NATO ENERGY SECURITY
CENTRE OF EXCELLENCE

ENERGY HIGHLIGHTS

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Liquefied Natural Gas (LNG) as an alternative propellant in the naval field

by **Ms Marju Kõrts**

EXECUTIVE SUMMARY

The fuel or energy source has a large impact on the operating emissions in shipping. For this reason, international and national emission regulation has already started to provide the incentive for shifts towards alternative fuels. Regulation has so far focused on air pollutant emissions, such as SO_x, NO_x, and particulate matter (PM). These concerns are enhanced by the introduction of environmental regulations intended to reduce the impact of climate change - primarily MARPOL Annex VI and the Energy Efficiency Design Index (EEDI) regulations together with the possible introduction of carbon taxes.

The diesel engine is currently the most widespread of marine prime movers. It is a well-understood technology and a reliable form of marine propulsion and auxiliary power generation, with engine manufacturers having well-established global repair and spare part networks. In addition, there is a supply of trained engineers with appropriate training facilities available. However, diesel engines will continue to produce CO_2 emissions as well as NO_x, SO_x, volatile organic compounds and particulate matter. All these aspects have led many in the sector to question whether the present methods of ship propulsion are sustainable.

Liquefied natural gas (LNG) can be used in reciprocating engine propulsion systems and it is a known technology with classification society rules for the fuel systems already in place. The LNG carriers have used liquefied natural gas as fuel for decades whereas the other ship types have done so since 2001. The main technical systems used in LNG as fuel are the containment systems used to store LNG on board, the process systems for conditioning LNG and the engines to generate propulsion power and electrical energy.

by **Ms Marju Kõrts**

Ms Marju Kõrts is an Estonian career diplomat who has hold several positions at the Estonian Ministry of Foreign Affairs. She graduated with her Masters degree in political science at Tartu University in Estonia. With the current function as the Estonian Subject Matter Expert at the Research and Lessons Learned Division of the NATO Energy Security Center of Excellence in Vilnius she focusses on the new energy technologies. At present she is conducting a research study "The use of LNG as an alternative propellant in the naval field" that will be launched this spring by the NATO Energy Security Center of Excellence. E-mail:marju.korts@enseccoe.org

The switch to natural gas as a ship fuel is possible today. In light of sulphur limits in Emission Control Areas (ECAs), LNG-powered ships are a viable option to achieve compliance. However many ship owners and operators are asking themselves which engines are the best for changing over to a gas-fuelled ship. The two key engines on the market today are dual-fuel and gas-only types. All of the 4-stroke engines available today are low-pressure engines. The mixture of fuel and air takes place outside of the cylinder behind the turbocharger. This means that the fuel gas pressure is approximately 5 to 6 bar. Nevertheless, the pressure is low and therefore the gas can be provided either directly from a pressurized storage tank or by use of a compressor.

The fleet has grown exponentially since the early 2000s and currently available data on confirmed ship orders indicate that the fleet is expected to double and grow by another 123 vessels in the next years. Despite all this the uptake of LNG-powered vessels remains fairly marginal, but it is growing. There is an increase in government backed initiatives such as Japan, Korea and China to develop LNG bunkering infrastructure as a part of their commercial strategies and greenhouse gas reduction targets. These trends seem to indicate that the shipping industry considers LNG as an attractive solution. Service experience with dual fuel and converted diesel engines, although limited at the present time, has been satisfactory. LNG while free from harmful emissions, has benefits in terms of CO_2, as well as NO_x, SO_x emissions, given that methane slip is avoided during the combustion and fuelling processes.

The present study examines the potential use of LNG as marine propulsion in the context of the international efforts aimed to reduce the carbon intensity of shipping. In this case the new propulsion methods can considerably contribute to this end. The other focus of the study is on the safety aspects of LNG storage and handling that can bring along certain concerns. In order to provide readers a wider perspective, a range of short-, medium-, and long term propulsion options are identified.

Biofuels are potential medium-term alternatives to conventional fuels for diesel engines. Synthetic fuels based on branch-chain higher alcohols and new types of E-coli as well as algae and other microorganisms are medium-to long-term possibilities, but further work is necessary to examine their storage, handling, and impacts on health, safety and environment.

Fuel cells offer potential for ship propulsion with good experience gained in auxiliary and low-power propulsion machinery. For marine propulsion, the high temperature solid-oxide and molten carbonate fuel cells are more promising, while for lower temperature proton exchange membrane fuel cells seem to be more suitable option. While hydrogen is the easiest fuel to use in fuel cells, this would require a worldwide infrastructure to be developed for supply to ships.

Battery technology is developing rapidly, offering some potential for propulsion. However, full ship battery propulsion requires further technical development and is likely to be confined to relatively small ships. Nevertheless, battery-based propulsion would be beneficial due to producing no CO_2, NO_x, and SO_x, volatile organic or particulate emissions in operation. Batteries may offer a potential hybrid solution in relation with other modes of propulsion for some small-to medium-sized ships provided that their recharging does not increase the production of other harmful emissions from land-based sources or elsewhere.

Hydrogen, compressed air and liquid nitrogen are likely to be long-term propulsion considerations. While the latter two options are energy storage media, hydrogen is fuel which generates CO_2 or SO_x emissions to the atmosphere and would use land-based sources of power for its creation. It would need a supply infrastructure to be viable in a marine context, but it is ideal for use in fuel cells. Compressed air and nitrogen would use land-based sources of power for creation and the tank storage technologies are well understood – through tank corrosion is an issue in salt-laden environments. The size, pressure rating and cryogenic capabilities, in the case of liquid nitrogen, of the ship storage tanks will determine the amount of energy storage and hence usefulness of this concept. As with hydrogen, a supply infrastructure and distribution network would be needed.

LNG as a mature technology is a good option for cruise ship and ferry segment, but it is not a good option for the militaries due to the safety aspects of LNG as a ship fuel (potential for spills, leakages and its inherent flammability rate). At the same time it can be an option for smaller vessels where dual fuel engines are used and it is possible to switch from one fuel to the other. In this case LNG can be used either with fuel cells or with other residual marine fuels (e.g MGO). Therefore, the use of LNG cannot be excluded, but more testing and technical feasibility studies of this options should be carried out.

To achieve effective improvements in efficiency and reductions in emissions for ships, an integrated systems engineering approach is required. This must embrace all of the elements of naval architecture, marine and control engineering alongside operation practice. With any propulsion option it is essential that the overall emission profile and the fuel used is properly assessed, so that reductions in exhaust emissions from shipping are not at the cost of increasing harmful emissions in land-based sectors that produce either the propulsion machinery or the fuel.

INTRODUCTION

Seaborne transport in general is dominated by the use of fossil fuels, mainly heavy fuel oil (HFO) and marine gas oil (MGO). The conventional marine fuels have worked efficiently through the last decades, especially with regard to adaptability, performance and safety. But during the last few years, and due to the high quantity of emissions emitted from ships, strict emission regulations have been introduced by the International Maritime Organization (IMO). With demand for transport ever rising, and fossil duel-engines still dominant, the sector needs to undergo a fundamental transformation if the global warming targets set in Paris 2015 are to be met.

According to the World Resources Institute's statistics, transport emissions - which primarily involve road, rail, air and marine transportation - accounted for over 24% of global carbon dioxide (CO_2) emissions in 2016. The carbon emissions of transport can be expressed as the product of transport demand (using capacity ton miles i.e. ton nautical miles) and transport supply represented by emissions intensity (gCO_2/ton miles i.e. grams of CO_2 emitted per ton nautical mile). Most energy scenarios - including those that take into account existing national commitments under the Paris Agreement - show transport-related energy consumption continuing to increase, and oil continuing to comprise the largest share, through 2050. Transport's reliance on fossil fuels needs to shift dramatically in order to be constant with a trajectory of limiting global temperature increase below 2 degrees Celsius.

Technology improvements in recent decades have reduced the fuel consumption and environment impact on ships. There is a myriad of new technologies that are being tested at the moment, e.g a solar-powered ship that is called EnergySails[1] is currently under development.

However, shipping remains a significant contributor to global emissions of greenhouse gases (GHG), volatile organic compounds (VOC), particulate matter (PM), hazardous air pollutants, nitrogen oxide (NO_x). The largest amount of noxious emissions is observed especially in the coastal and harbor areas where the marine traffic density is also much higher in comparison with traffic density observed at an open ocean.

Low carbon fuels play an important role in reducing emissions by displacing fossil fuel use, and their increased use have made one of the most significant contributions to reducing greenhouse gas emissions (GHG). The IMO, a United Nations agency that is responsible for environmental impacts of ships, has played a big role in pushing for green shipping. It has mandated that the emission of sulphur content in fuel used in ships must come down from 3.5% to 0.5% by 1 January 2020. It has also set targets for the shipping industry to cut down GHG emissions by at least

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[1] The patented EnergySails is a rigid sail and wind assisted propulsion device that allows ships to harness the power of the wind and sun in order to reduce fuel costs and lower noxious gas and carbon emissions. The sails were developed by Japanese renewable energy systems company Eco Marine Power as part of a larger project known as Aquarius Marine Renewable Energy.

50% by 2050 from 2008 levels and reduce the sector's average carbon intensity by at least 40% until 2030, and 70% by 2050.

In July 2016, the European Commission adopted a "European Strategy for Low-Emission Mobility" which among other topical issues highlighted the need for speeding up the deployment of low-emission alternative energy for transport, such as advanced biofuels, electricity, hydrogen and renewable synthetic fuels[2]. At the same time, these proposals will dramatically reduce Europe's dependence on imported oil and cut carbon emissions in transport. The European Union's goal is also reducing its annual CO_2 emissions from shipping by at least 40% by 2050 compared to 2005 (European Commission White paper, 2011)[3]. To achieve these CO_2 emission reductions, the implementation of energy efficiency measures needs to be supplemented by the introduction of alternative marine fuels with lower CO_2 emissions than conventional fuels. This may also lead to reductions in NO_x, SO_x (which are regulated in certain emission control areas, and particulate matter). It is suggested that reducing global greenhouse gas (GHG) emissions 50 to 80 per cent below 1990 levels by 2050 it is necessary to stabilize the climate and avoid dangerous climate change impacts.

The current political and public discussions about reducing greenhouse gas reductions in transport focuses on regulating carbon emissions and the market maturity of alternative fuels. Alternative fuels known as non-conventional fuels are any substances that can be used as fuels, other than conventional fuels like fossil fuels (e.g petroleum, coal, and natural gas) as well as nuclear materials such as uranium and thorium. The European Commission's Communication of 24 January 2013 entitled "Clean Power for Transport: A European alternative fuels strategy" defined electricity, hydrogen, biofuels, natural gas, and liquefied petroleum gas (LPG) as currently the principal alternative fuels with a potential for long-term oil substitution, also in light of their possible simultaneous and combined use by means of, for instance, dual-fuel technology systems. Dual-fuel operation means that engine uses two fuels (gas and diesel oil) at the same time, as opposed to bi-fuel which would mean the engine could have the option of using either fuel separately.

Climate change requires urgent action in all sectors of the economy – including maritime shipping which is considered a hard-to-abate sector. A broad range of local and national actions are needed to bring the sectors on to low-carbon development path. The so-called hard-to-abate sectors such as trucking, shipping and aviation - and industry -steel, cement and plastics represent 40% of carbon emissions from the energy systems today, but this share will grow to 60% of remaining emissions by 2040 in a 2 degrees Celsius scenario, as other high-emitting sectors are decarbonized. The decarbonisation of shipping and its energy value chain can only be achieved through a close co-operation and deliberate collective action between the maritime, energy and infrastructure stakeholders. There are several ways to reduce emission levels from shipping. These include: engine improvements, such as exhaust gas recirculation, exhaust gas after-treatment, like scrubbers or selective catalytic reduction; and finally the use of different marine fuels (e.g low sulphur diesel or liquefied natural gas)[4].

