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LPG AS A MARINE FUEL

SAFER, SMARTER, GREENER

LPG AS A MARINE FUEL

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CONTENT

BACKGROUND

Sulfur emission control areas (SECAs), in combination with the upcoming 0.5% global limit on sulfur, call for alternative fuels as a means for compliance. Several alternative fuels are available and at the same time more conventional fuel oil products with low sulfur content have been introduced. Alternatively, compliance may be achieved by using scrubbers to reduce sulfur emissions from the exhaust.

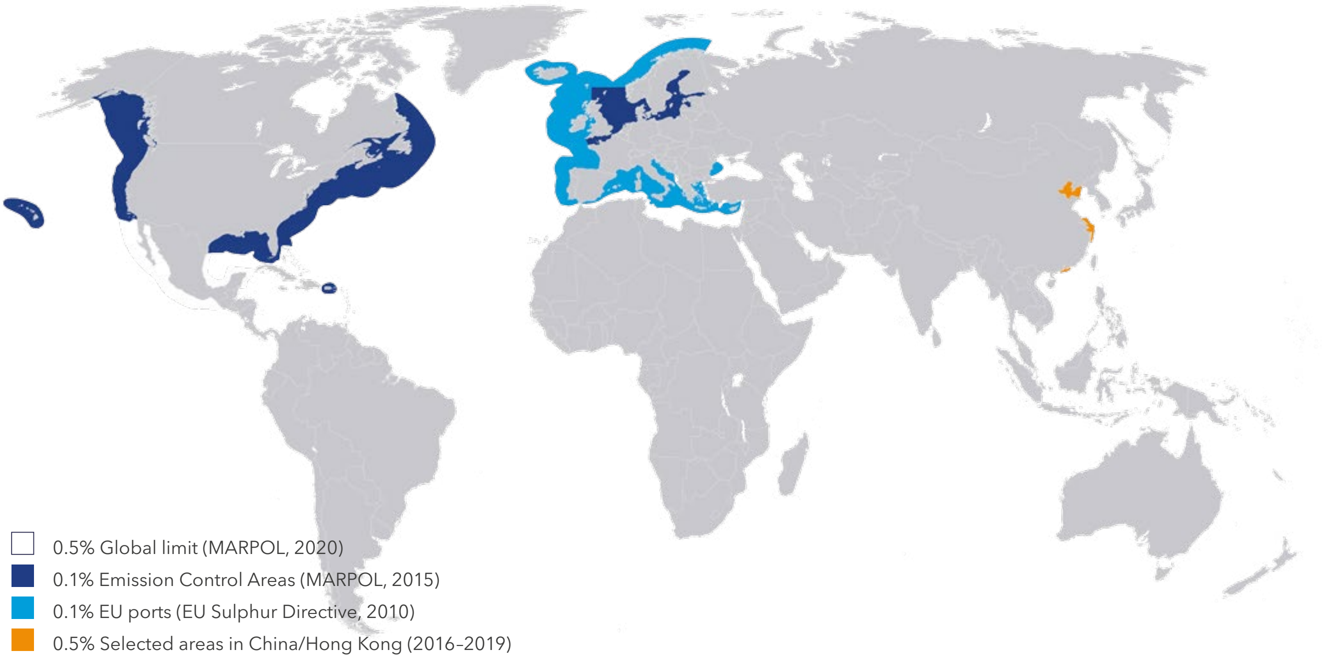

Figure 1: Sulfur Emissions Control Areas

SECAs, limiting sulfur content of maritime fuels to 0.1%, are in place in North-America (USA and Canada) and Northern Europe (Baltic Sea, North Sea and English Channel). Furthermore, three local sulfur control areas have been defined in China (Pearl River Delta, Yangtze River Delta and Bohai Bay) and the gradual introduction of 0.5% sulfur fuel is planned from 2016 to 2019, starting with the enforcement of low-sulfur fuel at berth in core ports from April 2016. At the 70th session of the IMO's Maritime Environmental Protection Committee in October 2016, it was decided to reduce the global sulfur cap to 0.5% from 1 January 2020.

There is a variety of alternative fuels that can be used for propulsion and power generation in shipping such as Liquefied Natural Gas (LNG), methanol, dimethyl ether, ethanol, Liquefied Petroleum Gas (LPG), biodiesel (renewable diesel, FAME-based biodiesel or diesel from Fischer-Tropsch-related processes), electricity, biogas, hydrogen and nuclear power.

Today, LNG is the most widely used alternative fuel. As of November 2016, there are 88 LNG-powered vessels in operation (excluding LNG carriers and inland waterways vessels), and 98 confirmed orders for vessels that will be built in the next few years.[1]

In March 2015, one passenger ferry, the Stena Germanica, operating between Gothenburg and Kiel, was converted and can use methanol or MGO. In April 2016, the first three of seven newbuild 50,000 DWT chemical tankers operated by Waterfront Shipping were launched, featuring two-stroke dual fuel engines that can run on methanol or fuel oil. In early 2015, the first fully electric ferry entered service in Norway. It is powered by three lithium-ion batteries with a combined capacity of 1,000 kWh, and can transport 120 cars and 360 passengers. It needs 20 minutes for a six-kilometre crossing of a fjord, repeated 34 times per day. There are currently many electric-ferries initiatives in Norway, Denmark and Finland. In 2016, several ferries in Norway replaced marine gasoil (MGO) with hydrogenated vegetable oil (HVO) after successful testing by the engine manufacturer.

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In a recent DNV GL – MAN joint study, it was concluded that on a cost basis, LPG is at least as attractive as LNG."

The ongoing developments in alternative fuels reflect the need to provide environmentally friendly transportation services while making best use of sustainable resources. Most likely, there will be different optimum solutions for different applications and different geographic areas, based on the local availability of fuels and particularities of each shipping segment. The fuels that will be able to meet these criteria at an affordable price are the ones that will be the established fuel options in the future. This also means that there will be a diversification of fuels to meet local conditions and requirements. As an example, with current technology, electricity can be a good solution for short fjord crossings in Norway, but not for larger vessels with higher speed requirements over much longer distances.

This inevitably raises the question of what the costs and benefits of each alternative fuel option are for different applications. Many studies have been performed on single alternatives or comparisons with a general focus on environmental impact and availability. Examples of such studies are position papers published by DNV GL in 2014 and 2015,[2,3] a MAN – GL joint study of LNG as fuel for container vessels released in 2012,[4] and a DNV GL – MAN joint study of alternative fuels for an LR1 product tanker completed in early 2016.

In the latter study, some of the most prominent alternatives for deep-sea shipping were considered, namely LNG, methanol, LPG, ultra low sulfur fuel oil and renewable diesel. It was concluded that, on a cost basis, LPG is at least as attractive as LNG in that it has shorter payback periods, lower investment costs and less sensitivity to fuel price scenarios.

This position paper provides an overview of aspects related to LPG as a marine fuel, including production and utilization, engine and tank technology, safety considerations, environmental performance, pricing, and financial feasibility.

PRODUCTION AND UTILIZATION OF LPG

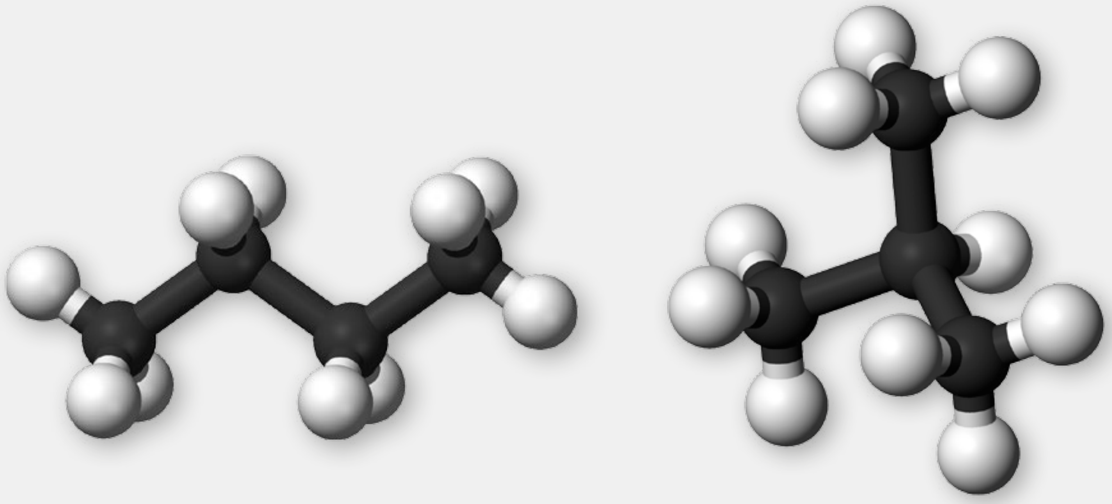


Figure 2: Chemical structure of n-butane (left) and isobutane (right)

WHAT IS LPG?

