ scrubber, SCR, LNG as fuel, energy management system, ballast water treatment system.

7 DNV GL CLASS SERVICES

Based on years of experience, DNV GL has developed several class notations to support the switch to low-sulphur fuels, preparing shipowners for lower sulphur limits and more. The notations are briefly described below.

Gas Ready notation

LNG as ship fuel is spreading rapidly through the maritime world. To be more flexible and competitive, you need to ensure your newbuilding is ready for future LNG conversions. Based on the experience we have gained from our LNG Ready Service, as well as the 50 LNG-fuelled vessels we already have in class with our Gas Fuelled notation, we have developed the new Gas Ready notation. This notation enables you to ensure that a future LNG-fuelled version of your vessel complies with the relevant safety and operational requirements. It also helps you specify and quantify the level of investment you are making at the newbuilding stage.

The basic notation – with nominators D and MEc, GAS READY (D, MEc) – verifies that the vessel is in compliance with the relevant rules in terms of its overall design for future LNG fuel operations, and that the main engine can be converted or operate on gas fuel.

You can also choose to add extra optional levels to the newbuilding under the notation – putting the vessel further along the LNG track and thereby speeding up and simplifying a later conversion.

Scrubber Ready notation

DNV GL has created a class notation to help ship owners prepare their newbuildings for the installation of a scrubber. It ensures that the necessary preparations are in place for a smooth and cost-efficient scrubber retrofit at a later stage. The notation can be awarded to ships that have planned and partly prepared for the installation of an exhaust gas cleaning system (EGCS) for the removal of SO_X at a later date. The notation identifies the general type and category of scrubber systems that can be installed on the vessel. It also details the level of scrubber readiness, with the minimum scope attesting that the space available and future installation arrangement meet class and statutory requirements. This can be expanded to include more extensive preparations, through to a complete review of the scrubber documentation according to main class rules, including the certification and installation of piping and subsystems. For shipyards, working with the Scrubber Ready standard gives an easy framework within which to offer future-ready ship designs to the market.

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Gas Fuelled notation
The Gas Fuelled notation's requirements cover all aspects of the gas-fuel installation, from the ship's gas-fuel bunkering connection all the way up to and including all gas consumers. The rules are applicable to installations where natural gas is used as fuel. Other gases are subject to special consideration. The class notation is mandatory for any newbuilding being built with gas as fuel, either with gas-only or dual-fuel concepts.

Low Flashpoint Liquid (LFL) fuelled
Methanol is a low-flashpoint liquid (LFL) fuel that is gaining interest in the market because it does not contain sulphur and can therefore meet the existing 0.1 per cent SO_X limit in Emission Control Areas as well as the global sulphur cap. Methanol has a flashpoint of about 12 degrees Celsius, and therefore some additional requirements are needed to make the installations as safe as a conventional fuel oil system.

DNV GL can rely on long-standing experience with LFL cargo handling on board chemical tankers and offshore supply vessels designed to transport low flashpoint cargo. DNV GL also has 15 years of experience working with alternative fuels, in particular in gas-fuelled ship installations, and developed an appropriate class standard. The class notation "LFL fuelled" is mandatory for ships using methyl alcohol or ethyl alcohol as fuel.

