Summary

As the world moves towards greener solutions for reduction in pollution by any source, the transportation industry will be greatly affected and hence major changes are taking place throughout. From automobiles, logistics, aviation and each and every machine in the supply chain is looking to cut down the emissions.

Shipping contributes to 3% of the world's total manmade carbon emissions. 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.

The objectives of the paper are to provide decision support for investment in ships for the upcoming 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.

Marine fuel currently contributes approximately 3 per cent to global man-made CO2 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 CO2 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.

Introduction

IMO has made resolution to cut emissions by imposing restrictions on the fuel used. The 2020 Sulphur Cap has limited the use of sulphur fuels to 0.5% worldwide. Further on recently adopted ambition is to reduce GHG emissions to 50% by 2050. 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).

On application of the above restrictions related to sulphur from 1st January, 2020 70-88% of the fuel consumed onboard will be low sulphur fuel (0.1-0.5%). 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. 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.

The restrictions also imply in terms of carbon, nitrogen and particulates. In the advent of the decisions taken the industry is looking for solutions that are economically viable as well as environment friendly so as to form a win-win situation.

LNG-powered vessels have been in operation since 2000. As of 1 December 2018, 137 LNG-fueled ships were in operation and 136 newbuilding orders were confirmed.

Short sea shipping: 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.

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.

Alternative Fuels:

- LPG
- LNG
- METHANOL
- BIOFUEL
- HYDROGEN

Newly proposed technologies

- Batteries
- Fuel cell
- Wind assisted propulsion

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.

CO2 Emissions:

GHG emissions are measured as CO2 equivalent emissions. Of all relevant fossil fuels, LNG produces the lowest CO2 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 (CH4) has 25 to 30 times the greenhouse gas effect compared to CO2. Nevertheless, engine manufacturers claim that the tank-to-propeller (TTP) CO2-equivalent emissions of Otto-cycle dual-fuel (DF) and pure-gas engines are 10 to 20 per cent below the emissions of oil-fueled engines.

The comparison between the CO2 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 CO2 reduction potential. However, liquefied methane produced from biomass (biogas) has extremely high CO2 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.

NOx Emissions:

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 NOX limits.

Overall Emission Behavior:

Diesel Cycle (HFO):

- Cost added
- Addition of EGR and Scrubbers

Diesel Cycle (LSHFO/HFO):

- SOx emission compliant
- NOx reduction techniques required

Diesel Cycle (LNG):

- Zero SOx emissions
- EGR/SCR still to be used to reduce NOx emissions
- Zero methane slip achieved in High Pressure Diesel LNG cycle

Otto Cycle (LNG):

- Medium speed and low speed (LNG & DF engines)
- Meets NOx Tier III without additional requirements
- 10-20% reduction in CO2 emission compared to oil-fueled engines.

Fuel Pricing:

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.

- Market Conditions
- Distribution Facilities
- Ease of availability of fuel
- Source of production (e.g. Hydrogen produced from renewable sources is expensive & cheaper comparatively when produced from LNG)

Fuel Availability:

The use of alternative fuels can meet the demands of the shipping industry in the upcoming years but availability of the fuel with ease depends on the demand. A particular fuel may catch attention of the ship owner's but its availability then becomes the deciding factor.

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.

Concluding Remarks:

Environmental and price challenges are driving the interest in alternative ship fuels, but the number of realistic candidates is small. 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.

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 CO2 reduction. CO2-neutral shipping seems possible only with fuels produced from renewable sources. If the shipping sector resorts to synthetic fuels produced from hydrogen and CO2 using renewable energy, the available alternatives will be liquefied methane (which is very similar to LNG) and diesel-like fuels.

Alternative Fuels:

- Biofuel
- LNG
- Methanol
- Hydrogen
- LPG
- Batteries
- Fuel cell
- Wind assisted

International Regulations and Class:

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.

Brief Overview:

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*: CO2, NOX, SOX, 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

Reference Fuels:

HFO & MGO

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 (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 SOX 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 NOX-restricted areas. This means that ships keel-laid after 31 December 2015 must comply with Tier III NOX requirements. The same restrictions will apply in the North Sea and Baltic Sea from 2021 onward.

Scalability: 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: GHG emissions, SOx, NOx and particulates.

Technology: 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.

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 SOX 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

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).

LNG

The main component of liquefied natural gas (LNG) is methane (CH4), the hydrocarbon fuel with the lowest carbon content and therefore with the highest potential to reduce CO2 emissions (maximum reduction: roughly 26 per cent compared to HFO).

Using LNG as fuel consequently does not produce any SOX 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/m^3). This results in roughly twice the volume compared to the same energy stored in the form of HFO.

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.

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

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.

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.

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 SOX emissions related to it, particle emissions are very low, the NOX 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 CO2 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 NOX limit without requiring exhaust gas treatment.