The existing vessels are not fit to switch to just any alternative fuel and therefore the vessels may be retrofitted with auxiliary energy-saving technologies. Retrofitting is defined as the installation onboard ships of state-of-the-art or innovative components or systems and could in principle be driven by the need to meet new standards or by the ship owner's interest to upgrade to higher operational standards. There are also a plethora of technologies available for retrofitting on existing ships: main engine tun-

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[2] European Commission "Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee of the Regions: "A European Strategy for Low-Emission Mobility", COM (2016) 501 final

[3] White Paper 2011 "Roadmap to a Single European Transport Area – Towards a competitive and resource efficient transport system"

[4] Scrubber systems are a diverse group of air pollution control devices that can be used to remove some particulates and/or gases from industrial exhaust streams. Selective catalytic reduction is a means of converting nitrogen oxides with the aid of a catalyst into diatomic nitrogen and water. More detailed overview of the exhaust gas after-treatment devices is provided in Chapter 7 that deals with natural gas engine technologies and emissions abatement techniques.

ing, propeller and rudder upgrades, fin and duct energy saving devices, to name a few. For these reasons, it should become an established practice in the shipping industry involving the entire value chain and exploring the possibilities that may open to the industry on a continuous basis.

Another aspect that makes decarbonisation of shipping complicated is the fact that over the next three decades, the rate at which vehicles in maritime, aviation and road transport are replaced and renewed will vary very significantly, while heavy-duty vehicles for long-haul transport are replaced in the market for every 2 to 4 years, aircraft and ships are often in the transport market for up to 40 years. In the light of IMO 2020 global sulphur cap, conventional oil-based residual marine fuels will need to either change in their specification or be replaced by alternative fuels like liquefied natural gas (LNG). There is an urgent need for standardization of alternative fuels and technologies. This a necessary condition for increased promotion and adoption of alternative fuels, and no less importantly, the general acceptance of engine and vehicle manufacturers, in addition to fuel distributors.

Increasing energy efficiency is another way of decreasing carbon intensity of shipping by using some new innovative solutions. Marine organisms accumulate on the surface of the hull, increasing both the weight, drag and ultimately fuel consumption by up to 40%. Modern anti-fouling paints[5] use chemicals to inhibit the growth of organisms, but the chemicals damage the organisms and interrupt the food chain. A new solution developed at Kiel University uses the mechanical properties of poly-thiourethane to create better contact to the hull in order to prevent organisms growing on hulls by making it harder for them to latch on. This new solution had found to be significantly better for the environment (Hopwood, 2019). A lot of technology is already available and some of it is relatively easy to implement, slow steaming, improved voyage planning, and trim optimization, hull coating and propeller cleaning. Not all solutions can be applied to all types of ships, and individual saving measures cannot simply be added together. Currently uptake of many of these technologies is limited due to the cost of implementation and a lack of knowledge regarding their effectiveness on specific ship types/sizes/routes.

A sea change is in the making as the global shipping industry strives to reduce its impact on the environment with innovative solutions like battery-operated vessels, wind-powered ships and carbon-neutral shipping. A variety of approaches have been developed to reduce the carbon intensity of shipping, such as improving the energy efficiency of vessels, integrating exhaust gas treatment and waste heat recovery, but these alone cannot decarbonize shipping. As the industry sets new environmental goals for itself green shipping is emerging as the key trend changer.

Green shipping is about cleaner practices on the emission control, port management and equipment lifestyles i.e., circular economy. Achieving this will require a lot of effort by the industry in collaboration with regulators, port authorities and communities. With the rapidly developing energy sector, new and emerging technologies and innovations are paving their way for opportunities and capabilities that were previously unthinkable.

Although the switch to alternative fuels is essential in breaking the dependence upon fossil fuels, the process is a complex one and will take decades to implement fully. Existing infrastructure, which is for liquid and gaseous fossil fuels, does not support all new fuels and energy carriers. As demand for electricity increases in harbors, major investments will be required to strengthen the grid. Moreover, due to the varying physical and chemical properties of the fuels, storage solutions differ, as do handling requirements. For example, energy densities vary enormously in commonly used energy storage materials, ranging from 1 MJ/L for lithium-ion battery to 40 times that for fossil fuels. In other words, fossil fuels require 40 time less space (volume) than an

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[5] Anti-fouling paint is a category of commercially available underwater hull paints, a specialized category of coatings applied as the outer (outboard) layer to the hull of a ship or a boat, to slow the growth and facilitate detachment of subaquatic organisms that attach to the hull and can affect a vessel's performance and durability.

energy-equivalent battery, but at the same time, an electrical motor is much more energy efficient than a combustion motor (90 versus 30 in energy efficiency). Differing properties and consumption processes also result in a host of waste products and emissions to air, water and sometimes soil, requiring various degrees of after-treatment and recycling of components of waste.

In the context of tightening environmental regulations and limits set on worldwide set worldwide shipping emissions have increased the attractiveness of gas as marine fuel, and LNG has emerged as the principal alternative fuel option being adopted today.

All these trends increase the attractiveness of gas as marine fuel as it brings along many possibilities regarding the phasing in other types of fuels, including synthetic fuels, biodiesel, hydrogen and ammonia. However, these fuel technologies will take considerable time to develop, and in the meantime, LNG should be viewed as more than just a “bridging fuel” because it offers an immediate carbon-reducing option which could well be used in the construction of the next generation of ships.

Unlike conventional fuels such as heavy fuel oil (HFO) and diesel used in maritime shipping, LNG produces 15 per cent to 29 per cent less carbon dioxide. It also produces less sulphur oxides, particulate matter and nitrogen oxide, which reduces air pollution and the threat to human health. By 2030, 10% of the global shipping fleet will be powered by LNG. However, switching to LNG combustion does not come without risks. The extraction, processing and transport of natural gas produces leaks and greenhouse gas emissions, and LNG is carbon-based, making it a transitional fuel. Switching the rest of the global fleet to other low-carbon fuel alternatives will be driven by market-based strategies, such as taxes or levies on heavy fuel oil and diesel. It can be assumed that LNG as a mature technology and a long-term solution can later be substituted by a renewable form of LNG (e.g liquefied bio- and synthetic methane).

Despite the fact that LNG is a hydrocarbon it is better to start with something that reduces emissions, rather than waiting for a better alternative. Aside from LNG, no commercially viable replacement fuel has emerged that can be used for marine engines, at least before 2030. Even then, LNG can be used alongside the possible bio- and synthetic replacement under development, such as ammonia and hydrogen, because they would use the same bunkering infrastructure. Hydrogen and in particular ammonia have the potential to address carbon emissions, however the technology and supply chains for hydrogen are not currently commercially developed, with higher costs than some competing options. The maritime industry has already identifying the significant potential for ammonia as a green fuel for shipping, noting its ease of storage, existing networks and flexible use in both fuel cells and combustion engines. Ammonia's potential as a transport fuel has been demonstrated by NASA in its deployment in rockets.

Liquefied bio-LNG and synthetic methane have long been advocated by supporters of liquefied natural gas as viable decarbonisation options, as they can use the same infrastructure and would require minor vessel modifications. These future fuels have the potential to be competitive zero-carbon fuel, but carbon pricing policies and greater renewable electricity supply will be necessary, according to a study by CE Delft. Based on an extensive review of the global availability of biomass, and the maturity of technologies to produce biomethane and synthetic methane, in principle sufficient amounts could be produced to fuel the shipping sector. However, other sectors are also likely to demand methane, and it is necessary to make significant investments in the production capacity.

The focus on environmental agenda is also seen in the defence sector where international militaries have set ambitious environmental targets, most noticeably based around significant reductions in energy consumption, increased focus on energy efficiency, reliance on fossil fuel and carbon emissions. In this context, Navy is not an exception as it too contributes to the global dioxide (CO_2) emissions. There is definitely a societal pressure on the Navy to play its part and become greener.

For example, the Netherlands Ministry of Defence has declared the ambition to reduce fossil fuel dependency by at least 20% in 2030 and by at least 70% in 2050. For the Dutch Royal Navy (RNLN), these targets seem more stringent than the initial strategy on greenhouse gas reduction for ships agreed by the IMO, which aims for 50% reduction in total annual global shipping emission by 2050. The RNLN is currently investigating the replacement of a series of support vessels, 5 ships between 1000 and 2000 tons that perform hydrographic, submarine exercise support and seamanship training operations. These vessels perform support operations and are not volume critical in their design and have a limited mission duration of 2 to 3 weeks, and thus they seem to be good candidates for alternative fuels.

To reduce emissions in the Navies, innovative solutions need to be found and these solutions will come from new and emerging technologies and improvements in through life environmental impact in shipyards, maintenance facilities and system and equipment suppliers. All of this must be done while maintaining the capabilities of a Navy which can be deployed anywhere in the world on sustained operations to project power in the maritime environment.

In recent years, many states have developed and implemented green solutions for defence. Building on these initiatives NATO formulated the NATO Green Defence Framework in 2014. This framework provides a broad basis for cooperation within the Alliance on green solutions by unfolding how green technologies and green strategies have been developed and used to handle current security challenges. Green defence initiatives are often borne out of the desire to untether the military from exorbitant fuel requirements. In addition to being seen as cost reducing measures, interest in green defence stems from a desire to mitigate operational risks, such as attacks on fuel convoys, that jeopardize troop safety and sometimes to increase energy independence. Green defence refers to the development and implementation of eco-friendly processes undertaken by armed forces to increase energy efficiency and mitigate adverse effects on the environment without negatively affecting operational readiness.

The clear leader of green defence is the USA, with each military service enacting its own strategy. The Department of Defence, responsible for 80 per cent of total US government energy usage, seeks to increase energy independence, decrease costs, and enhance troop safety. The US Navy's *Great Green Fleet* has received the most attention, with the US Air Force Energy Flight Plan and Operational Energy Strategy as close seconds. In October 2009, Navy Secretary Ray Mabus committed the Navy and Marine Corps to creating a *"Green Strike Group"* composed on nuclear vessels and ships powered by biofuels by 2012 and deploying it by 2016. By 2020, at least 50 % of the energy the Navy consumes is to come from alternative sources. The "Great Green Fleet" was the next step in a service-wide energy conservation effort that had seen the Navy cut its oil consumption since 2009 by 15% and the Marine Corps curbed its oil consumption even by 60%.

On the other hand, the Great Green Fleet initiative was more about showing symbolic support for alternative fuels than actual military need. However, Congressional pressure has curbed USA efforts, notably disabling the Department of Defence from purchasing biofuels when petroleum is less expensive, not taking into account the greater efficiency returns that over time make green technologies more cost effective. Furthermore, the lack of a Pentagon-wide strategy on green defence has been criticized for creating "strategic cacophony" between the services, which could be avoidable in small states. Based upon the U.S example it can be said that investment in facilities which support biofuels are needed and there are concerns over land use where bio-crops are grown rather than edible foods, adding to food insecurity.

CHAPTER 1

LOWERING EMISSIONS-POLICY AND REGULATORY CONTEXT IN THE SHIPPING SECTOR

This chapter focuses on lowering emissions from the shipping sector. It discusses marine transportation as a source of airborne emissions and the efforts undertaken to limit its emissions. Various regulations which have been implemented by the

International Maritime Organization (IMO) in order to limit these emissions are also evaluated. These include limiting sulphur content in fuels and declaration of Emission Control Area (ECAs), adoption of NO_x Emission Standards for Engines and Energy Efficiency Design Index (EEDI). The implications of these regulations are studied and the chapter concludes with an assessment of the challenges in lowering emissions from the shipping sector.

The need to achieve net-zero greenhouse gas emissions from all human activities has never been clearer. Reducing the intensity of emissions from fuel sources is a priority as recommended by the world's most authoritative global climate science body, the Intergovernmental Panel on Climate Change (IPCC). The IPCC shows that there is a need to increase the share of low-carbon transportation fuels (e.g. biofuels, electricity, hydrogen) from around 3 percent today to nearly 10 percent by 2030, and around 35 percent by 2050 (Olson et al., 2015)[6].