Liquified petroleum gas is by definition any mixture of propane and butane in liquid form. In USA, the term LPG is generally associated with propane.

Propane is a gas under ambient conditions, but it has a boiling point of -42°C and hence by applying a moderate pressure it can be handled as a liquid at room temperature. At pressures above 8.4 bar at 20°C, propane is a liquid. Propane tanks are equipped with safety valves that can open at pressures corresponding to temperatures in the range of 50 to 70°C, which keeps the propane pressure below about 25 bar.

Butane can take two forms, n-butane and isobutane, with boiling points at -0.5°C and -12°C, respectively. Since both isomers have higher boiling points than propane, they can be liquefied at lower pressure.

Due to the lower boiling point of propane, the propane content of LPG for use as fuel has to be higher in cold climates than in warmer ones.

A tank of LPG will typically have three times larger volume than a tank with oil-based fuel, even though the lower heating values of 46.3 MJ/kg for propane and 45.4 MJ/kg for butane are slightly higher than for oil-based fuels. This is partly because of the round shape of a cylindric tank and partly due to lower density. The densities of propane and n-butane are 0.49 kg/dm^3 and 0.57 kg/dm^3, respectively.

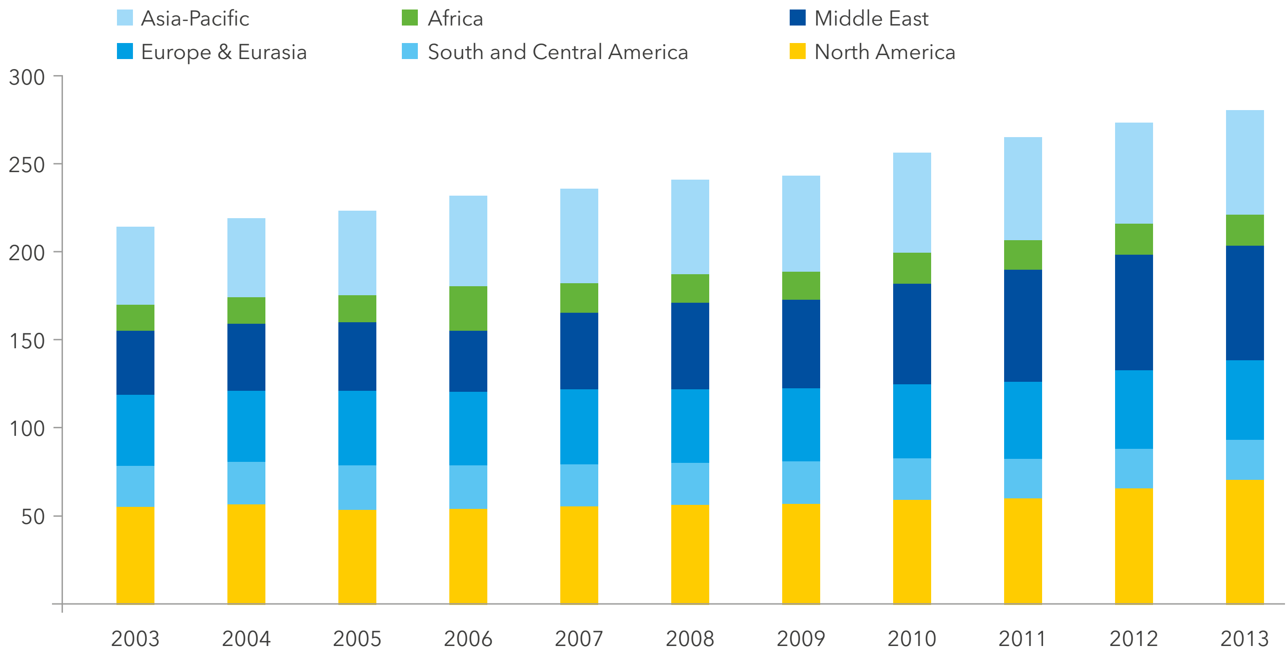


Figure 3: LPG production in different regions for the years 2003-2013.
Source: Argus Media: Statistical review of global LP gas 2014.[11]

PRODUCTION

There are two main sources of LPG: as a by-product of oil and gas production and as a by-product of oil refining.[6] Natural gas liquids (NGL) come from natural gas wells and associated gas from oil production. NGLs are treated to remove water, CO_2, N_2 and sulfur in a gas plant. Subsequently, propane and butane are separated from the other NGLs (ethane and natural gasoline), typically by refrigeration followed by distillation/fractioning. This is the source of approximately 60% of the global LPG production.[7]

Another source of propane and butane, corresponding to 40% of the total production, is as a by-product of various processes in oil refineries. The yield is approximately 1% to 4% of the crude oil processed, depending on the type of crude oil and sophistication of the refinery.

It is also possible to produce LPG from renewable origins, e.g. bio-LPG can be separated as a by-product in the production of renewable diesel by hydrogenation of the triglycerides of vegetable oil or animal fat.[8]

According to the World LPG Association,[9] the global LPG production in 2015, was 284 million tonnes, equivalent to about 310 million tonnes of oil by energy content, and is increasing by about 2% per year. In comparison, the fuel consumption in the maritime sector was estimated by IMO to be 307 million tonnes on average in the period from 2010-2012.[10] The production increase has been most profound in North America and the Middle East. The production increase in North America in the last few years can be attributed to the substantial increase in shale gas production, which has turned the USA into a net exporter of LPG since 2012.

Photo: BW LPG Limited

TRANSPORTATION

The global LPG trade was approximately 85 million tonnes in 2015 (Ref: BW annual report 2015),[7] and hence about one third of the LPG is exported. LPG can be transported by three different ship types, depending on how the cargo is stored:

- refrigerated, typically at -50°C at close to ambient pressure
- semi-refrigerated, typically at -10°C and 4-8 bar pressure
- under pressure, typically at 17 bar, corresponding to the vapour pressure of propane at about 45°C.

There are currently about 200 very large gas carriers (VLGCs) that can transport some 80,000 m^3 of LPG.[12] Semi-refrigerated ships typically have a capacity of 6,000 to 12,000 m^3, whereas compressed LPG ships typically take 1,000 to 3,000 m^3.

The transportation of LPG is covered by the International Code for the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk (IGC Code), which is aimed at the safe carriage of liquids with a vapour pressure above 2.8 bar at 37.8 °C, and applies to all ship sizes. If an LPG carrier was to be powered by LPG, this is in principle for this particular ship type covered by the IGC Code without having to comply with the IGF Code (International Code of Safety for Ship using Gases or Other Low-flashpoint Fuels). However, the IGF Code can be used for further clarification. For other ships, the use of LPG as fuel has to be covered through alternative compliance with the IGF Code.

UTILIZATION

Propane is mainly used for cooking, heating, petrochemical feedstock and as a motor fuel in some countries. Normal butane is used to blend in gasoline to add volatility, used as a petrochemical feedstock and to some extent also used for heating and cooking. Isobutane is used in refineries to make blending components for gasoline by alkylation.[6]

The largest use is domestic at 44%, followed by chemical industries 28%, industry 11%, refineries 7% and farms 1%.[7] Only 9% is used as transportation fuel, half of which is consumed in South Korea, Turkey, Russia, Thailand and Poland. However, its use as transportation fuel increased by 24% from 2009 to 2014.

The consumption pattern varies a lot from country to country, as indicated in Figure 4. Regionally, Asia is responsible for the largest share of LPG consumption at 36%, followed by North America, Europe, the Middle East, Latin America and Africa, as illustrated in Figure 5 for 2014.

AVAILABILITY

Global LPG production is at the same level as the fuel oil consumption in the marine sector (as well as the global production of LNG), and is increasing by 2–3% per year. Furthermore, LPG prices in the USA have dropped relative to crude oil prices since 2011, as explained in the section on LPG Pricing below. This indicates that there is sufficient availability to gradually introduce LPG into the maritime sector's fuel mix, but not to replace fuel oil entirely.