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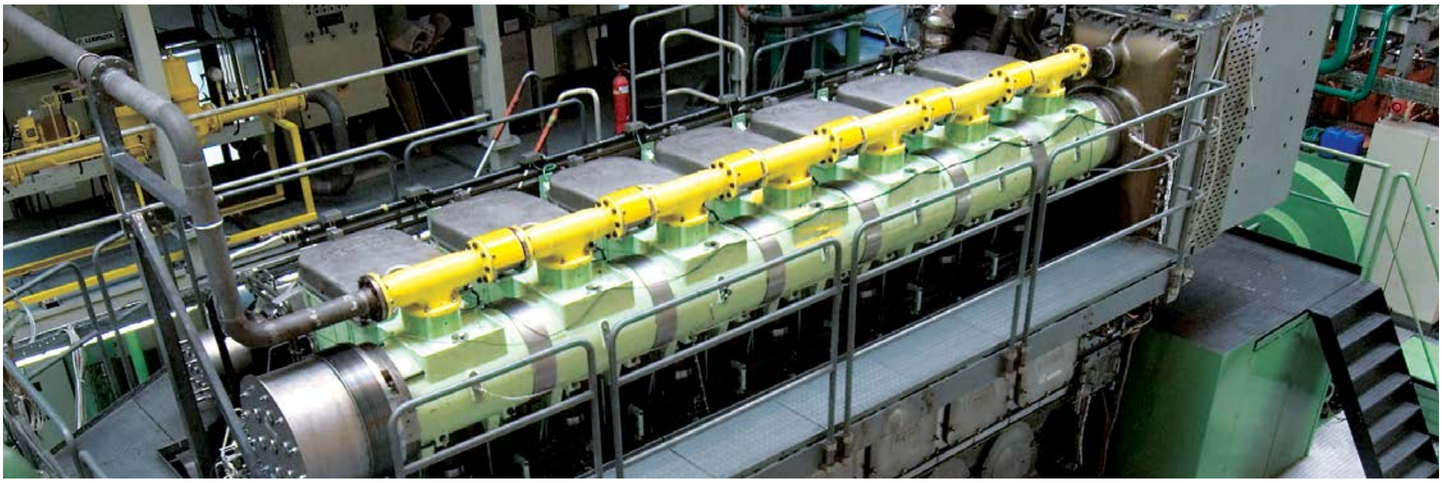
ENGINES FOR GAS-FUELLED SHIPS

The engine technology to use natural gas as ship fuel is available today. A wide range of engines in all power ranges are on the market. This article highlights the basic working principles of the different engine types and indicates the positive effects on emissions to air gained through switching from oil-based fuel to natural gas.



Engines for gas-fuelled ships

The use of gas as a ship fuel outside of the LNG carrier business is a young technology, as are gas/dual-fuel engines. While gas engines have been used in industry for decades, the first non-LNG carrier vessel, the LNG-fuelled ferry *GLUTRA*, with gas engines and storage, came into service in the year 2000. The engines of this vessel are pure gas Otto-cycle engines. The Mitsubishi GS12R-PTK ultra-lean-burn natural gas engines in a V12 configuration attain a power output of 675 kilowatts at 1500 rpm.

Four-stroke gas engines on board the MS *GLUTRA*.

The engine room configuration of the *GLUTRA* is an ESD engine room configuration, as currently defined in the IMO IGF Code. Since *GLUTRA's* first sailing, some 50 more LNG-fuelled vessels have come into service – 35 since 2010.

It should be noted that until 2013, all vessels operated in Norwegian waters. In 2013, the Fjordline Cruise ship-like ferry *Stavangerfjord* started operating between Denmark and Norway. The *Viking Grace*, which is a similar ferry, operated by Viking Line came into service between Stockholm and Turku, and the fast ferry Francisco operated by Buquebus started operating between Buenos Aires and Montevideo. Today, the orderbook for the next four years contains approximately 70 vessels, with 14 container ships among them.

The *Stavangerfjord* uses Rolls-Royce gas engines, while the *Viking Grace* uses Wärtsilä dual-fuel engines. Both engine types are four-stroke Otto-cycle engines, fulfilling the IGF Code requirements for the so-called inherently safe engine room. Wärtsilä was the first manufacturer to introduce four-stroke dual-fuel engines in 2005. Today, Wärtsilä, MAN, Caterpillar and HiMSEN are the most prominent manufacturers of dual-fuel engines.

Diesel-cycle and Otto-cycle processes: volume-pressure diagram

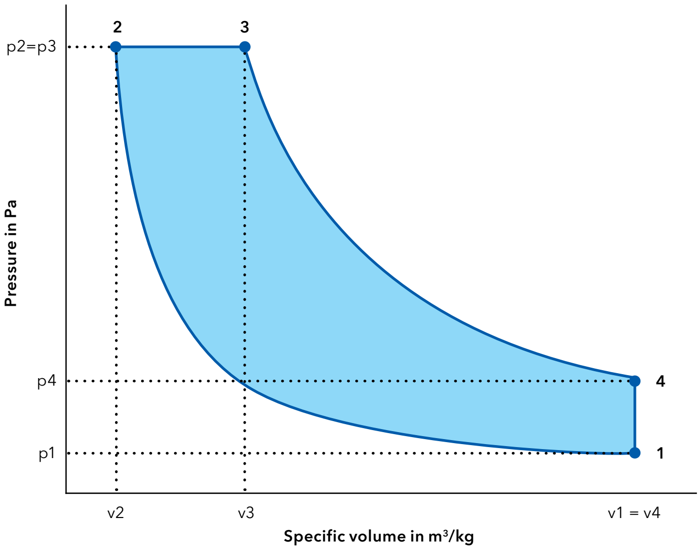


Figure 1: Dual-cycle process – constant pressure during combustion (2→3)