The oil and gas industry is usually divided into 3 major sectors: upstream, midstream, and downstream. The downstream sector is the refining of petroleum crude oil and the processing and purifying of natural gas, as well as the marketing, distribution of products derived from crude oil and natural gas. Downstream is converting these resources into the fuels and finished products including refining crude oil into gasoline, natural gas liquids, diesel and a variety of other energy sources. Upstream is about extracting oil and natural gas from the ground, whereas midstream is about safely moving those thousands of miles. Emissions from fuel production are a growing source of impacts within transportation as alternatives to conventional petroleum, such as unconventional sources and natural gas, are associated with higher potential for emissions that occur "upstream".

There are largely mature technologies available within the buildings, industry and transport sector that could enable significant improvements in energy productivity. Improvements within transport can be made through incremental improvements in mature technologies, such as higher efficiency internal combustion engines. Fuel substitution (e.g advanced biofuels, hydrogen vehicles and particularly electric vehicles) will increasingly deliver abatement, and energy productivity in transport can be further improved through demand reduction (e.g mode shifting, improved routing in freight).

Innovative technologies could allow fugitive emissions from oil and gas production to be reduced by up to 40% compared to business as usual scenario in future. Fugitive emissions from liquefied natural gas (LNG) production could be reduced by deployment of Carbon, Capture and Storage (CCS). It is a technology designed to capture CO_2 emissions produced from the use of fossil fuels in electricity generation and industrial processes, including its transport and storage underground, so that it does not enter the atmosphere. It is considered to be of critical importance to industrial sectors, such as cement, iron and steel, chemicals and refining, as it can also target their high share of non-energy related CO_2 emissions that relate to industrial processes and cannot be reduced by energy efficiency measures.

Carbon, Capture and Storage (CCS) in industrial applications is projected to facilitate a reduction of CO_2 emissions by up to 4.0 Gt a year by 2050, which would consequently result to approximately 9% of the global reductions needed to halve energy-related CO_2 emissions in 2050. Such an outcome would require the installation of CCS equipment to 20-40% of industrial and fuel transformation plants by 2050.

Forecasts to 2040 predict that global energy demand will increase for all modes of transport, including these "hard to reach" areas. The decarbonisation of transport will require the replacement of energy dense fossil fuels (diesel, aviation and bunker fuel) with low or zero-carbon sustainable fuels. Production routes to synthetic fuels, such as the Fischer-Tropsch conversion

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[6] Olson, M., Garcia, M, Robinson, M., Rooy, P., Dietenberger, M., Bergin, M., Schauer, J. "Investigation of black and brown carbon multiple-wavelength-dependent light absorption from biomass and fossil fuel combustion source emissions" in Journal of Geophysical Research Atmospheres, pp 1-16 (2015)

and methanol synthesis, are well-known and are currently applied commercially to fossil carbon sources, such as coal and natural gas.

Fischer-Tropsch synthesis is a catalyzed chemical reaction in which synthesis gas (syngas), a mixture of carbon monoxide (CO) and hydrogen (H_2), is converted into gaseous, liquid, and solid hydrocarbons and an appreciable amount of oxygenates (Chadeesingh, 2011)[7]. This process is a highly promising, developing option for environmentally sound production of chemicals and fuels from biomass, coal and natural gas reserves, and significant, projected increases in demand for liquid fuels. It is expected to play an ever increasing role in the coming decades. Thus, as crude oil production decreases and its price increases, the Fischer-Tropsch (F-T) technology which enables the production of synthetic hydrocarbons from coal or natural gas feedstocks is becoming an increasingly attractive technology in the energy mix.

In fact, coupled with this is the fact that Fischer-Tropsch products are ultra clean fuels in that they contain no aromatics, sulphur or nitrogen compounds. With the intensification of global pressures to reduce greenhouse gas emissions, legislative frameworks in Europe and the USA have already been put in place to force producers of liquid transportation fuels to comply with stricter emission standards. The impact of such legislation is that dilution of petroleum derived fuels with the cleaner Fischer-Tropsch derived hydrocarbons is becoming an increasingly important way to achieve environmental compliance. It is thus not surprising that Fischer-Tropsch technology now occupies a visible place in the energy mix required for sustainable global development.

A Fischer-Tropsch plant incorporates three major process blocks: (1) production of synthesis gas, i.e. mixture of carbon monoxide and hydrogen (steam reforming), (2) conversion of synthesis gas to aliphatic hydrocarbons and water (Fischer-Tropsch synthesis process), and (3) hydrocracking of the longer chain, waxy synthetic hydrocarbons to fuel grade fractions. Of these three steps, the production of synthesis gas is the most energy intensive as well as expensive and this step can account for as much as 50 to 75% of capital costs (Speight, 2014)[8].

The shipping industry explores how to decarbonize by mid-century, and at a minimum meet the level of ambition set out in the initial IMO Strategy on reduction of GHG (greenhouse gas) emissions from ships (MEPC.304 (72)) of reducing absolute GHG emissions by at least 50% from a 2008 baseline by 2050. Zero-carbon fuels will need to be commercially available and produced from either renewable electricity, biomass or natural gas with Carbon, Capture and Storage.

Biomass-derived fuels are being tested as drop-in fuels on certain routes because they can burn on existing combustion engines. A drop-in fuel is a synthetic and completely interchangeable substitute for conventional petroleum-derived hydrocarbon (e.g gasoline, jet fuel, and diesel). It means that it does not require adaptation of the engine fuel system or the fuel distribution network. Biofuels are likely to be only a transitional solution because they have capacity constraints as production of biomass is in competition with food production. Other industries' transition away from fossil fuels, the competition is going to be high - and it is not shipping that is going to win. So hydrogen and other synthetic non-carbon fuels seem to have the highest potential long term solution. Although, it is not clear which of the potential zero-carbon alternatives to fossil fuels has the winning combination of availability, sustainability and competitiveness. There is definitely a potential for these and other new production routes to contribute to the future decarbonisation of the transport sector as a direct route from power (electricity) to liquid.

1.1 SHIPPING CONTEXT

A broad coalition of large maritime companies have joined together to accelerate the transition to zero-carbon shipping, setting a clear milestone for meeting the IMO 2050 goal of a 50 per cent reduction in carbon emissions. Efficiency measures

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[7] Chadeesingh, R. (2011), "The Biofuels Handbook", Chapter 5, Cambridge, UK

[8] Speight, G (2014), "Gasification of Unconventional Feedstock"

can only keep emissions standing still, not bring it down. The short-term efficiency approaches being embraced by carriers and ship-owners are a myriad, for example, a Finnish company Norsepower is testing 30-meter, cylindrical, mechanical sails. During a year-long testing on a Danish shipping company Maersk tanker, the sails cut fuel consumption almost 8.2%.

Over the long-term, sustainable shipping will require a major breakthrough in low-carbon fuel and propulsion technologies. The ambition of the new consortium - the Global Maritime Forum's "Getting to Zero Coalition" - is to have commercially viable zero emission vessels (ZEVs) operating along deep sea trade routes by 2030. In order to make zero-emission vessels a reality by 2030, the shipping sector and the fuel supply chain - the supply and demand side need to move in tandem. A transition needs to take place requiring government initiatives, investment, and R&D. For short sea shipping, like ferries, electrification is a possibility and hybrid and electric ferries already exist in Norway, Denmark and Sweden.

Zero-emission vessels' concept aims at ending the utilization of fossil-fuels (ZEV) and it can provide the logistics of current fleets but without operational emissions. It can be assumed that improving energy efficiency will not be enough to reach this goal: commercially viable, zero-emission vessels must start entering the global fleet by 2030, with their numbers radically scaled through the 2030s, and 2040s. Zero-emission vessels will be technology-neutral, focused on the zero carbon energy sources that are most likely to be technologically, economically, and politically feasible at large scale. It calls for immediate action towards the goal: since ships can be operated for decades, the vessels entering the world fleet around 2030 can be expected to be operational in 2050. This means that new building orders placed in just 10 years' time will factor into whether the goal is achieved or not. Similarly, infrastructure associated with fuel supply chains can have a long economic life of up to 50 years, and reconfiguration to new fuels can be a lengthy process. The large amounts of zero carbon energy resources required will also need to be sourced.

From a technological point of view, there is also a Norwegian company that uses Vindskip concept, a hybrid vessel design using wind and LNG that mimics an airplane wing. Another promising example is an Ecoship from NYK which combines "flapping foil" with hydrogen and solar power. Thus, zero-emission vessels and new fuels are not yet reality, and their competitiveness with fossil fuels and vessels remains unclear. Price and availability present barriers to low-carbon fuel adoption. A major barrier to preparedness is the price differential as carbon prices increase and the low-carbon fuels come down. Although currently very expensive, electro-fuels are set to become affordable by 2050. Electro-fuels (synthetic fuel) are an emerging class of carbon-neutral drop-in replacement fuels that are made by storing electrical energy from renewable sources in the chemical bonds of liquid or gas fuels.

With regard to the IMO sulphur cap regulation that entered into force on 1 January 2020, shipping companies and fuel providers have been using new blends of fuels to meet the sulphur guidelines. But instead, research suggested that the new fuels could lead to an increase of the sector's climate impacts. A study conducted by Finland and Germany and submitted to the IMO found that the new very low sulphur fuel oil (VLSFO) used by ships contained more aromatic compounds which are causing a surge of black carbon emissions - a short lived pollutant that strongly absorbs sunlight and traps heat in the atmosphere, contributing to global warming.

According to the study, the new hybrid fuels resulted in the 10% to 85% increase in black carbon emissions compared to previously used heavy fuel oil. Black carbon is already estimated to represent up to 21% of shipping's climate impact. Whilst the decarbonisation of electricity is progressing and many transport modes can feasibly be electrified, some transport modes, such as heavy-duty vehicles, aircraft and shipping will require different technological options. Successful decarbonisation requires a combination of measures from areas such as technological, operational and alternative energy. The simplest solution that has been identified so far is a form of liquid fuel to replace heavy fuel oil. There are three options being explored. Biomass-derived fuels, so biofuel or biogas. Hydrogen and synthetic non-carbon fuels, like ammonia, for example, which are derived from renewable energy or fossil fuels combined with Carbon, Capture and Storage (CCS). Synthetic fuels, like e-methanol, that can be carbon-neutral based on the production process.

The recent strengthening of sulphur standards is essentially encouraging a shift away from marine fuel oil, yet by focusing on sulphur in isolation, the regulations are incentivizing changes that ignore opportunities to address the climate change challenge at the same time. Technology offers huge potential for decarbonizing the shipping sector, even in the short- to medium term. But if the sector is to step up to the decarbonisation challenge, then the scale of change offered by the technologies and any co-benefits or trade-offs necessary needs to be examined in detail.

1.2 EUROPEAN UNION CLIMATE POLICY

The greenhouse gases generated by industrial activity constitute a significant share of total emissions in the European Union. The EU Emissions Trading System (EU ETS) is the cornerstone of policies leading to reduction in industrial emissions that was officially launched in 2005 and can be considered the first and largest market based regulation mechanism to reduce GHG emissions. It is the key policy instrument for reducing industrial GHG emissions cost-effectively. The EU ETS applies to heavy energy-intensive installations in power and heat generation, as well as several energy-intensive manufacturing industry sectors and commercial aviation, mainly dealing with CO_2 emissions. In total, it includes more than 11,000 power stations and industrial plants across the EU, covering around 45% of total GHG emissions from the 28 EU countries.

The EU has set itself objectives for reducing GHG emissions up to 2050. For 2020, the EU gave a commitment to reduce GHG emissions by 20% relative to 1990 levels. This is one of the binding key targets in the 2020 Climate and Energy Package. Looking beyond 2020, the EU has set itself a binding target of reducing GHG emissions to 40% below 1990 levels by 2030. The objective is part of the 2030 Climate &Energy Framework, which builds on the 2020 Climate and Energy Package. For 2050, the EU leaders committed to reduce emissions by 80-95% by 2050 as part of efforts by developed countries as a group to reduce their emissions to a similar extent. In 2016, the European Commission published a roadmap for building a "low-carbon" European economy in which this long-term goal is also implemented.