A large network of LPG import and export terminals is available around the world to address trade needs. Recently more LPG export terminals have been developed in the US to cover the increased demand for competitively priced LPG products. In Figure 6, import and export terminals of various sizes in Europe are shown to illustrate this point, while many other storage facilities can be found in several additional locations.[13] In these locations, it is possible to develop bunkering infrastructure by creating distribution systems in addition to the existing storage facilities.

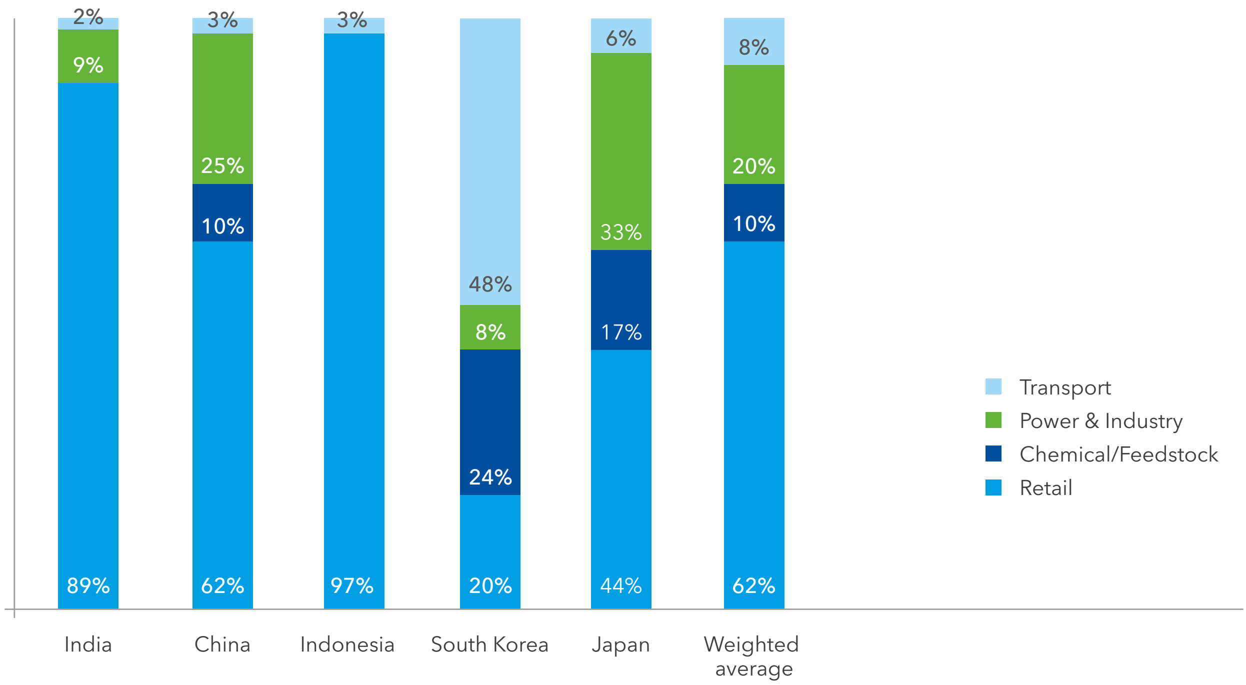


Figure 4: LPG consumption pattern in the main consuming Asian countries. Source: Argus Media: BW LPG Annual report 2015.[7]

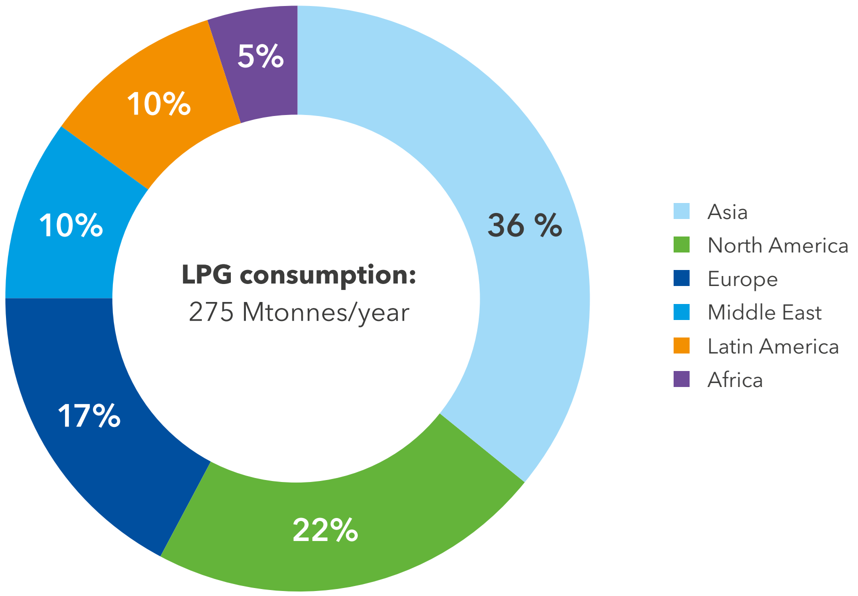


Figure 5: LPG consumption in different regions in year 2014. Source: Argus Media: BW LPG Annual report 2015.[7]

Figure 6: Overview of European import and export LPG terminals. Many more storage facilities of various sizes can be found in other locations.

LPG PRICING

Since 2011, propane has been sold in the USA, on an energy basis, at a discount to crude oil, but significantly higher than that of natural gas, as shown in Figure 7. In the years 2005 to 2010, the propane price closely followed the price of Brent oil. Since 2011, we have observed a decoupling of LPG and oil prices, and the reduction in the price of LPG may be attributed to the increased yield of propane from shale gas production. This development also resulted in the US turning from a net importer into a net exporter of LPG after 2011, as illustrated by weekly data from the EIA, presented in Figure 8. Similar data for n-butane also show a net export from the USA.

The drop in oil prices since 2014 has affected the prices of not only various oil-based fuels, but also natural gas, methanol and LPG, as illustrated in Figure 9. However, the extent to which each fuel has dropped in price varies, and the relative position of the fuel price has changed over time. For example, LPG prices are now at the same level as or lower than LNG prices in the USA. For the last few years, LPG has on average been cheaper than HFO in the USA. On the other hand, methanol has become more expensive than MGO in the last three years.

Normal butane has about 10% higher volumetric energy density than propane, but is typically more expensive. Furthermore, the high boiling point of normal butane prevents the use of pure butane in colder climates. Therefore, we expect the use of propane or a propane-rich mixture of propane and butane when LPG is used as fuel for ships.