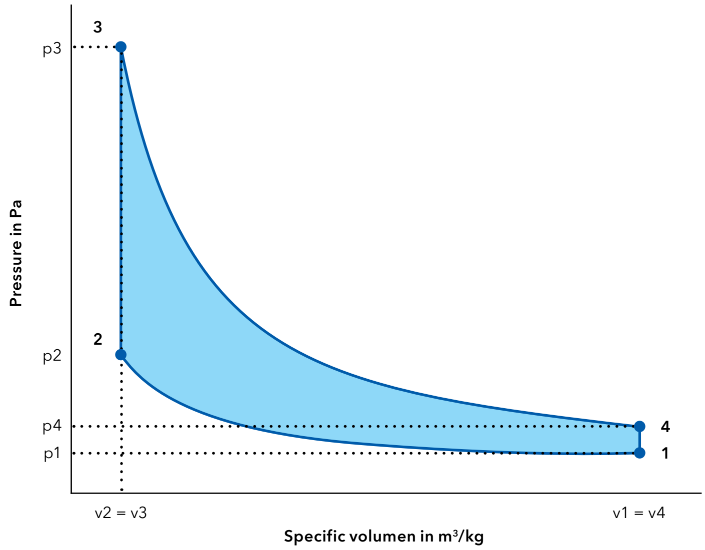


Figure 2: Otto-cycle process – constant volume during combustion (2→3)

The workhorse of shipping is the two-stroke engine. Two-stroke natural gas-fuelled engines have been available for the market since late 2012 when MAN presented their ME GI engine at HHI on 9 November 2012. Wärtsilä, as the second big player in this market, sold their first dual-fuel two-stroke engines in 2014 (RT-flex50, X62DF). The two-stroke technology for gas as a ship fuel has been on the market for less than two years. This short availability of this core technology has to be considered when looking to the relatively small number of ships already running on LNG.

Low pressure engine

All of the four-stroke engines available today are low pressure engines. The fuel/air mixture formation takes place outside of the cylinder behind the turbocharger. This means that the fuel gas pressure is approximately 5 to 6 bar, as it must be higher than the charge air pressure after the turbocharger. Nevertheless, the pressure is low and therefore the gas can be provided either directly from a pressurized storage tank or by use of a compressor. If a compressor is used, the specific energy consumption of the compressor is below 1 per cent of the lower heating value of the gas (Hu), even if 10 bar pressure is required as needed for the two-stroke low pressure engines from Wärtsilä. If the gas has to be compressed to a high pressure of 300 bar, the compressor's specific energy consumption will be much higher, approximately 4 per cent of Hu (Figure 4). This is the reason the two-stroke MAN engines use pumps to increase the pressure to 300 bar in the liquid phase and not in the gaseous phase of the fuel.

Engine operating principles

An overview of piston engine principles for gas-fuelled ships is given in Figure 3. The self-ignition temperature of natural gas stored as LNG is too high to be reached by the compression