The EU is therefore very ambitious in setting its reduction goals. It is also participating in international efforts to tackle climate change under the framework of UNFCC.[9] The EU has committed to a second phase of the Kyoto Protocol (2013-2020), with its internal 20% reduction target forming the basis for this commitment. The EU is also part of the Paris Climate Agreement, which was adopted in 2015.

In the EU context, the fight against climate change is generally split into 2 fields: the sectors that fall under the EU Emissions Trading System (EU ETS), and those that are subject to the Effort Sharing Decision (ESD)[10]. The EU ETS is based on the principle of "cap and trade", where a cap is set on the total amount of GHG emissions admissible under the scheme. Companies are required to hold or purchase sufficient emissions allowances to cover the emissions they produce. By creating a price on emissions, the system aims to incentivize efforts to reduce emissions. Participants in this emissions trading system must have an approved monitoring plan, according to which they commit to monitor their emissions on an annual basis. As far as the industrial installations are concerned, the monitoring plan is a part of the approved permit that is also required. In case, participants do not surrender the appropriate amount of emission allowances that cover emissions generated by their activity, they have to pay severe fines.

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[9] UNFCC – United Nations Framework Convention on Climate Change.

[10] The Effort Sharing legislation establishes binding annual greenhouse gas emissions targets for Member-States for the periods 2013-2020 and 2021-2030. These targets concern emissions from most sectors not included in the EU Emissions Trading System, such as transport, buildings, agriculture and waste.

Due to a repeated oversupply of allowances, initially due to a lenient allocation on the national level, and from 2008 onwards due to the financial and economic crisis, allowance prices have declined significantly and only provide a limited incentive for emission reduction. Therefore, a temporary withdrawal of a number of allowances (so-called "back loading") has been agreed until 2019-2020, in order to increase demand. However, GHG emissions restrictions posed by the EU ETS have created competition between European and developing countries; the latter are not subject to such limitations. This situation can result in "carbon leakage", which specifically refers to businesses transferring their production to other countries with laxer GHG constraints, due to economic costs.

As at present shipping sector is not covered by the EU ETS, the European Commission also plans to extend its Emissions Trading Scheme to Shipping, Aviation and Road transport. These non-ETS sectors - such as transport, buildings and agriculture- should cut emissions by 10% by 2020 compared to 2005 levels. Individual contributions for each member-state were broken down according to gross domestic product (GDP). Both international shipping and aviation are mentioned in the Kyoto Protocol as sectors that should be regulated under auspice of the International Commercial Aviation Organization (ICAO) and the International Maritime Organization (IMO). Due to slow progress of the international scheme under ICAO, aviation was nonetheless unilaterally included in the EU ETS in 2012. The international nature of the industry and need for an international approach is also the reason why shipping has not yet been included in the EU ETS system. The call for an improvement in ETS comes two years after shipping was excluded from the EU ETS. At the end of 2017, a potential inclusion of shipping in the EU's Emission Trading System faced strong opposition by ship-owners who would rather lobby with the IMO on the imposition of global standards.

The supporters of the inclusion of shipping in the EU ETS saw a way to push IMO to reach more tangible decisions for minimizing shipping emissions. However, ship-owners through the European Community Ship-owners' Association (ECSA) as well as other major associations like International Chamber of Shipping (ICS) and Danish Shipping claimed that putting unrealistic pressure on IMO with regional rather than global measures was not the way to proceed. Instead, a more global and unified approach through the cooperation of EU with the IMO would achieve more tangible results. As such the EU opted for giving time to the shipping industry to realize its initial CO_2 reduction objectives, demonstrating confidence that the IMO would make efficient progress.

The implementation of the maritime sector in the EU ETS might be ambitious, but there are several challenges which cannot be overlooked. The main purpose of an EU ETS is to reduce GHG emissions. However, with a regional scheme, the scope is only limited, so it is important that it is designed in a way that it is environmentally effective. The geographic scope is thereby very important. The EU ETS for shipping also entails an administrative challenge, such as compliance and enforcement. Until recently, there was only limited data available on emissions from shipping, which makes cap-setting, enforcement and monitoring more difficult. However, in 2015, the EU adopted a Regulation on the monitoring, reporting and verification of carbon dioxide emissions (MRV) from maritime transport, which makes it possible to acquire more information on ships' emissions. The MRV Regulation could be a first step to implement shipping in the EU ETS.

The European Green Deal

In the last decade, the European Union member-states have led the global shift towards renewable energy and set up the largest emissions trading system to price carbon and reduce reliance on more polluting fuels.

The European Commission (EC) presented the European Green Deal on 11 December 2019, with the ambition of becoming the first climate-neutral bloc in the world by 2050. The new climate policy foresees the inclusion of the maritime sector in the EU Emissions Trading System, (ETS) following years of contradictory negotiations. The Green Deal also highlighted that transport accounts for 25% of the EU's greenhouse gas emissions, and to achieve climate neutrality, a 90% reduction in transport emissions is needed by 2050. The EU should also ramp up the production and deployment of alternative transport fuels. In addition to its proposal to extend emission trading to maritime sector, the Commission will take action in relation to maritime transport.

A European Green Deal shares targets for a more environmentally oriented Europe, with six key areas of focus:

- A climate neutral EU by 2050;
- An improved EU ETS;
- A carbon border tax;
- A move away from unanimous decision-making on climate and energy;
- 2030 emission reduction targets of at least 50% and moving towards 55%.

The carbon border adjustment mechanism envisioned by the European Commission as a part of its Green Deal package could lead to trade disputes with other countries. The governments like the US and Australia have a completely different approach to climate. They might consider it as an arbitrary and unjustifiable discrimination. Additionally it would be very difficult to assess the CO_2 footprint of complex products which parts have been manufactured in several countries.

1.3 IMO REGULATIONS

The International Maritime Organization (IMO) is the regulator of international shipping providing the institutional framework for promoting the safety, security and environmental performance of international shipping. This organization has identified "the promotion of sustainable shipping and sustainable maritime development" as one of its major priorities in the next few years. The implementation arm of IMO is the Marine Environmental Protection Committee (MEPC) which has adopted many international treaties for control of pollution from ships. These include air emissions, ballast water discharges, oil spillages, ship recycling, and garbage disposal at sea, and emission of volatile organic compounds (VOCs).

The international framework for LNG as a fuel, similarly to the European context, starts with the main environmental instrument MARPOL, imposing restriction on air emissions from ships, through its Annex VI regulations 13 and 14, for NO_x and SO_x emissions respectively that was forced on 19 May 2005. These annexes cover emissions of ozone depleting substances (ODS), nitrogen oxides (NO_x), sulphur oxides (SO_x), particulate matter (PM), etc., and it specifies the percentage of sulphur which is permissible to be used as fuel onboard ships.

Three key agreements have been adopted by the IMO for control of airborne emissions since 2010, and these continue to be implemented by the Marine Environment Protection Committee (MEPC) in a phased manner. These are: (a) limiting sulphur content in fuel and adoption of Emission Control Areas (ECAs), (2) adoption of NO_x Emission Standards for Engines, (3) implementing Energy Efficiency Design Index (EEDI) for ships, and (4) Ship Energy Efficiency Management Plan (SEEMP) onboard ships.

1.3.1 LIMITING SULPHUR CONTENT IN FUEL

There are two sets of fuel quality requirements which are defined for bunker fuels onboard ships. These requirements were adopted under the International Convention for the Prevention of Pollution from ships (MARPOL). This above-mentioned convention adopted in 1973, as amended by and incorporated in the protocol of 1978 (MARPOL), is the most important international maritime convention for the prevention of vessel-source pollution. MARPOL consists of a framework convention, as amended by the protocol of 1978, and six annexes, the first two of which are mandatory, while the rest are optional. There are 155 state parties to the convention proper and mandatory annexes (oil pollution, noxious liquid substances in bulk), representing 99.14 of global tonnage. Optional annexes III (harmful substances carried in package form), IV (sewage), and V (garbage) also enjoy high subscription levels. Annex VI was introduced into MARPOL through the protocol of 1997. Although optional, Annex VI is the regulatory vehicle for GHG emissions from international shipping.

In principle, states that are not parties to Annex VI are under no legal obligation to implement and enforce those rules. In accordance with Annex VI of MARPOL convention, certain stringent requirements are applicable to ships in Emission Control Areas (ECAs) while more relaxed requirements are applicable globally in regions outside the ECA. Figure 1 shows the sulphur content in fuel which is permitted outside an ECA

Figure 1. Allowable limits of sulphur fuel outside ECA

Date	Sulphur content (% m/m)
Prior to 01 January 2012	4.50
On and after 01 January 2012	3.50
On and after 01 January 2020	0.50

Modified from the article "Lowering Emissions from the Shipping Sector" by Kapil Narula.

Earlier ships used marine bunker fuel having a sulphur content of more than 4.5% m/m. This was lowered to 3.5% m/m on 01 January 2012, and it was agreed to lower it further to 0.5% from 01 January 2020, subject to a feasibility review which was to be completed no later than 2018. This review was conducted in the 70th meeting of the MEPC in October 2016 and it upheld its decision to go ahead with the implementation date of 01 January 2020 for a global reduction of sulphur content in fuel used onboard ships to 0.5% m/m. These regulations are expected to lower emission of SO_x by a large extent from the shipping sector after 2020.

Emission Control Areas (ECAs) are specially protected areas which are sensitive to marine pollution and have high density of shipping. An Emission Control Area can be designated for SO_x and PM, or NO_x, or all three types of emissions from ships, subject to a proposal from a Party to Annex VI. The existing established ECAs under MARPOL are as follows (IMO 2018b):

- Baltic Sea area - defined in Annex I (SO_x only),
- North Sea area - defined in Annex V (SO_x only)
- North American area (designated coastal areas around the coast of US and Canada, effected from 01 August 2012) - defined in Appendix VII of Annex VI (for SO_x, NO_x, and PM),
- US Caribbean Sea area (areas around Puerto Rico and the US Virgin Islands, effected from 01 January 2014) - defined in Appendix VII of Annex VI (for SO_x, NO_x, and PM).

Expanding the ECA to Singapore, Australia and the Mediterranean region is also under active consideration by IMO. Figure 2 shows the sulphur content in fuel which is permitted inside an ECA.

Figure 2. Allowable limits of sulphur content in fuel inside an ECA

Date	Sulphur content (% m/m)
Prior to 01 January 2012	1.50
On and after 01 January 2012	1.00
On and after 01 January 2020	0.10

Modified from the article "Lowering Emissions from the Shipping Sector" by Kapil Narula.

When a ship is entering an Emission Control Area (ECA), it has to mandatorily use a fuel with lower sulphur content. This reduction of sulphur content limits the SO_x and PM emissions from dual combustion thereby contributing to a cleaner marine environment in the ECA. Hence, only ships which have an onboard arrangement to carry out fuel switching or use low sulphur fuel through the entire journey can dock in ports located in the ECA. This restricts the entry of only a select class of ships in the ECA areas. The latest regulations implemented on 01 January 2015 reduced the permissible amount of sulphur content in fuel oil used onboard ships by ten times from the earlier 1.00% m/m (by weight) to 0.10% m/m. It is estimated that a shift from 1 to 0.1% in sulphur content of the fuel will have positive implications on the marine environment as it will lead to a 90% reduction in SO_x emissions and approximately 20% reduction in PM emissions. Adoption of a larger number of ECAs would drive the growth of environmental sustainability in the shipping industry.

Countries are also free to undertake measures to lower emissions from ships in their maritime areas of jurisdiction. In this regard, China has declared three emission control areas (ECAs) from 01 January 2016 (e.g in Pearl River Delta, Yangtze River delta and Bohai Sea). Although these are not linked to the IMO declared ECAs they pave the way for low sulphur fuel content used onboard ships.