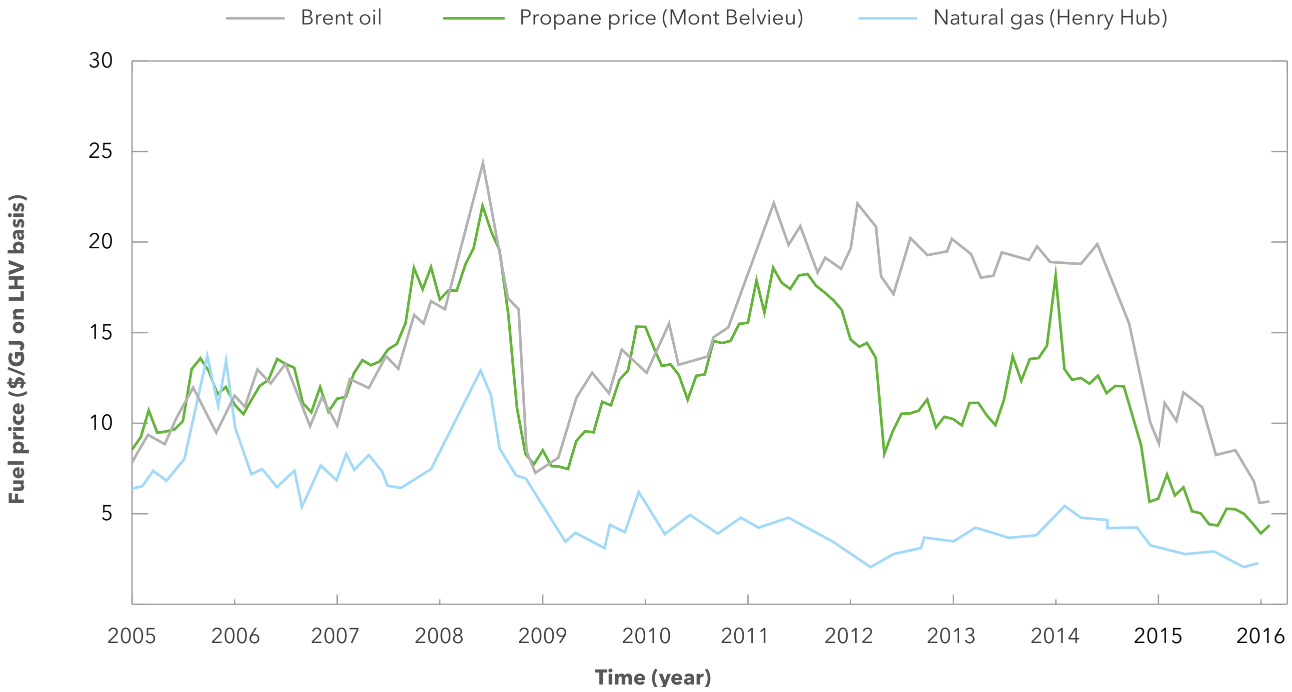


Figure 7: Historic prices of Brent oil, propane and natural gas, 2005-2015

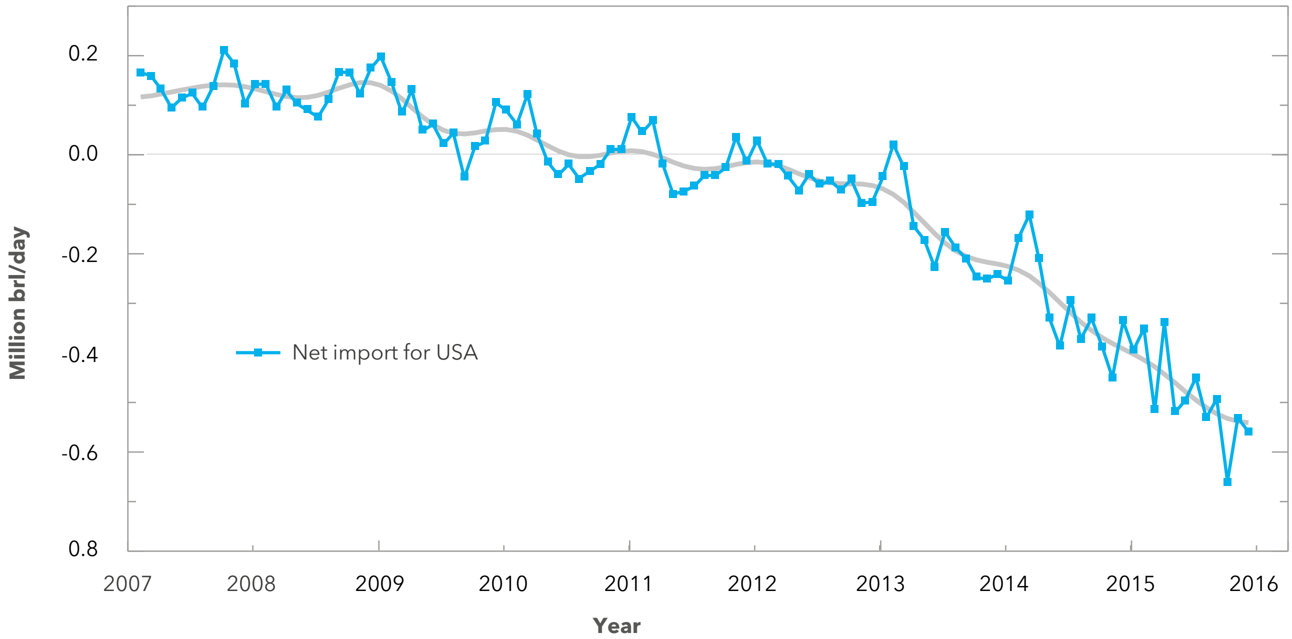


Figure 8: Propane quantities imported/exported from the USA, 2007–2015

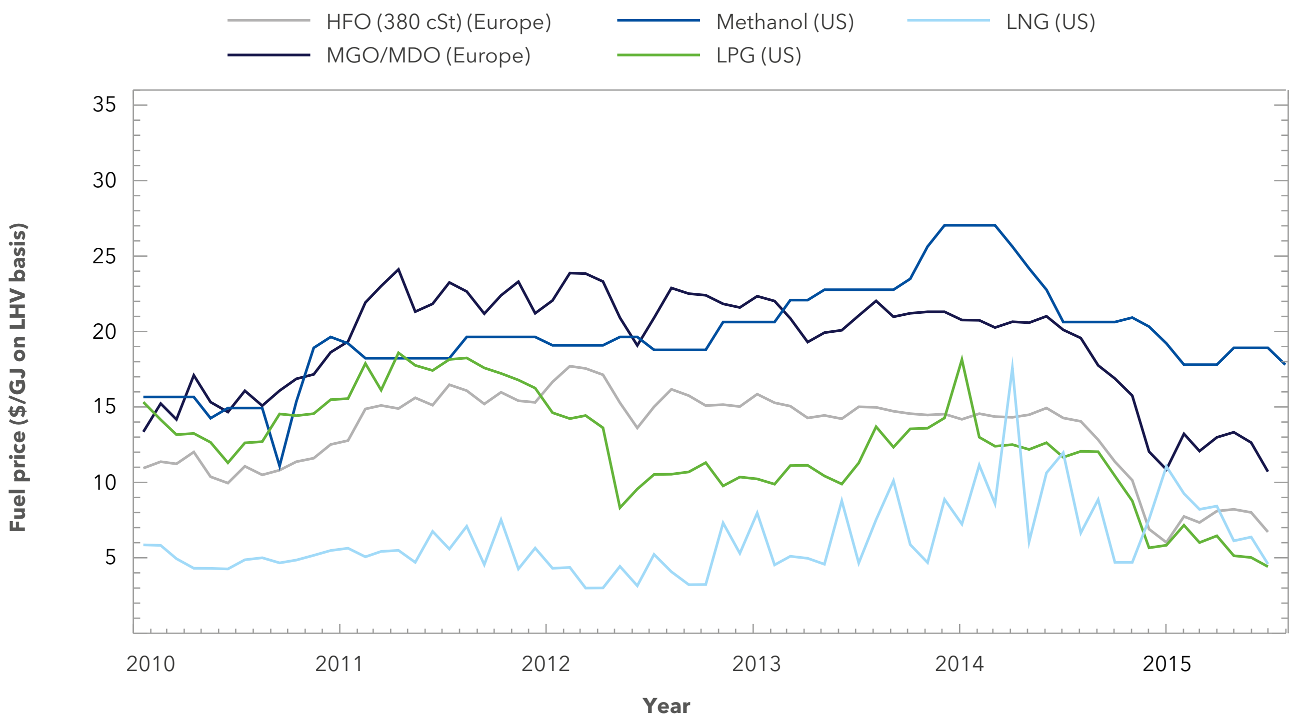
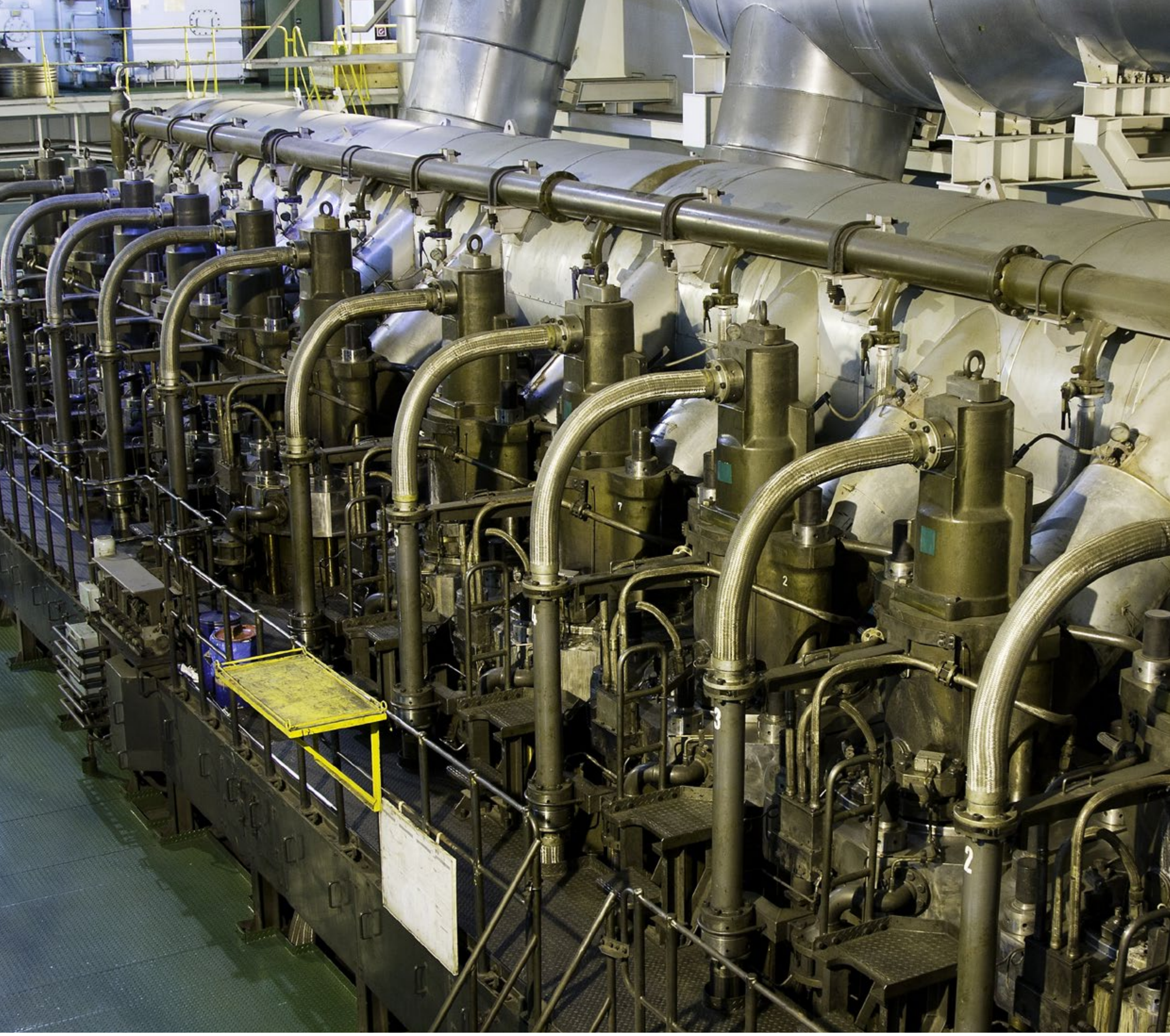