Overview of piston engine principles for gas-fuelled ships

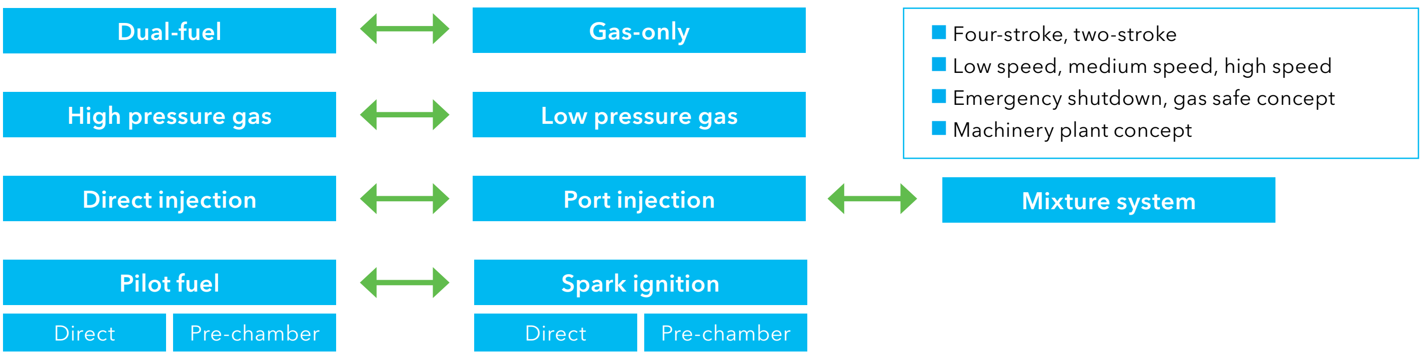
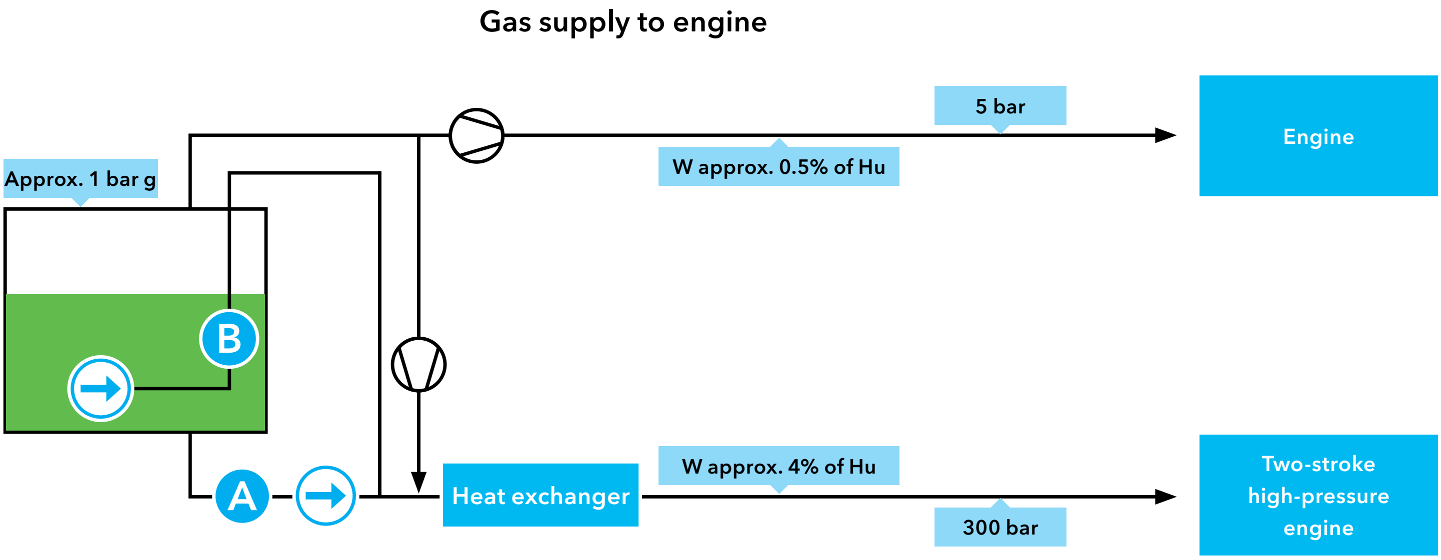


Figure 3



A Bottom line from tank (exclude loss of tank content in case of pipe failure)

B In-tank pump (redundancy required, boil-off must be handled separately)

Hu = lower heating value

Figure 4

cycle in the cylinder. Thus, the combustion must be initiated by an ignition source. Engines running only on gas use a spark plug to initiate the combustion process. The dual-fuel engines use so-called pilot fuel to start the combustion process. A small amount of pilot fuel is injected into the cylinder, where it is ignited by the high temperature of the gas air mixture at the end of the compression cycle. Typically, the amount of pilot fuel oil is below 1 per cent of the energy used by the engine.