1.3.2 IMPLEMENTING ENERGY EFFICIENCY DESIGN INDEX (EEDI) FOR SHIPS

The second IMO GHG Study that was adopted in 2009 identified a significant potential for further improvements in energy efficiency, mainly through the use of already existing technologies such as more efficient engines and propulsion systems, improved hull designs and larger ships or, in other words, through technical- and design-based measures that can achieve noteworthy reductions in fuel consumption and resulting CO_2 emissions on a capacity basis (ton-mile). The study also concluded that additional reductions could be obtained through operational measures such as lower speed and voyage optimization, etc.

The Kyoto Protocol recognized and acknowledged that greenhouse gas (GHG) emissions from ships cannot be attributed to any particular country or economy due to the complex international nature of the shipping industry. In response, the IMO's Marine Environmental Protection Committee (MEPC) 62 session held in July 2011, amended Annex VI with Resolution MEPC. 203(62) and a new chapter IV was introduced which includes regulations to control the energy efficiency of ships. These regulations imply a number of mandatory, cost effective, operational and technical measures for various ship types which are responsible for approximately 85% of GHG emissions, primarily CO_2 which is the most significant GHG effect contributor.

The Chapter IV of the Annex VI came into force on 1 January 2013. It has been amended over the years, to contain regulatory provisions, including guidelines which were further developed to assist in the implementation of the regulations. It currently comprises six regulations and 13 related guidelines which apply to all internationally trading ships of 400 GT and more.

The main technical measure of compliance with the regulations is the Energy Efficiency Design Index (EEDI) which is a performance based mechanism for a new ship or one which has undergone a major conversion and represents its minimum required energy efficiency calculated using an IMO developed formula. It has been developed as a tool to monitor and reduce the carbon emissions from ships by improving their energy efficiency. As a result, higher requirements are placed on the propulsion design of ships, especially for those conventional ones, in order to meet the EEDI regulations (Hon, G et al., 2019).

Since EEDI is mandatory, the Norwegian Marine Technology Research Institute investigated the application of existing analytical tools and methods to figure out GHG emissions reduction possibilities through different technical, operational and market-based approaches, and according to the study, EEDI indeed promotes the improvements on ships to decrease CO_2 emissions (Henning Sen et al., 2000). According to this report ship hull optimization, alternative energy, innovative energy efficient technologies and ship speed reduction are the popular methods to reduce CO_2 emissions and meet the EEDI regulations.

Ship hull optimization is mainly used to the new ships, and taking into account the influence of hull structure on EEDI restrictions, a reasonable criterion to optimize the energy structure of ship hull under EEDI can be given. Liquefied natural gas (LNG) as a green fuel has been increasingly used as an alternative energy for marine vessels to have better environmental protection. After the comparison between classical fuel type (heavy fuel oil, HFO) and LNG propulsion systems, it turned out that LNG has a lower EEDI value under the same ship operating conditions (Faitar et al., 2016).

Aimed at promoting use of more energy-efficient equipment and machinery, the Energy Efficiency Design Index (EEDI) has been introduced in several phases with more stringent requirements each time, which require vessels to demonstrate a minimum ton-mile energy efficiency level, calculated depending on vessel size and segment. Phase 3 was originally scheduled for introduction in 2025 but has been brought forward to 2022, meaning vessels constructed after that date will need to demonstrate a design efficiency at least 30% lower than the reference line.

1.3.3 ADOPTION OF NO$_x$ EMISSIONS STANDARDS FOR ENGINES

Similar to the regulation for control of SO$_x$ emissions, there are regulations to control NO$_x$ emissions. NO$_x$ limits have been defined in tiers which are divided according to the date of ship construction as follows (IMO, 2018c):

- Tier I – Ships constructed from 01 January 2000 to 31 December 2010;
- Tier II – Ships constructed after 01 January 2011;
- Tier III – Ships constructed after 01 January 2016, while operating with ECA established to limit NO$_x$ emissions.

These limits are applicable to installed marine diesel engine of over 130kW output power. Within a particular tier, the actual limit value of NO$_x$ emissions (measured in g/kWh) is a function of the rated speed of the engine and decreases with an increase in speed. The total weighted cycle emission limit defined for an engine rpm less than 130 was 17.0 g/kWh in Tier I, 14.4 in Tier II and 3.4 in Tier III. Limits were also defined for higher engine speeds in different tiers. These regulations have resulted in lowering NO$_x$ emissions from ships globally as well as in ECAs limiting NO$_x$ emissions.

1.4 IMPLICATIONS OF THE MARPOL CONVENTION IMPLEMENTATION FOR THE NAVAL VESSELS

Although government vessels are currently exempt from much of the international legislation & regulation (e.g MARPOL), some Navies still comply with these regulations, for example the UK Royal Navy aims for compliance based on the UK Government's policy.

Notwithstanding the obligation to meet regulatory emissions standards, there are other compelling arguments to do so. Local populations and their attitudes to the environment have changed over the last two decades, and when warships steam in and out of harbor with clearly visible black funnel gases, the reputation of the vessel owner and associated nation can be tarnished. Meeting emissions regulations ease access into new areas: these could include a future need to patrol ice free areas of the Arctic. If emission reductions are achieved through reduced platform energy consumptions this offers the Navies and individual ship commanders an opportunity to enhance capability advantage through improved range, endurance and time of station.

Specific emissions challenges evolve, but 3 key areas are currently regulated at an international level:

- Sulphur oxides (SO$_x$) emissions are directly linked to sulphur content within fuel. Based on the UK example, the Royal Navy and Royal Fleet Auxiliary, operating with advanced gas turbines and high speed diesel use, use a mix of naval grade F-76 diesel and higher grades of commercial Marine Gasoil (MGO). Both of these fuels already have low sulphur levels resulting in limited impact to the Royal Navy and Royal Fleet Auxiliary.

- Reducing emissions of greenhouse gases (e.g CO_2) requires direct reduction of fuel use through improvements in prime mover efficiency or through reduction in energy demand on the platform. For example, the UK Ministry of Defence has and continues to investigate solutions to reduce energy demand, and has via the induction of integrated electrical power systems and the more widespread use of modern efficient diesels already made significant improvements in Platform efficiency.

- While increasing use of modern diesels has reduced GHG emissions for a given maritime capability, it leaves the Royal Navy more susceptible to changes in Nitrogen Oxide (NO_x) regulations. The Royal Navy is therefore, attempting to meet IMO MARPOL Tier III NOx regulation when operating in Emission Control Areas.

Compliance, therefore creates specific technical challenges for the Ministry of Defence. These include matching evolving changes in emissions policy and regulation, to transient and evolving emission control technologies, onto platforms with operating lives that typically exceed 30 years.

Emission control technologies developed for commercial maritime use are often designed with less focus on space and weight constraints that are found on naval platforms. Retrofitting of these options, therefore, is often unfeasible within naval space and weight limitations, with solutions also having the potential to aggravate other competing requirements in areas such as platform survivability and machinery availability. For example, Selective Catalytic Reduction (SCR) would necessitate a wholesale change to the modus operandi of naval task-groups through the necessity to provision liquid or pellet based urea in bulk. Finally, the failure of such systems must not affect operational capability, and so redundancy in terms of being able to by-pass such systems is essential, but again adding to the weight, space and cost of integration.

CHAPTER 2 MARINE FUELS

It has been estimated that as much of as 10% to 20% of global petroleum derived fuel is consumed in the marine applications. The fuels used in international shipping are called marine fuels, also known as bunker fuels. However, the annual global consumption of marine fuels is currently estimated at around 300 million tons (Shell LNG study, 2019)[11].

More than three quarters of the marine fuels are heavy fuel oils (referred to as HFO); nearly half (46%) of the global heavy fuel demand comes from shipping. Marine gas oil (MGO) constitutes approximately a quarter of bunker fuels. The largest consumers of marine fuels are coming from Asia to Europe.

Marine fuels normally have to comply with particular requirements for viscosity, specific gravity, sulphur content, ignition point etc. The main international standard for marine fuels is ISO 8217, which divides marine fuels into two categories, distillate and residual fuels, which are subdivided into six or seven further fuel categories.

Distillate fuels, commonly called as "Gasoil" or "Marine Gasoil" are composed of petroleum fractions of crude oil that are separated in a refinery by a boiling process called distillation which makes them comparable to off-road diesel fuel in terms of technical properties and specification limits (JRC, 2016)[12] . Marine gas oil (MGO) has similar product characteristics to heating oil, except for the ignition temperature. These fuels have a low viscosity and flash point and a lower energy content measured by volume (by weight they have a higher energy content) than more viscous fuels but are generally cleaner and produce less polluting emissions. Large values such as 700 describe very viscous residual fuels. The lower the kinematic viscosity value, the thinner the fuel. As a rule, the thinner the viscosity, the higher the quality of the marine fuel.

Distillate fuels are divided into four classes: DMX, DMA, DMB and DMZ. DMX is a distillate that is used only in smaller engines (lifeboats/emergency units) and is intended for use outside the engine room. DMA is the most common compression ignition engine fuel for small and medium sized marine engines. DMB has some limited amount of contamination that DMA may pick up in dirty storage or transfer. DMB is not a fuel that is intentionally manufactured. DMC is intentionally manufactured from either heavier boiling fractions of straight-run distillate, called "cycle oil", or is blended in marine fuel terminals from DMA and residual fuels (JRC, 2016)[13] . The fourth distillate class, DMZ, must not contain residual

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[11] AShell LNG Outlook 2019.

[12] Moirangthem, K. (2016), "JRC Technical Reports: Alternative Fuels for Marine and Inland Waterways. An exploratory study", European Commission, Brussels

[13] Ibid, 2016.

fuel constituents, has a higher aromatics content and a slightly increased viscosity at 40 degrees Celsius compared with other distillate fuels. This is to ensure that the fuel injection can continue to cool and lubricate when switching from a low-quality marine fuel to DMZ (such as when moving into an ECA).

Residual fuels called “Marine fuel oil” or “Residual fuel oil” are derived from the fraction that did not boil in the distillation process, and are sometimes referred to as “tar”; they are waxy and denser in structure; have relatively high viscosity and high sulphur content. The blends of heavy fuel oil (e.g LSFO, ULSFO) and distillates frequently used in practice are described as marine diesel oil (MDO) or intermediate fuel oil (IFO). Heavy fuel oil (HFO) is a residual fuel from crude processing. Unlike MGO, heavy fuel oil must be heated before it can be used.

Residual fuels are divided into six fuel types depending on their viscosity (kinematic viscosity) - RMA, RMB, RMD, RME, RMG and RMK - in combination with their maximum kinematic viscosity limit value at 50 degrees Celsius. There are fifteen residual fuels in national and international specifications.

Figure 3. Fuel types for marine use

Fuel type	Fuel grades	Common industry name
Distillate	DMX, DMA	Marine gas oil (MGO)
	DMZ, DMB	Marine diesel oil (MDO)
Intermediate	IFO 180, 380	Intermediate fuel oil (IFO)
Residual	RMA-RMK	Fuel oil or residual fuel oil

Source: adapted from the article by K.Kolwzan and M. Narewski “Alternative Fuels for Marine Applications”, conference paper published in Latvian Journal of Chemistry, October 2012.

Distillate fuels are also available in standard and low sulphur versions with the former currently averaging 1-15% sulphur and the low sulphur version being ECA compliant at 0.1%. Of the two main types mentioned, MGO is the lightest and contains least sulphur. MDO is effectively MGO with a small proportion of residuals and is likely to have a higher sulphur content. Because they can be used in main engines normally run of HFO, distillates represent the easiest means of meeting the 0.5% global cap if availability is the main criteria. However, although readily available, distillates currently account for less than 25% of all marine fuels used. They are also heavily used in many non-marine sectors in far greater quantities.