Figure 9: Historic prices of HFO, MGO, LPG and LNG, 2010–2016



ENGINE AND FUEL TANK TECHNOLOGY

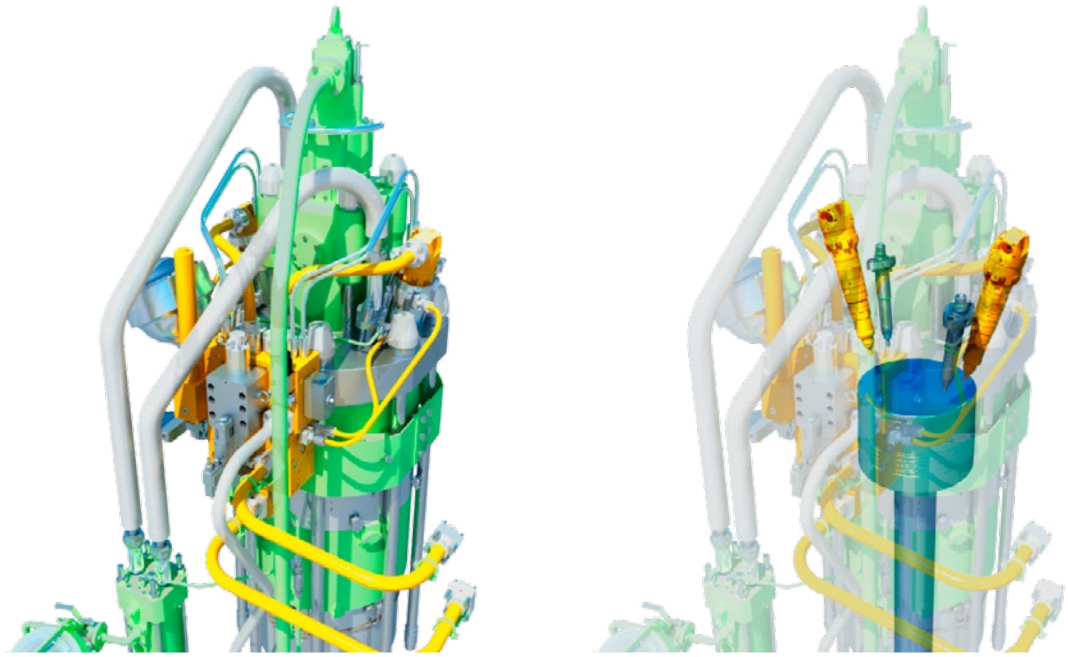


Figure 10: MAN ME-LGI engine. LGI components coloured yellow

ENGINE TECHNOLOGY

There are three main approaches that can be applied in order to use LPG as a fuel:

- In a Diesel cycle two-stroke engine, as offered by MAN as part of the MAN ME-LGI series.[14,15]
- In an Otto cycle, lean-burn, four-stroke engine, as offered by Wärtsilä, currently only for stationary power plants, as part of the Wärtsilä 34SG series.
- In a gas turbine as offered by GE in its LM2500 series, possibly in combination with a steam turbine or CO_2 turbine.

Diesel cycle – two stroke approach
The MAN B&W ME-LGI engine series has been introduced by MAN Diesel & Turbo in order to address low flashpoint liquid fuels (such as methanol, ethanol, dimethyl-ether and LPG). The operation principle and safety measures are similar to those of the already established ME-GI concepts that are used for LNG and ethane as fuels. A pilot fuel oil injection corresponding to 3% of the energy in the fuel at 100% engine load is required to trigger the ignition process. The engine can run on LPG fuel for engine loads above 10%. This results in SO_X emissions reduction of up to 90–97%, compared to engines operating on HFO. The expected reduction in NO_X emissions is of the order of 15-20% when operating on LPG, and EGR and SCR systems are also available to make the engine compliant with Tier III NO_X standards.

The main differences between the ME-GI and ME-LGI series are in some components and auxiliary systems necessary to address the different properties of liquid fuels. Fuel injection takes place via a so-called fuel booster injection valve, which uses hydraulic power to raise the fuel pressure and thus eliminates the need for high-pressure fuel lines. The low-pressure fuel supply system reduces the cost and weight and adds to the simplicity of the system. Both fuel oil and LPG injectors are mounted on the cylinder cover. The fuel oil injector is used to inject pilot oil when operating on LPG. An overview of the fuel lines and injectors in the system is given in Figure 10.

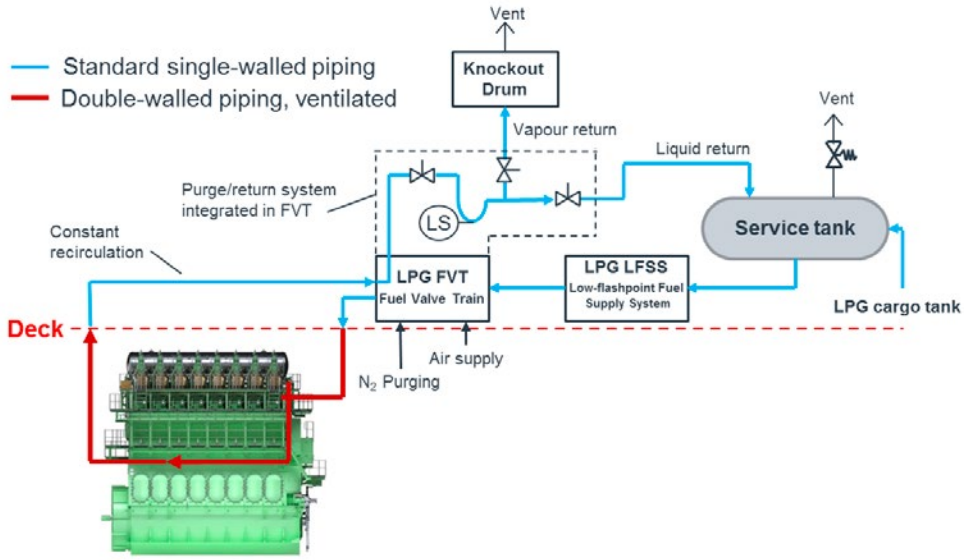


Figure 11: Schematic diagram of engine, fuel service tank and piping. Source: MAN

An additional feature of the ME-LGI engine series is the sealing oil system integrated into the engine. This is necessary to provide the fuel injection components with the required lubrication and sealing that prevents LPG contamination of the system oil.