Opex: Gas-fueled engine systems have about the same efficiency as conventionally-fueled systems. For this reason, the energy consumption of an LNG-fueled ship is roughly the same as that of an oil-fueled ship. Maintenance of a gas-burning engine may be less expensive thanks to cleaner fuel. Currently, the maintenance intervals of conventional and gas-fueled 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.

LPG

General: Liquefied petroleum gas (LPG) is by definition any mixture of propane and butane in liquid form. 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.

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: There is 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.

Regulations: 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.

Scalability: 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 CO2 emissions that are approximately 16 per cent lower than those of HFO. When accounting for the complete life cycle, including fuel production, the CO2 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 CO2. 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 NOX emissions depends on the technology applied.

SCR/EGR will still be needed to comply with the NOx regulations.

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 CO2 and hydrogen. This mixture can then be used in a regular gas or dual-fuel engine without derating.

. 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-fueled vessels without a scrubber system. Practical experiences are currently not available.

Methanol

General: Methanol, with the chemical structure CH3OH, 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.

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.

Price: 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.

I*nfrastructure*: 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: 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.

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 CO2 emissions (tank-to-propeller [TTP] value) by approximately 10 per cent compared to oil.

When considering the complete life cycle (well-to-tank [WTT] and TTP) including the production of the fuel from natural gas, the total CO2 emissions are equivalent to or slightly higher (in the order of 5 per cent) than the corresponding emissions of oil-based fuels.

It is also expected that particulate matter (PM) emissions will be significantly lower. The reduction of NOX emissions depends on the technology used. In the case of a two-stroke diesel engine, the NOX 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 NOX 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-fueled vessels without scrubber technology.

Biofuels

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.

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: 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: CO2 from the combustion of biological materials adds CO2 to the atmosphere similar to combustion of fossil fuels. However, CO2 emitted from combustion of biofuels is considered as part of the natural CO2 cycle in which an equivalent amount of CO2 is captured from the atmosphere by the feedstock plants as they grow. For this reason, bio fuels are regarded as CO2-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.

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 fueled 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.

Hydrogen

General: Hydrogen (H2) is a colorless, odorless 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 H2 (LH2) (71 kg/m3) 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.

Price: The cost of H2 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 H2 produced by electrolysis range from about 3.5 to 8.3 USD per kilogram (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 1.51 to 6.5 USD per kilogram (800 to 2,170 USD per tonne of fuel oil equivalent), averaging around 4.1 USD per kilogram (1,370 USD per tonne of crude oil equivalent). These cost estimates include production, compression, storage and transport.

Infrastructure: Today, most hydrogen is produced from natural gas using a related, mainly industrial, land-based infrastructure. Since there is currently no demand for H2 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 Kawasaki12) 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.

Scalability: More than 50 million tonnes of H2 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 H2 to the shipping industry.

Environmental Impact: There are energy losses associated with H2 production and possible compression or liquefaction. When H2 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 CO2 (CCS). Hydrogen used in fuel cells as energy converters does not produce any CO2 emissions and could eliminate NOX, SOX and particulate matter (PM) emissions from ships. Hydrogen-fueled internal combustion engines for marine applications could also minimize greenhouse gas (GHG) emissions, while NOX emissions cannot be avoided when using combustion engines.

Technology: Power generation systems based on H2 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-fueled internal combustion engines for marine applications are said to be less efficient than diesel engines. Hydrogen fueled 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-fueled engines. Storage tanks for liquefied hydrogen (LH2) 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 and 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-fueled 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.

Assessment of selected alternative fuels and technologies 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.

Other: 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).

Wind assisted propulsion

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

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.

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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.

Environmental Impact: A wind propulsion system can reduce fuel consumption. The energy savings achieved are directly proportionate to the reduction of fuel-related CO2, NOX, SOX, particulate matter (PM) and other emissions.

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.

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 preselected 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.

■ 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.

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.

Batteries

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.

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 marketleading 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.

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 oilbased 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 CO2-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 NOX 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 NOX is 1.5 and 0.3 months, respectively. For the fully electric ferry, the environmental payback period for GWP and NOX 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 con42 DNV GL – Maritime Assessment of selected alternative fuels and technologies tinually 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. 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 FIGURE 17: LIFETIME OF BATTERIES DEPENDS ON THE DEPTH OF DISCHARGE 20 30 40 50 60 70 80 90 100 Cycle size (depth of discharge, %) 0 20 40 60 80 100 120 140 160 180 200 Cycles to 80% capacity (thousands) NCM high NCM low Titanate LTO Source: DNV GL Assessment of selected alternative fuels and technologies DNV GL – Maritime 43 600 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 conventionallypowered 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.

Fuel Cells

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 studies1 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).

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.

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 rules2, 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 NOX, SOX and particulate matter (PM) nearly to zero. Due to the high efficiency of fuel cells, a reduction of CO2 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 CO2, NOX, SOX and PM are zero.

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.