MARINE FUELS OUTLOOK

The IMO has decided that the final reduction of permitted sulphur levels in fuels is currently regulated under MARPOL Annex VI takes place in 2020. In order to comply with the IMO 2020 limitations, the responsibility is divided between refining industries and shipping industry, both of which have their own characteristic solutions to offer. Refineries will increase the production of compliant fuels (marine gas oil and low-sulphur fuel oils) while simultaneously reducing the high sulphur fuel oil output. In addition, they create new marine fuels that comply with the 0.5% sulphur cap, the so-called “low-sulphur fuel oils” including the VLSFO (very low-sulphur fuel oil) and the ULFSO (ultra-low-sulphur fuel oil). All these measures require intensive investment to increase desulphurization capacity in the refineries, while utilization rates of existing capacities will be maximized (Sardines, 2019)[14].

One of the biggest surprises since the implementation of new IMO sulphur regulation is the weakness the experts have seen in the middle distillate market (Patterson, 2020). The term “middle distillates” is assigned to petroleum products obtained in the “middle” boiling range about 180-360 degrees Celsius during the process of crude oil distillation. Middle distillates, which are hence also known as gas oil, primarily include extra light heating oil, and diesel fuel, as well as

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[14] SARDINES (2019), “IMO 2020 Regulation and the Potential Effects to the Refining sector”, NATO Energy Security Center of Excellence”

marine diesel oil (MDO). Expectations were that a large share of the shipping industry would shift to marine gas oil, but instead, gas oil cracks are trading at levels last seen in 2017, falling by more than 50% from their October 2019 high levels. A milder than usual winter, and the outbreak of the COVID-19 virus are just two factors adding further pressure on middle distillates.

Previously, the IEA has informed for high sulphur fuel oil demand will reduce 60% in 2020, as marine gas oil demand would double because of upcoming international regulation on shipping fuel. More specifically, it was said that a fuel type aiming to comply with the new cap, very low-sulphur fuel oil (VLSFO) would be in limited supply, and quality discrepancies at different ports would mean that operations could use compliant, but more expensive fuel, MGO under this light, IEA forecasted VLSFO demand to reach 1 million bpd (barrel per day) and 1.8 million bpd by 2024, while MGO demand would peak in 2020 and reduce to 1.8 million bpd in 2024.

Despite initial concerns about availability of very low-sulphur fuel oil at the end of 2019, the preferred compliant supplies at key hubs (e.g Singapore, Rotterdam, and Fujairah) now seem to be adequate according to the International Energy Agency (IEA). The first data on the transition appears that deliveries of the new VLSFO bunkers are increasing.

However, from a shipping perspective, one of the key reasons why there has not been a strong demand in the market is the fact that demand for very low-sulphur fuel (VLSFO) has been stronger than expected. As a result, the pick-up in marine gas oil has not been as much as anticipated. There also seems to be an element of hesitancy to move towards marine gas oil, with concern over viscosity. This is evident in Asia, where we have seen VLSFO actually trading at a premium to marine gas oil.

The strong demand for VLSFO has led to a sharp increase in price in recent months which sharply narrowed its spread with the more expensive marine gas oil. Refineries' profit are tied directly to the spread, or difference, between the price of crude oil and the prices of refined products. Thus, refineries around the world have responded by boosting VLSFO production. In the light of 2020 sulphur cap, shipping industry along with oil and gas sector are preparing for the future changes.

While some weaknesses have been seen in the middle of barrel products, fuel oil has strengthened, defying market expectations. There are several reasons behind this strength. Firstly, refiners would have made any adjustments they could, be it through refiner upgrades, or adjusting feedstock accordingly to minimize HSFO (high sulphur fuel oil) yields as we moved into 2020. Secondly, there has been increased interest from US refiners to process HSFO and, looking at fuel oil imports into the US over the last few months, particularly towards the end of 2019, volumes did increase. This move does also appear to reflect the limited availability of heavier crude grades for refiners in the US Gulf, given US sanctions against Venezuela. Thirdly, and this should not come as a surprise, we see more ships with scrubbers installed coming online. This would provide some additional support to the demand picture of HSFO. The corona-virus could even have an impact here, with a potential delay in scrubber installations.

Finally, a factor which was more of a risk than a reality was the potential for the US not to extend waivers which allow Iraq to import natural gas and electricity from Iran (Patterson, 2020)[15]. If this were to happen, it would likely mean that Iraqi domestic fuel oil consumption would increase for power generation needs, so reducing export availability of fuel from the country.

The VLSFO market was performing well until the news that China would provide tax waivers to refineries in the country for lower sulphur fuel oil production, which has set the path for VLSFO output in China to grow. Already there are reports that Petro-China has delivered volumes of VLSFO into bonded storage, where it will likely be retailed to ships. The idea is that China wants to build its capabilities as a bunkering hub, rather than wholesale exports of VLSFO.

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[15] Patterson, W (2020), "The surprising move in marine fuel spreads", ING.

While low sulphur fuels have gained the largest market share, it is worth noticing how HSFO (high-sulphur fuel oil) still accounts for 28% of total sales, driven by bunker fuels purchased for scrubber-fitted ships. Global supplies of marine fuel compliant with the new environmental rules are increasing fast as concerns over quality remains marginal. In 2020, the global limit on sulphur fuel content for all marine fuels is lowered dramatically, sending shock waves through global refined product markets while widening margins and differentials. Most refineries are still trying to come to grips with the potential threat and opportunities that will emerge as a result of this regulation.

An increased use of distillates as a means to meet the 0.5% sulphur cap will therefore bring the shipping industry into competition with other users with no guarantee that sufficient supplies will be available. Increased use of distillate fuels for shipping generally will also badly impact those ships that have been specifically designed to operate with them and which are mostly employed in short sea trades and for local passenger and cargo ferries. The current cost of distillates is around 5-10% higher than ULSFO in major bunkering centers such as Rotterdam. In the past MGO prices have been as much as double that of IFO380.

CHAPTER 3 ALTERNATIVE FUELS

Shipping is going through its biggest change since switching from coal to heavy fuel oil more than a century ago as it looks for new fuels that will drastically cut the industry's footprint. Fuels that have the potential to reduce emissions below required levels can play a significant role in the future as substitutes for heavy fuel oil (HFO) and marine diesel oil (MDO). To meet the sulphur rules that entered into force in 2020, shipping companies can use low sulphur fuels, install a scrubber and continue to use heavy fuel oil, or switch to LNG.

Many ship-owners and industry observers question whether the business can meet the carbon-cutting deadline, noting research on new propulsion systems is still in its early stages and that there is no consensus on what type of fuel would carry, for example oceangoing vessels into a new cleaner future. It seems probable that more oceangoing vessels will be powered by natural gas. However, increased natural gas use in the marine sector may increase GHG emissions globally, due to the global warming potential of natural gas (i.e., methane) in our atmosphere and the potential for methane leakage along the fuel production and delivery pathway (Brynolf et al., 2014a, Lowell et al., 2013, Meyer et al., 2011)[16].

It is expected that alternative fuels will play a more prominent role in the decade to come in view of the European Union objectives of gradually substituting fossil fuels with fuels of renewable origin. However, there is currently a lack of attractiveness of fuel alternatives for consumers and businesses, and no clear market signals with regard to the potential of the different new alternative fuels. Additionally fuel (low-sulphur fuel) consumption in the ECAs is estimated at approximately 30-50 million tons of fuel per year and it is going to increase as more areas are included in the ECAs in the future (DNV GL, 2015)[17]. Both the demand for low-sulphur fuels, as well as the need to reduced GHG emissions can be addressed by the introduction of alternative, low carbon fuels, provided that these fuels and the necessary technology are offered at competitive price levels.

In the future, ships could be fueled by methanol, biofuels, fuel-cell systems or hydrogen, but these are not technologically advanced yet and very costly. The alternative fuels that are most commonly considered today are liquefied natural gas (LNG), electricity, and biodiesel. The present chapter also gives an overview of the other alternative fuels in the shipping sector such as ammonia and methanol. Synthetic fuels could also play an important role in the future, e.g hydrogen (particularly for use in fuel cells).

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[16] Brynolf, S., Andersson, K., Fridell, E. (2014), "Environmental assessment of marine fuels: liquefied natural gas, liquefied biogas, and biomethane" in Journal of Cleaner Production.

[17] DNV GL (2015), "LNG as Ship Fuel. Latest developments and projects in the LNG industry"

3.1 BIOFUELS

Unlike other renewable energy sources, biomass can be converted directly into liquid fuels called *"biofuels"* to help meet transportation fuel demands. The two most common types of biofuels in use today as ethanol and biodiesel, both of which represent the first generation of biofuels technology.

Biofuels are usually categorized as first, second and third generation, based on the technology and/or the raw materials that are utilized for their production. In the first generation biofuels the carbon source comes from sugar, lipid or starch which is directly extracted from a plant. The representatives of the first generation of biofuels include biodiesel, vegetable fats, biogas, bio-alcohols, and synthetic gas. The first generation biofuels can offer substantial CO_2 benefits and can help to improve domestic energy security. The production of the first generation of biofuels is commercial today, with almost 50 billion liters produced annually (Tyrovola et al., 2017)[18]. Nevertheless the first generation biofuels seem to create great concerns about the environmental impacts and carbon balances - reasons that set remarkable limits in their production. The main disadvantage of the first generation biofuels is the food-versus-fuel debate and one of the major reasons for rising food prices is due to increase in the production of these fuels. This is only an issue in the case of the first-generation fuels. Advanced biofuels or the third generation biofuels are considered more sustainable since they do not compete with food crops. Additionally biodiesel is proven to be not a cost efficient emission abatement technology.

The second-generation biofuels can broadly grouped into those produced either biochemically or thermochemically, either route using non-food crops, especially lignocellulosic feedstocks from crop, forest, or wood process residues. Such crops are likely to be more productive than most crops used for the first generation, in terms of the energy content of the biofuel produced annually per hectare. In the second generation biofuels are included the following: methyl esters derived from used cooking oils, bio-oils, butanol, mixed alcohols and Hydrogenated Vegetable Oils (HVO). So both advanced biofuels from the second and third generation could, in theory, reduce problematic effects by using degraded land or residual biomass, but most of those are still in a development phase.

The incorporation of biofuels in marine distillate fuels is still one of the major options for the transition to a smarter and greener transport system with low carbon footprint. Biofuels derived from plants or organisms biodegrade rapidly, posing far less of a risk to the marine environment in the event of a spill; flexible as they can be mixed with conventional fossil fuels to power conventional internal combustion engines or act as replacement. On the downside, one should be careful while selecting certain types of biofuels for marine application, since some specific biofuels have a tendency to oxidize and degrade when stored more than six months. This tendency heavily depends on the conversion technology from feedstock to biofuel.

It is technically possible to produce marine biofuels that are compatible with the existing marine engines, pipelines and bunker infrastructure, so adaptation costs are limited. By 2030, biofuels are set to play a larger role, provided that significant quantities can be produced sustainably, and at an attractive price (DNV GL, 2014)[19].

The most promising biofuels for ships are biodiesel (e.g. hydro-treated vegetable oil (HVO), biomass-to-liquids (BTL), fatty acid methyl ester (FAME) and liquefied biogas (LBG). Biodiesel is most suitable for replacing MDO/MGO, in turn LBG is the best replacement of fossil LNG, and straight vegetable oil (SVO) can substitute HFO. Since 2006, several demonstration projects have tested feasibility of various FAME biodiesel blends in shipping. Challenges reported for FAME biofuels include instability, corrosion, susceptibility to microbial growth, and poor cold-flow properties. Recently, ferries operating in Norway have started to use HVO biodiesel.

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[18] Tyrovola, T., Kalligros, S., Dodos, G. (2017), "The Introduction of Biofuels in Marine Sector", 15th International Conference of Environmental Science and Technology at Rhodos Island, Greece.

[19] DNV GL, (2014), "Alternative fuels for shipping", DNV GL Strategic research & Innovation position paper 03-2015.

Renewable HVO biodiesel is a high-quality fuel in which oxygen has been removed using hydrogen, which results in long-term stability it is compatible with existing infrastructure and can be used in existing engines, subject to approval by the manufacturer. The GHG emissions from lifecycle perspective are about 50% lower than for diesel, and the NO_x and particulate matter (PM) emissions are likewise lower. The third-generation algae-based biofuels are still at the research and development stage, but were tested in 2011 on the container ship *Maersk Kalmar*. The US Navy has also carried out some testing.