An overview of the fuel tank, fuel supply system and engine, as well as the piping is given in Figure 11. The Low flashpoint Fuel Supply System (LFSS) takes the fuel from the service tank and boosts its pressure to the engine supply pressure, which ensures that the fuel remains liquid and that no cavitation occurs until it reaches the fuel booster injection valve. The flow of fuel should at all times be higher than the engine's fuel consumption. To ensure the fuel delivery temperature, a heater/cooler is placed in the circulation circuit.

The fuel valve train connects the fuel supply system with the engine through a master fuel valve. For purging purposes, the valve train is also connected to a nitrogen source. Typically, the valve train will be placed outside the engine room above the weather deck to improve safety. From the valve train, the fuel is fed to the engine in a double-walled ventilated pipe through the engine room. The system is monitored by hydrocarbon sensors (sniffers). If LPG vapour is detected inside the double-walled pipe, the safety system will switch to fuel oil operation smoothly and without any loss of power.

Otto cycle – four-stroke approach

Wärtsilä has followed a different approach than that of MAN in its natural gas engines series and has developed lean-burn Otto gas engines with a spark plug or pilot fuel injection for ignition. These engines are characterized by their lean-burn operation, which consists a lean air-gas mixture being introduced into the cylinder, in other words more air than needed for stoichiometric combustion. This strategy results in a lower peak temperature during combustion and, consequently, lower NO_X emissions. The accurately control of the exact air-gas ratio, means that the engine can operate without knocking or misfiring while maintaining high thermal efficiency. Ignition of the mixture is initiated using either with a spark plug located in a pre-chamber or pilot fuel injection. The gaseous fuel is introduced into the cylinder through gas admission valves located immediately upstream of the air intake valves. The gas valves are controlled independently of the air intake valves, to feed the correct amount of gas to each cylinder at the correct timing. The Otto gas engine concept requires a relatively low gas pressure of about 4–5 bar, and thus does not require additional equipment such as pumps and/or compressors to pressurize the gas before it enters the engine.

In 2014, Wärtsilä was awarded a contract for a pair of Wärtsilä 20V34SG-LPG GasCubes to be installed for an industrial customer in Central America. This was to generate electricity using LPG consisting of a minimum of 97% propane and maximum of 3% butane.[16,17] The Wärtsilä 34SG-LPG is the first medium-speed engine capable of running on propane, and is the same engine as the 34SG series that is optimized for propane operation. The same engine can be used with natural gas and ethane, and the fuel switch takes place without stopping the engine. When operating on natural gas, the unit's normal output is 9,341 kWe, while the engine output is reduced to 6,995 kWe (75%) to maintain a safe knock margin when operating on LPG, which has a methane number of 34.

An engine such as the Wärtsilä 34SG-LPG could also be used with pilot fuel injection in a dual-fuel configuration, so that it can be used for marine propulsion. An important benefit would be the compliance with Tier III NO_x standards without the need for EGR or SCR systems. In principle, the 34SG engine could also be marinized, but it will not have the fuel flexibility of a dual-fuel engine.

An alternative option offered by Wärtsilä to utilize LPG for propulsion is the installation of a gas reformer to turn LPG and steam into methane in a mixture with CO_2 and some hydrogen. In this case, the energy content of the gas produced in the reformer is sufficient for a regular gas or dual fuel engine to be used with no need for derating. A reformer will, however, lower the efficiency. It is stated to reduce the efficiency in the chemical reactions by 2% and an additional 7% is transferred to low temperature water, whereas steam for the process can be generated by waste heat recovery from exhaust gases. The price is about €2 million for an 8 MW engine. Hence, a reformer adds complexity, costs and space and at the same time reduces efficiency and introduces the potential for methane slip.

However, when faced with a large variation in the fuel composition, e.g. for volatile organic compounds in shuttle tankers, this is a feasible solution. The gas reformer also allows the fuel gas quality and methane number to be improved by treating only a split of the feedstock and mixing it back into the main stream, thereby saving cost and space. Wärtsilä gas reformers received Approval in Principle from DNV GL for shuttle tankers in 2015.

Gas turbine

Recently, a Memorandum of Understanding was signed with GE in South Korea to cooperate with Korean and global partners on an LPG-fuelled ferry design, using a combined cycle gas turbine, electric and steam (COGES) system.[18] As mentioned above, the transportation sector accounts for a large part of the LPG consumption in South Korea today.

GE is offering turbines in the LM2500 family for maritime applications, with technology based on turbines used in aircrafts for decades. These turbines are now available to burn LPG as a fuel without changes to the fuel injection system. However, the safety systems used for LNG will require modification because of the density of LPG, so the leak detectors and ventilation system must be adapted.

The LM2500 family can provide turbines with an output of 22–33 MW and 36-38% efficiency in single-cycle mode.[19] The minimum load on the gas turbine is 50%. A gas turbine can be combined with either a steam turbine to increase the efficiency to 53–55% or a CO_2 turbine, which GE has recently started to offer.

"Two-stroke engines and gas turbines for marine use are currently available in LPG versions."

SAFETY CONSIDERATIONS

Propane and butane are heavier than air and this causes different risks than e.g. methane, which is lighter than air. Both propane and butanes will burn (or explode) if an ignition source is introduced in a concentration range of about 2 to 9% in air. As a gas, it burns quickly with a high energy content. In addition to this, and like LNG, liquid propane or butane in a pressure vessel constitutes a risk when the pressure vessel is heated, e.g. by a leak catching fire.

The vessel may rupture due to the high vapour pressure, and the liquid evaporates immediately causing a rapid expansion and mixture with air. This leads to combustion at high velocity and a large explosion; a so-called BLEVE (Boiling Liquid Expanding Vapour Explosion). The appropriate design of fuel storage, bunkering and fuel supply systems can mitigate these risks, as described below.

LPG AS FUEL

The preferred way of storing LPG for use as propulsion fuel is in a pressurized tank at ambient temperature. Storage in a semi-refrigerated tank made of cheaper steel types than for LNG is also possible, but in order for such an arrangement to be sufficiently reliable, back-up systems must be in place to ensure low temperature in the tank. This makes pressurized tank storage a more reliable, affordable and simple solution.

LPG has a higher density than air and any spillage will collect in lower spaces, requiring a different approach to leak detection and ventilation in the case of leaks. LPG is a low-flash-point liquid, and when used in a high-fire-risk space of the ship with a constant personnel presence, like in the engine room, a double-walled pipeline must be used as secondary containment. Hydrocarbon sniffers will detect any leakage and contain the fuel within the secondary containment before it reaches areas where humans are present. Double-walled pipelines must be used below the deck line.

The autoignition temperature for LPG (490°C) is lower than for LNG (580°C), which may require a lower surface temperature near electrical equipment. Compared to LNG, LPG has fewer challenges related to temperature because it is not kept at cryogenic temperatures, but on the other hand it has challenges related to higher density as a gas and a lower ignition range, with a lower explosion limit of about 2%. The challenges are different, but overall the safety management is probably somewhat simpler for LPG than for LNG.

LPG BUNKERING

LPG bunkering can in principle take place in many different ways, e.g. from terminals or trucks on-shore or from bunkering ships. Bunkering from terminals to LPG-carrying ships is today handled safely with proper specialized training, and the safety is believed to be improved by using a bunkering ship as an intermediate between the terminal and the ship using LPG as fuel. At least for deep sea shipping with significant amounts of fuel to be bunkered, a bunkering ship would be the preferred solution. LPG in terminals is typically stored onshore in steel spheres called bullets, mainly under pressure, but LPG can also be stored in refrigerated tanks or underground, e.g. in salt domes.

The LPG may be stored under pressure or refrigerated, and LPG will not always be available in the temperature and pressure range that the ship can handle. The bunkering vessel and the ship to be bunkered must therefore have the necessary equipment and installations to bunker safely. The tank design temperature is related to the steel type used, and the minimum temperature for a pressurized tank is typically at or above 0°C. Refrigerated or semi-refrigerated tanks typically have a design temperature of about -50°C, but on the other hand have a limited pressure range compared to pressurized tanks.