DF engines run on gas or on diesel fuel. In gas mode, the engines run on the Otto-cycle and in diesel mode they run on the diesel cycle (refer to Figures 1 and 2). The main manufacturers of dual-fuel four-stroke engines are Wärtsilä, MAN and Caterpillar. It is also possible to run diesel engines partly on gas. In such engines, up to approximately 70 per cent of the energy is provided by gas and 30 per cent by diesel fuel. This option can, in particular, be a refit option for engines which cannot be converted to DF engines.

MAN and Wärtsilä also offer two-stroke engines for ship propulsion. The MAN engines compress the air, start the combustion process by injecting fuel oil and inject the gas into the burning air/oil fuel mixture. This also enables the operation according to the diesel cycle in gas mode and is the reason that the gas pressure must be high (300 bar for natural gas). The Wärtsilä engines inject the gas at the beginning of the compression after the air has entered the cylinder. At the low pressure at the beginning of compression, only a low gas pressure is required. The gas/air mixture is ignited at the end of the compression stroke by the pilot oil. The engine thus works as an Otto-cycle engine.

Emissions

Compared to HFO, LNG greatly reduces emissions to air (refer to Table 1). In terms of NO_x emissions, the four-stroke and two-stroke low-pressure engines reduce these emissions by 85 per cent compared to HFO. While the high-pressure two-stroke

ENVIRONMENTAL REGULATIONS		
Emission component	**Emission reduction with LNG as fuel**	**Comments**
SO_X	100%	Complies with ECA and global sulphur cap
NOx, low-pressure engines (Otto cycle)	85%	Complies ECA 2016 Tier III regulations
NOx, high-pressure engines (Diesel cycle)	40%	Need EGR/SCR to comply with ECA 2016 Tier III regulations
CO_2	25–30%	Benefit for the EEDI requirement, no other regulations (yet)
Particulate matter	95–100%	No regulations (yet)

Table 1

COMPARISON OF EMISSIONS FROM DIFFERENT FUELS					
	CO_2 equivalent [g/MJ] (Tab 3, DNV-2012-0719)			**% CO_2 (HFO = 100%)**	
Data from DNV No. 2011-1449, Rev. 1 (Tab 16 mainly); DNV NO 2012-0719	**Well-to-tank CO_2 emissions (WTT)**	**Tank To Propeller CO_2 emissions (TTP)**	**Total CO_2 emissions**	**% total**	**% Tank To Propeller**
Oil fuel (HFO)	9.80	77.70	87.50	100.00	100.00
Oil fuel (MGO)	12.70	74.40	87.10	99.54	95.75
LNG (from Qatar used in Europe)	10.70	69.50	80.20	91.66	89.45
LNG (from Qatar used in Qatar)	7.70	69.50	77.20	88.23	89.45

Table 2

engines still reduce NO_X by 40 per cent without exhaust gas treatment, particle emissions are reduced by 95 per cent and more. Because LNG does not contain sulphur, these emissions are eliminated completely. All emissions to the atmosphere relevant for human health and the so-called black carbon effect on global warming are reduced significantly by burning natural gas instead of HFO or MGO. As explained below, the effect on CO_2 emissions is also positive.

DNV GL evaluated the greenhouse gas emissions from production to the tank of the ship (well-to-tank [WTT]) and the emissions from the combustion of the fuel (tank-to-propeller [TTP]) in two studies in 2012. Methane has a much higher greenhouse warming potential than CO_2. The Kyoto Protocol gives methane a value that is 21 times the global warming potential (GWP) of CO_2. This means that an unburned methane molecule has 21 times the GWP of one molecule of CO_2.

A comparison of emissions from different fuels indicates that the WTT emissions for HFO, MGO and LNG are similar and small compared to the TTP emissions (refer to Table 2). For LNG, the methane slip has been considered for WTT and TTP. In the engine process, methane is mainly released as blow-by of the cylinders into the crankcase, valve overlapping effects and from incomplete combustion.

The DNV GL study assumed the methane slip for four-stroke engines at 1.5 per cent of the fuel. Taking this into account, the GWP is still reduced by 8 to 12 per cent, as can be seen in Table 2. The greatest reduction in greenhouse emissions is reached by the high pressure engines, which reduce the CO_2 effect by 26 per cent compared to HFO. ∎

SAFER, SMARTER, GREENER

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DNV GL
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