3.1.1 INNOVATION AND TECHNOLOGY PROGRESS AND OTHER TECHNOLOGIES IN DEVELOPMENT

Emerging new biofuels obtained from sustainable biomass either from biochemical- or thermochemical-based pathways are at advanced stage of development and new investments in Europe will be boosted by the new legislative EU framework for the next 10 years. Challenges connected to biomass logistics, trade and end-use can be overcome by upgrading to standardized and more-energy-dense bioenergy carriers. Technologies like pelletisation, torrefaction (solid products) and pyrolysis (bio-oils) can play a significant role in this respect. Such energy carriers can facilitate the conversion of fossil plants to biomass on large scale, thereby also contributing to the grid stability in view of the increase of variable renewable power production. This increase in the availability of renewable power also opens up a path for hybrid plants using renewable power to produce hydrogen for use in other biofuels plant or for the conversion of CO_2 stream to biofuels or renewable fuels, depending on the source of the CO_2.

Both thermochemical and biochemical conversion routes will be deployed in the coming decade to produce biofuels directly such as ethanol, methanol and Fischer-Tropsch (FT)-diesel. Also, thermochemically-produced intermediates such as bio-oils will be produced by processes like pyrolysis[20] and, regarding high-moisture content feedstocks, by hydrothermal liquefaction.

Such intermediates will predominantly be converted to drop-in biofuels by refinery-like processes, either as an integrated biofuel value chain or as co-feed to fossil refinery value chain. Key innovation on bioenergy for the next 10 years are expected to occur both by evolution of technologies now being demonstrated or piloted and by development of new technologies that will in some years possibly reach such a stage.

The rapid build-up of renewable power capacity and the associated reduction in cost has generated an interest for using energy to produce hydrogen from electrolysis. Such component can later be used as a biofuel, as a co-feedstock in the production of other biofuels by thermochemical pathways. Another option is chemical conversion of e.g alcohols of lipids or it is even to recycle CO_2 captured from industrial process by conversion to fuels like methane or methanol. The latter technology, named power-to-gas or power-to-liquids (PtG, PtL) is being tested at pilot scale (Benetti, 2018)[21].

Many technological options for novel biofuels are being studied at laboratory scale. One interesting and challenging technology is to harness solar energy by bipolar cell factories (BSCF). By this technique, phototrophic microorganisms (e.g cyanobacteria, eukaryotic algae) directly catalyse the conversion of CO_2 and H_2O into oxygen and chemical energy (e.g. fuel) in a CO_2-neutral way and they by-pass the production of biomass intermediate. Another approach for the future is the use of extremophiles microorganisms that could be engineered as bio-solar cell factories, since their ability to grow at extreme conditions (high temperature, high saline, high/low pH values) minimises the risk of microbial contaminations at open ponds as well as in closed unsterile photobioreactors (ibid, 2018).

Both civilian and military circles are actively investing research and development (R&D) funds

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[20] It is the thermal decomposition of materials at elevated temperatures in an inert atmosphere that involves a change in chemical composition.

[21] Benetti, C., "Building Biofuels Research" BE Sustainable, 21 May 2018

into other forms of biodiesel and biofuels, as well as into measures to increase the efficiency of all biomasses. Often a small quantity of biodiesel can be added to mineral diesel to produce a more stable fuel. There are few cases of biodiesel being used on a commercial scale in large marine engines but its use in leisure engines is more widespread. Likely the largest use of biodiesel in commercial marine is by the Meriaura Group of companies based in Finland. Using a process developed by another Finnish company - Sybimar - the waste stream of fish and aquaculture plants are converted into EcoFuel which being sulphur-free. It can be used directly as heavy marine fuel or in blend with fossil diesel, or it can be processed to light marine fuel. It is also used as environmentally friendly heating oil. Some trials of another bio-diesels have been carried out on ships, with Maersk Line in particular being an enthusiastic pioneer. Fuels derived from algae may have some potential as might fuels derived from lignin a vegetable product that remains after other useful products have been extracted. Presently lignin is used mostly as a soil improver.

The track record of militaries using biofuels is mixed, sometimes with complaints that they are too expensive. For example, the USA significantly decreased its green initiatives after a scandal of buying biofuels at four times the price of oil (Shactman, 2011)[22].

Various forms of organic matter are used for biofuels, with camelina-derived fuels in the lead for defence applications, particularly given their track record to meet supersonic flight requirements. A second-generation biofuels like camelina can empower the massive fleet of warplanes. Second generation biofuels technology, where not only oils, sugar and starch, but also lingo-cellulosic compounds are transformed into fuels which serve as more sustainable feedstock. This leads to higher conversion efficiency and facilitates the use of alternative feedstock like wood, grass or bio-waste. Therefore, biofuels produced in this manner does not compete with food crops and, according to studies from the past decade, reduce carbon emissions by 50-85 per cent against petroleum jet fuel (Moore et al., 2017)[23].

One of the challenges are the volumes that are required to supply the shipping sector. On one hand, considering that the land required for production of 300 million tons of oil equivalent (Mtoe) biodiesel based on today's (first and second generation biofuels) technology is slightly larger than 5% of the agricultural land in the world, securing the necessary production volume is a challenge. On the other hand, supply of biofuels might be insufficient to power the whole shipping fleet. The current biofuels supply, which consists of both biodiesel and bio-ethanol, can only cover about 15% of the total demand (IEA, 2017). The IEA estimates is based on what can be delivered by adapting the current agricultural and forestry production technologies without adding land use or reducing food supply. As such, it excludes the biofuels that require the conversion of agricultural land or forests.

Prices and production volumes are the main barriers to widespread use in shipping. In most cases advanced biofuels will be more expensive than fossil fuels. The potential for reduction production costs is expected to be higher for second-generation biofuels compared to the first generation where a major portion of potential is already being realized (DNV GL, 2018). Both technical and logistic issues need to be resolved before biofuels can be introduced at a larger scale in the shipping sector, and a closer collaboration between biofuel producers, engine developers and ship owners is recommended as a path forward.

Biofuels have already entered the market, driven amongst other by their potential to improve energy security and to contribute to climate change mitigation. The market entry for biofuels is therefore most favorable onboard smaller vessels for coastal waters for use as auxiliary fuel in ports. Of the different current biofuels commercially available, only biodiesel derived from plants or pulping residues and bio-ethanol are produced in volumes that can possibly supply a part of the

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[22] Shactman, N. "Navy's Big Biofuel Bet: 450,000 Gallons at 4 Times the Price of Oil", Wired (December 5, 2011).

[23] Moore, R., et al "Biofuel Blending reduces particle emissions from aircraft engines at cruise conditions", Nature 543 (16 March 2017).

marine industry. Advanced biofuels provide an emission-reducing fuel option that could become more widely available with the necessary investments and policy targets. Although more knowledge on their performance and physical properties - more testing and standardization - might be required (Hsieh, 2017)[24].

3.2 LIQUEFIED PETROLEUM GAS (LPG)

In the race to take first place in the competition for shipping's best alternative to high sulphur fuel oil, the advantages of liquefied natural gas (LNG) have been highlighted. Not much so far has been said about LPG. However, the progression of LPG could be fast-tracked by the fact that infrastructure for distribution and bunkering is already largely available to serve potential marine market demand; other alternative fuels need infrastructure to be developed.

LPG is readily available globally and is lauded as clean, energy efficient and portable fuel with an affordable price. For example, Equinor, a Norwegian state-owned enterprise, is expected to launch its fleet of very large gas carriers (VLGC) powered by LPG in late 2020. LPG is currently sourced mainly from natural gas and oil production activities. However, in the wake of new technologies and techniques, LPG can also be produced from renewable sources.

As a mixture of propane and butane its density is higher than that of air, which means that in the event of leakage vapors will accumulate in the lower portion of the surrounding space. That means that it requires a different approach to leak detection and ventilation than LNG. LPG also has a lower flammability range, with a lower explosion limit of 2%. On the upside, LPG is less challenging with regard to temperature since it has a higher boiling point and, unlike LNG, is not stored in cryogenic temperatures.

According to the World LPG Association (WLPGA), LPG is a key enabler for IMO's 2050 regulation which calls for a reduction in total annual greenhouse gas emissions by at least 50% by 2050 compared with 2008. LPG is already becoming the preferred fueling solution for LPG carriers. For other ships, more focus should be paid on design, regulations, safeguards and safe practices, and operational processes and training to make LPG viable as a marine fuel. Taking all that into consideration, it can be said that there is a great potential in the shipping industry for LPG.

With the marine industry under pressure to take measures to reduce emissions to comply with IMO 2020, LPG can make significant inroads into the marine fuel market. To achieve that, LPG propulsion, starting with LPG carrier sector, needs to move beyond a niche fuel option, to gain the acceptance in the wider shipping sector that it deserves.

While LPG might be relatively new marine propulsion fuel, it is a fuel that the shipping sector knows well through its more than 50 years of storage, transport, and handling experience.

Supplies are also abundant, especially due to increased production coming from the US. LPG bunkering can take place in various ways, from terminals, refineries, onshore trucks, smaller LPG carriers or barges. There are more than 1,000 LPG storage facilities around the world that can be used for ship-to-ship bunkering.

LPG can be positioned as a relevant fuel for the future with a recognized role in the decarbonisation of the transport systems. Across many parts of the world LPG has replaced biomass as a source of cooking fuel leading to significant health benefits. LPG has also replaced other fuels such as heating oil in residential properties and other fuels used by businesses and agriculture enterprises.

The shipping class society DNV GL has developed new class rules and class notation for "Gas fueled LPG" ships in anticipation of growing industry interest. Currently, there are no international rules for LPG as a fuel. The rules and notation are based on DNV GL's rules for ships using LNG as fuel but account for the differences in proper-

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[24] Hsieh, C et al. (2017), "Biofuels for the marine shipping sector, an overview and analysis of sector infrastructure, fuel technologies and regulations", IEA Bioenergy.

ties and phases between LPG and LNG. The "Gas fueled LPG" covers internal combustion engines, boilers and gas turbines for both gas-only and dual-fuel operations. It also includes requirements for a ship's fuel supply, considering all aspects of the installation from the bunkering connection up to and including the LPG consumers (main and auxiliary engines, boilers).

A joint study of DNV GL and MAN evaluated that LPG is at least as attractive an energy source as LNG, with shorter payback periods, lower investment costs and lower sensitivity to fuel price scenarios.

One ship-owner has taken the leap and opted for LPG-fueled ships: BW LNG is retrofitting four of its fleet to enable them to burn LPG as part of their fuel mix. While BW LPG has been burning LNG boil-off for fuel for decades, LPG carriers have been re-liquefying the boil-off and returning it to the cargo. However, today there is a case greater use of LPG as a fuel because of economic and industrial developments.

3.3 HYDROGEN

Hydrogen (H_2) is another potentially attractive and viable alternative fuel since it emits zero carbon dioxide (CO_2), zero sulphur oxide (SO_x) and only negligible amounts of nitrogen oxide (NO_x). Hydrogen can be used as fuel in several different ways i.e. in fuel cells; in dual mixture with conventional diesel fuels (HFO); and lastly as a replacement for HFO for use in combustion machinery. The focus is on the potentials of hydrogen as a fuel for ship propulsion both as a mixture and a complete replacement of HFO, while the potentials of hydrogen as a fuel for fuel cells is described in the fuel cell section.

The use of hydrogen as a replacement for conventional diesel fuel still requires research and development, particularly to make it commercially viable. So far, there is no standardized design and fueling procedure for hydrogen powered ships and its bunkering infrastructure (Lindstad et al., 2015)[25]. Furthermore, remaining safety design issues with regard to the volatility of the fuel need to be resolved.