There are different possible combinations of bunkering vessels with pressurized tanks, semi-refrigerated tanks or fully refrigerated tanks and similar arrangements in the ship to be bunkered. Four cases illustrate some key bunkering challenges:

- In the case of **pressurized tanks** both in the bunkering vessel and the ship to be bunkered, the LPG is transferred using a general transfer pump located in the bunkering vessel. When filling the LPG tank, pressure will build up because of less gas volume available, and since it takes time to condense LPG, this can cause the safety valve in the tank to open. For practical purposes and to comply with safety regulations, the LPG tank must be equipped with a vapour return system back to the bunkering vessel, i.e. a gas outlet connection in addition to the liquid inlet connection.
- In the case of **semi-refrigerated tanks** in the bunkering vessel and a **pressurized tank** in the ship to be bunkered, it is necessary to have a heater and a booster pump in the bunkering ship and a vapour return system in the ship to be bunkered. The heater is needed because the fuel has a lower temperature than the tank design temperature, and this will typically be handled by a heat exchange system using heat from seawater. The LPG filled will have a lower than ambient temperature, but needs to be above the tank design temperature. The booster pump is needed to raise the pressure of the LPG before bunkering. Both the heater and booster pump are typically installed on semi-refrigerated LPG carriers, that may be used as bunkering ships. The vapour return from the ship to be bunkered may have too high a pressure for the semi-refrigerated tank, and must be handled by the re-liquefaction plant in the bunkering vessel, which may require some modifications. An alternative to vapour return in this case is to fill the cold LPG with a spray-line to condense the LPG vapour.

- In the case of **pressurized tanks** in the bunkering vessel and a **semi-refrigerated tank** in the ship to be bunkered, the pressure needs to be reduced by lowering the temperature in a liquefaction plant. An LPG carrier with pressurized tanks is typically not equipped with this, thus requiring comprehensive modifications of the equipment and cargo handling system. This case also requires a vapour return system with a compressor in the bunkering ship that needs to be set up to increase the pressure of the vapour return. LPG carriers with pressurized tanks are typically equipped with a compressor, but only for the purpose of emptying the cargo tanks.

- In the case of **semi-refrigerated tanks** both in the bunkering vessel and the ship to be bunkered, cooling (and probably not heating) may be necessary. A vapour return system and some modifications of the re-liquefaction plant in the bunkering vessel to ensure a higher capacity may also be necessary.

Based on the cases discussed above, a pressurized LPG fuel tank is the preferred solution when bunkering the ship, because the ship can be bunkered by a bunkering vessel based on an LPG carrier (either with pressurized tanks or semi-refrigerated tanks) without major modifications. Both types of bunkering vessels are possible, depending on the size of the fuel tanks to be bunkered and the number of ships to be served. Semi-refrigerated LPG carriers typically have larger capacity than pressurized LPG carriers and sufficient capacity for all ship types. They are also more flexible, e.g. in terms of filling ships with semi-refrigerated fuel tanks, and have a limited cost premium.

EMISSIONS TO AIR

Using LPG as a fuel can contribute to lower emissions to air, compared to conventional fuels, both in terms of greenhouse gas emissions and other pollutants.

LPG combustion results in lower CO_2 emissions compared to oil-based fuels due to its lower carbon to hydrogen ratio. Compared to natural gas CO_2 emissions are a bit higher, but some gas engines can suffer from methane slip, which increases their overall greenhouse gas emissions. Considered in a lifecycle perspective, LPG production is associated with lower emissions than oil-based fuels or natural gas. The combination of low production and combustion emissions yields an overall greenhouse gas emissions reduction of 17% compared to HFO or MGO.[20] This is comparable with the greenhouse gas emissions from LNG, which strongly depend on the amount of methane leak and could be slightly lower or higher depending on the production and combustion technology.

Greenhouse gas emissions in $kgCO_{2eq}/GJ$ for oil-based fuels, LPG and LNG are given in the table below (CIMAC, 2013). A methane slip of 1% and an energy consumption for liquefaction of 7% are assumed for LNG. Because the global warming potential for propane and n-butane are 3 and for isobutane 4 (times the global warming potential of CO_2) compared to 25 for methane, any slip of un-combusted fuel through the engine would result in less greenhouse gas emissions for LPG than for LNG.

	HFO	MGO	LPG	LNG (Qatar)
Well-to-tank	9.79	12.69	7.15	9.68
Tank-to-propeller	77.70	74.40	65.50	61.80
Well-to-propeller	87.49	87.09	72.65	71.48
Difference to HFO	**-**	**-0.50%**	**-17.0%**	**-18.30%**

The use of LPG also has benefits related to pollutant emissions. It virtually eliminates sulfur emissions, and can be used as a means of compliance with low sulfur local and global regulations. The reduction of NO_X emissions depends on the engine technology used. For a two-stroke diesel engine, the NO_X emissions can be expected to be reduced by 10–20% compared to the use of HFO, whereas for a four-stroke Otto cycle engine, the expected reduction is larger and may be below Tier III NO_X standards. In order to comply with these standards, a two-stroke LPG engine should be equipped with Exhaust Gas Recirculation (EGR) or Selective Catalytic Reactors (SCR) systems. Both solutions are commercially available. The use of LPG as a fuel will, like LNG, to a large degree avoid particulate matter and black carbon emissions.

FINANCIAL FEASIBILITY

In a comprehensive joint study, DNV GL and MAN Diesel & Turbo examined a set of scenarios for various versions of an LR1 product tanker to determine the most economically feasible fuel type to plan for.[5]

The goal of this study was to analyse the costs and benefits of various fuel options for a newbuild of 75,000 DWT. The alternative fuels selected were among others LNG, LPG and methanol. Costs and benefits were determined by looking at additional investment and operating costs compared to a standard fuel variant using HFO and MGO.

A fixed route was selected to perform a financial analysis, and for the selected operating pattern, 87% of the time is spent in transit, 3% in approach and 10% in port. The machinery set-up was the same, except for the fuel system.

The selected 6G60ME-C9.5 engine is available as a standard oil-fuelled diesel engine, but also in dual-fuel versions capable of burning LNG, methanol or LPG (the ME-GI and ME-LGI types, respectively). The propulsion system is equipped with a fixed-ratio power take off (PTO). The capacity of the PTO is 778 kW, offering a simple and cost-effective way to supply all the electric power requirements when the ship is in transit. The tank size for the alternative fuels was selected to give the vessel a half-round-trip endurance with a 20% margin. The capital investments vary from 2.8 to 9.6 MUSD depending on the fuel type and tank size derived from the extent to which the alternative fuel is used, cf. Figure 12.

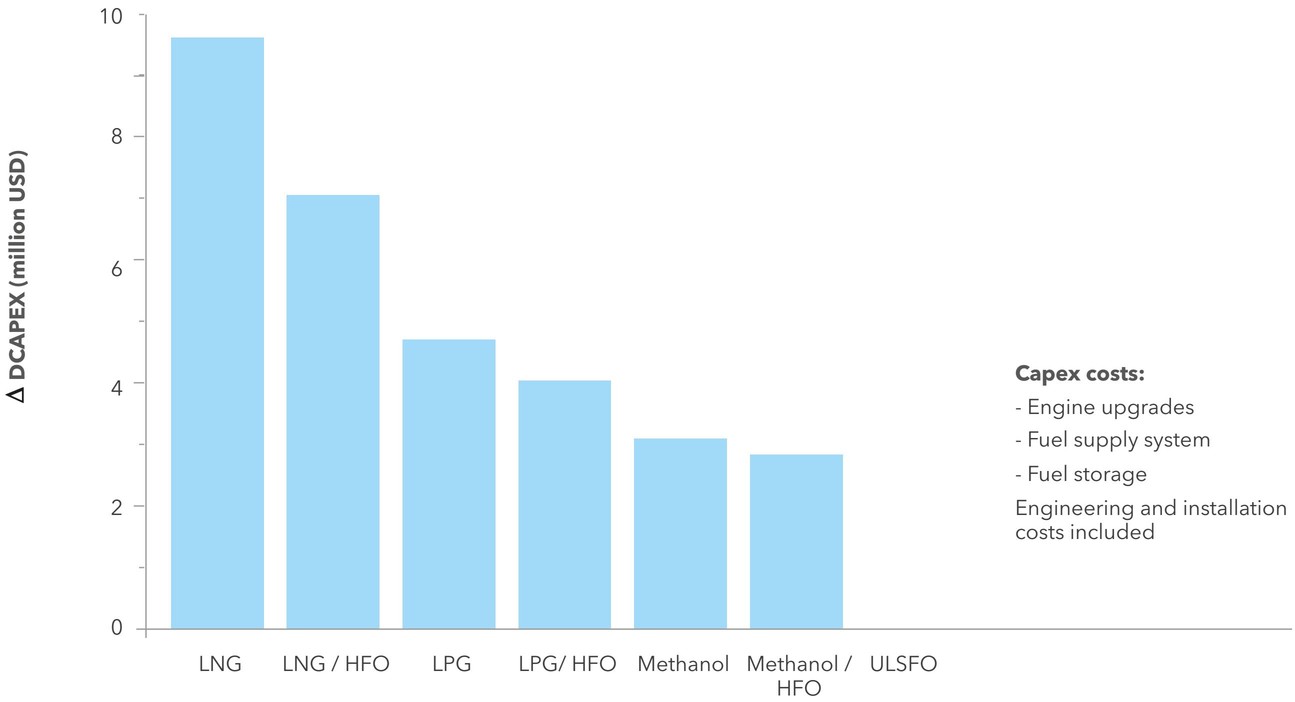


Figure 12: Incremental investment costs for the alternative fuel variants

Two price scenarios were developed: a high price scenario based on the fuel prices in mid-2014, at a time when the Brent oil prices were 100–110 $/barrel; and a low-price scenario based on fuel prices in mid-2015 when the Brent oil prices were about 50 $/barrel.

In the high-price scenario, LNG and LPG both deliver a cost advantage during operation compared to the reference vessel. There are, however, also substantial investments required for these alternatives related to investments for the tanks. The investments are substantially larger when LNG or LPG is used both inside and outside SECAs. However, the increased initial investments are more than compensated for by the lower prices for LNG and LPG compared to LSFO in the high-price scenario.

In the high-price scenario, both LNG and LPG have payback periods in the 5- to 10-year range, depending on speed and if it is used only in SECAs (e.g. "LPG/ HFO") or for the full trip (e.g. "LPG"), as shown in Figure 13.

In the low-price scenario, the payback time for LNG is more than 13 years, whereas LPG has a payback time of approximately 6.5 years. Payback times for LPG in both price scenarios are shown in Figure 14. Based on the fuel-price scenarios presented in this study, LPG can be understood to be at least as good as LNG based on the shorter payback time, reduced sensitivity to fuel price variations and lower initial investments.

Fuel prices, with their intrinsic uncertainty, are critical for the outcome of the financial analysis. In order to take uncertainty into account, a sensitivity analysis was carried out comparing LSFO to the alternative fuels. A wide price spread indicates a larger driving force for a fuel switch to LNG or LPG.

As shown in Figure 15, LPG requires a smaller discount than LNG to be financially attractive. This is due to its lower capital cost. Even though the expected discount is less for LPG than LNG, the payback time is shorter. Nevertheless, with reasonable prices for LNG and LPG in the high-price scenario, the additional investment due to the alternative fuel is paid back in the project period of 13 years.

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For the most attractive fuels, i.e. LNG and LPG, the best alternative is to use it both inside and outside SECA regions."

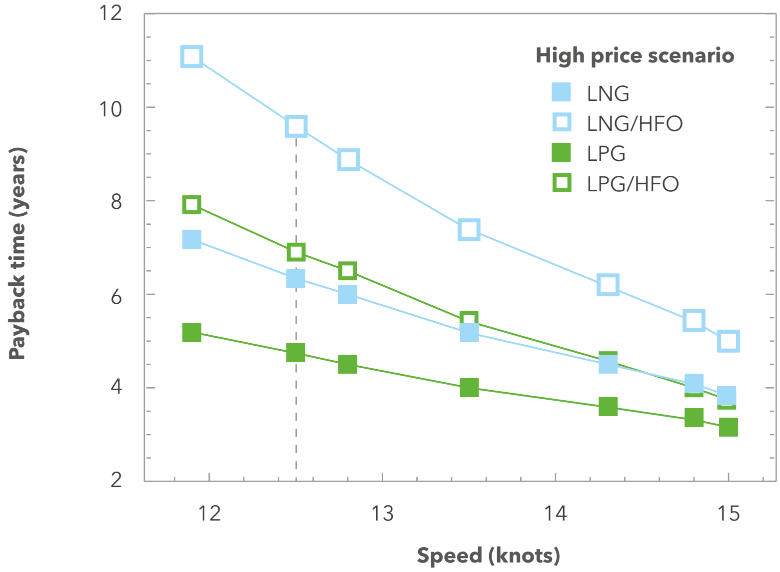

Figure 13: Payback time as a function of ship transit speed for LNG and LPG pure and combined variants in the high-price scenario. Dashed line indicates the reference speed.

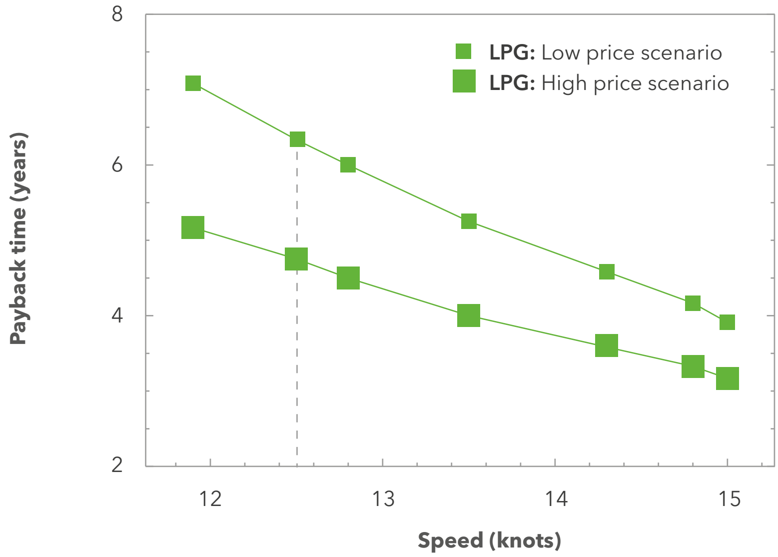

Figure 14: Payback time as a function of the ship transit speed shown for LPG in both price scenarios, with LPG used both inside and outside SECAs. Dashed line indicates the reference speed.

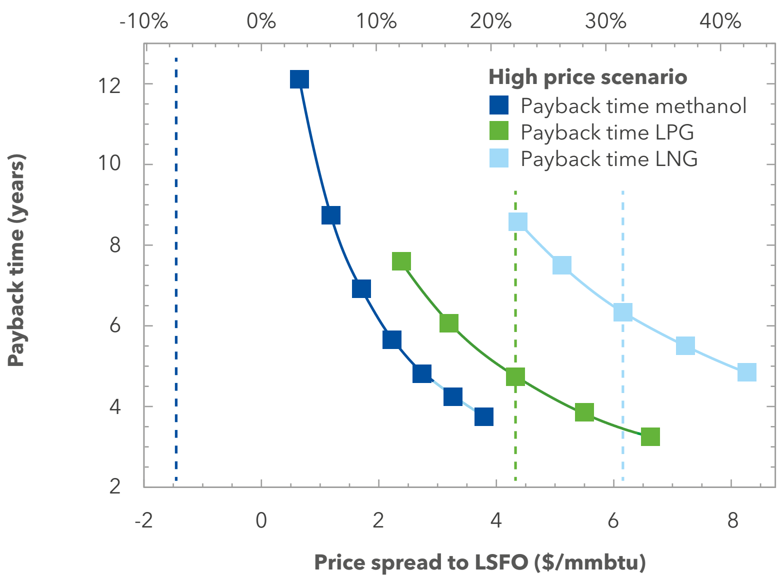

Figure 15: Payback time as a function of the price difference between LSFO (at 19.55 $/mmbtu) and the alternative fuel. Dashed lines represent the values used in the high-price scenario for each fuel.

CONCLUSIONS

Based on the above discussions, LPG can compete financially with LNG and probably also with low sulphur fuel oil after the global sulphur cap changes to 0.5% for newbuilds. Retrofits will be less cost efficient. The technology is currently available for large ships with two-stroke engines and turbines and can be developed for smaller ships with four-stroke engines if there is a demand for this. Safety issues linked to the use of LPG as a marine fuel must be addressed, but these should be no more challenging than for LNG. The current global production of LPG and the increase in this opens up the possibility for a gradual introduction of LPG as a marine fuel. The spatial distribution of LPG storage facilities favours LPG over LNG as a fuel.

Nevertheless, the development of a bunkering infrastructure remains a barrier for the use of the fuel. Market introduction for a non-drop-in fuel, such as LPG, will always be a challenge, but a first mover could be a VLGC where the fuel is already present or can be bunkered in connection to cargo loading, thereby reducing the distribution costs on ships where the safety risks of LPG are well known. We therefore consider LPG to be an interesting opportunity for a cleaner fuel for the future.

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