Despite the lack of rigorous commercial viability studies on hydrogen as a fuel, much research has focused on methods of sustainable hydrogen production. Nowadays, there are two common techniques that are used to produce hydrogen: by steam methane reforming and water electrolysis (Bicer, 2018)[26]. The latter has gained more attention due to its recent technological development making it possible to effectively use renewable power to split water into hydrogen and oxygen.

The electricity needed for the production process using the electrolysis method can be generated from solar, wind and hydropower plants (future production location of synthetic fuels are mentioned below). This significantly improves the overall mitigation potential of hydrogen taking into account its entire production life cycle. A recent assessment by Bicer (2018)[27] has indicated that hydrogen produced by using hydropower can yield 10 times less CO_2 emissions than HFO over the entire life cycle. Furthermore, hydrogen that is used as a mixture with HFO (50% of the total fuel) can reduce CO_2 emissions up to 43% per tonne-kilometre. This shows that even when the current conventional marine fuels (HFO) are partially replaced with hydrogen, a significant reduction in CO_2 and other GHG emissions can be achieved.

3.4 AMMONIA

Ammonia (NH_3) is a hydrogen carrier that can be used in fuel cells or as a fuel for direct combustion. It has the benefit of having a high hydrogen content containing no carbon atom. Ammonia hence emits zero carbon dioxide (CO_2), sulphur oxide (SO_x) and close to zero nitrogen oxide (NO_x). Unlike hydrogen, the deployment of ammonia as a marine fuel is still in a research and development phase although it has already been

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[25] Bouman, E., Lindstad, E., Rilland, E., Stromman, A. (2015), "State-of-the-art technologies and potential for reducing GHG emissions from shipping – A Review", in Transportation Research part D, Vol. 52, pp. 408-421.

[26] Bicer, J et al. (2017), "Clean fuel options with hydrogen for sea transportation: A Life cycle approach" in International Journal of Hydrogen Energy, Vol 42, pp 1179-1193.

[27] Ibid 2018

Figure 4 – The world's first carbon-free ammonia-fuelled supply vessel

Source: Viking Energy Ammonia fuelled vessel - Energy Industry Review, 2020

used successfully in land-based installations, e.g. for powering buses. To date, no ammonia powered ship is operational.

The advantage of ammonia compared to hydrogen is that its liquid form allows more hydrogen storage per cubic meter than in liquid hydrogen and without the need for cryogenic (high pressure, very low temperature) storage, which makes it a suitable hydrogen "carrier". Although the energy density of ammonia is not very different from liquid hydrogen, capital cost savings compared to hydrogen occur with different temperatures and pressures needed. Another advantage is that it can be stored at a temperature (-33.4°C) that is easier to maintain compared to hydrogen (-252.9 °C). It can be used in different ways for propulsion (e.g. in diesel engines, fuel cells, gas turbines, etc.), which makes it a very competitive option.

The Norwegian energy company Equinor has signed an agreement with Eidesvik Offshore for the modification of the Viking Energy supply vessel, to make it capable of covering long distances fuelled by carbon-free ammonia. The vessel will transport supplies to installations on the Norwegian continental shelf. This project will test whether the technology can deliver 100 percent carbon-free power over long distances.

The life cycle assessment study conducted by Bicer (2018)[28] shows that when ammonia is used as dual fuel with HFO, it can yield a 27% reduction of CO_2 emissions per ton-kilometer in the overall life cycle. Furthermore, ammonia produced using wind energy that is used as dual fuel - where 50% ammonia is used in combination with 50% HFO - can reduce total CO_2 life cycle emissions up to 34.5% per ton-kilometer. This implies that ammonia can offer an attractive

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[28] Bicer, J et al. (2017), "Clean fuel options with hydrogen for sea transportation: A Life cycle approach" in International Journal of Hydrogen Energy, Vol 42, pp 1179-1193.

short term solution in dual fuel configurations with reasonable commercial viability. In addition, further developments of ammonia as a complement or replacement for HFO can also offer a promising alternative to reduce CO_2 emissions in the long term.

Similar to hydrogen, ammonia production methods have advanced considerably in the recent years. That is partly due to the fact that ammonia is a widely traded commodity around the world and predominantly used as a fertilizer. There is already significant port loading infrastructure, handling experience and safety know-how. While production is theoretically feasible in every country, China currently produces about 31% of world total ammonia, followed by Russia (8.7%), India (7.3%), and the U.S (7%) (U.S. Geological Survey, 2018). Other large producers are Canada, Indonesia, Saudi Arabia and Trinidad and Tobago.

The common method to produce commercial ammonia is using the Haber-Bosch process converting hydrogen and nitrogen using high temperature and a catalyst. Nowadays, this method can be performed using solar, wind or hydropower through electrolysis which gives ammonia a comparative advantage compared to the production of HFO. "Green" production of ammonia could hence easily develop where renewable energy sources are abundant. Forthcoming hydropower plants in Africa for instance may provide large excess output that provides new possibilities for local ammonia production (Philibert, 2017)[29]. In order to become viable, sustainable ammonia must become more cost competitive compared to conventional ammonia, of which 90% of production still relies on fossil fuels such as natural gas. While in the U.S., under the most favorable conditions, the cost of producing green ammonia is still about twice as high as natural gas based ammonia, in regions where resources are especially abundant, the cost of hydro, solar and wind power can fall below USD 0.03 per kilowatt hour. According to IEA, this would include regions such as the Horn of Africa, Australia, North Africa, Northern Chile, Southern Peru, Patagonia and South Africa, as well as several regions in China. Such low electricity prices could allow a production of sustainable synthetic fuels competitive with natural gas reforming, oil-cracking or coal gasification (IEA, 2017)[30]. However, more conservative studies express the concern that global surpluses of renewable energy could not be sufficient to cover synthetic fuel demand in the future (Bracker, 2017)[31]. Developing these energy sources would need a significant amount of additional investments. If relevant, volumes of synthetic fuels, such as hydrogen and ammonia are used by 2035, it would be essential to ensure that production processes are based on renewable electricity generation. Otherwise, no improvement in CO_2 emissions compared to conventional HFO could be guaranteed.

3.5 METHANOL

Methanol could be one of the future marine fuels. Today, most of the methanol is produced from natural gas and has a CO_2 emissions reduction potential of around 25% compared to HFO. Compared with HFO, methanol has an emission reduction potential of 99% for SO_x, 60% for NO_x and 95% for particle matter (PM). However, methanol can also be produced from renewable energy resources, such as CO_2 capture, industrial waste, municipal waste or biomass which significantly reduces its greenhouse impact. Methanol is available in large quantities and can be made out of a wider number of resources. Since there is a long history of transporting it, experience in handling and operation already exists. Methanol is also convenient because it requires only minor modifications to ships and bunkering infrastructure since it is similar to current fuels in several respects. It can be used in combustion engines that most ships are already equipped with. Regulation is less constraining because it is generally safer than conventional fuels and LNG. So far, methanol has been employed as a transportation fuel on a significant basis only for cars in China, where it is inexpensive and readily available since

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[29] Philibert, C. (2017), "Renewable Energy for Industry: From green energy to green materials and fuels", IEA Insight Series, Paris

[30] IEA (2017), "Energy Technology Perspectives 2017: Catalyzing Energy Technology Transformations", Paris

[31] Bracker, J. (2017), "An Outline of Sustainability Criteria for synthetic fuels used in transport", Öko- Institut e.V, Freiburg

it is produced from coal thus having a negative GHG impact (IMO, 2016, Andersson and Marquez Salazar, 2015)[32].

Sweden has been at the forefront of the development of methanol-powered ships. A pilot project was launched with support from the EU Motorways of the Sea program, to convert a RO-Pax vessel[33] into a methanol-powered vessel and provide bunkering as well as other necessary facilities in ports. This project has led to the development of the Stena Germanica, a large passenger and car ferry operating between Gothenburg and Kiel. It is the first ship operating on methanol. Methanol used by the ship is supplied to Stena by Methanex, the world's largest methanol supplier and is produced from natural gas so it does not achieve the full potential of CO_2 emissions it could achieve. The company partnered with Wärtsilä for engine retrofitting and installed new tanks on the bottom of the ship by seizing void spaces at the bottom. This is considered a safety concern with conventional fuel, but does not pose a risk when using methanol. A pilot fuel to ignite the methanol is needed (5% diesel and 95% methanol), which is also feasible for any large vessel. Although the conversion cost EUR 22 million, Stena expects significant cost reductions of around two-thirds of the cost once applied to several ships at the same time. Stena is currently looking into ways to develop production based on biomass so that it fully achieves its greenhouse gases emissions reduction potential. The company has identified several potential sources for bio-methanol production in Sweden already. It has also developed a tool kit for ship conversion to methanol in order to support replication (ITF, 2018b)[34].

3.6 MARINE FUEL CELLS

A fuel cell is a device that converts the chemical energy from a fuel into electricity via electrochemical reaction of the fuel with oxygen, or other oxidizing agents. There are many types of designs for fuel cells. Most consist of an anode, cathode and an electrolyte that allows positively charged hydrogen ions (known as protons) to move from the anode to the cathode side of the fuel cell.

Fuel cells differ from batteries in that they require a continuous source of fuel and oxygen (usually from the air) to sustain the chemical reaction, whereas the availability of energy from a battery is fixed by the amount of energy it has stored. With its power capacity having grown over the last decade, the fuel cell asserts its position as a viable source of marine energy - and not only as a means of supporting auxiliary energy requirements or powering smaller ships. The technology is responsive enough to be used as a general energy source for most loads or electric ships - and can be deployed in combination with other systems to yield additional benefits. For example, vessels that operate predominantly on diesel engines could employ fuel cells to boost efficiency and comply with regulations in areas such as zero-emission ports.

Hydrogen is most frequently used in fuel cells. It can be produced from methane steam reforming, fossil fuel or biomass gasification or water electrolysis. (See more detailed explanation in section 3.3 of the present chapter). Hydrogen fuel cells technology has the potential to offer reliable, long-range power on an industrial scale with relatively quick refueling when compared to the emerging battery-powered options. Hydrogen itself has higher energy density than batteries, potentially making fuel-cell systems more practical for operators looking to replace or supplement traditional bunker-fueled propulsion units.

However, sourcing of hydrogen can be energy intensive. Without the incorporation of renewably generated hydrogen, the next impact on GHG gas for hydrogen produced by methane on similar processes is negligible. Also, adopting hydrogen as a deep sea marine fuel is not without challenges, even before safety factors are considered.

[32] Andersson, K., Salazar, C. (2015), "Methanol as Marine Fuel Report", Methanol Institute.

[33] RO-RO vessel built for freight, vehicle transport along with passenger accommodation.

[34] International Transport Forum (2018), "Decarbonizing Maritime Transport. The Case of Sweden" OECD, Paris.

2.7 THE USE OF ALTERNATIVE AND SYNTHETIC FUELS IN THE MILITARY

Concerns over climate change and security of supply from the oil producing regions have triggered a broad effort in the search for new sources and conversion processes. However, some countries like Japan, have begun to explore whether the time has come for new marine fuels, specifically liquefied natural gas (LNG), liquefied petroleum gas (LPG), or hydrogen.

The increasing availability of liquid alternative fuels, and their mixing with conventional petroleum distillate fuels, have led the need for the military to more closely study and mitigate any negative effects of the introduction of such fuel blends on their systems (air, land, or naval) as well as operational procedures.

Fuel cell technology, if successfully developed for Navy shipboard applications, could reduce naval vessel dual use substantially by generating electricity much more efficiently than is possible through combustion (O'Rourke, 2007)[35]. The USA as well as UK have programmers running, to study the advantages of using fuel cells for powering surface ships. Specific advantages are better efficiency compared to gas turbines and diesel engines, reduced smoke, reduced sound and thermal signatures, lower vibration levels, design flexibility due to modularity etc. Power rating required will be of the order of a few megawatts. On board fuel processing will be inevitable. Use of logistic fuel is very much desired, if dual modes are proposed. Hybridization of direct fuel cells with turbine cycles using the fuel cell by-product heat, as proposed by M/s Fuel Cell energy can give very high overall efficiencies (Narayana Das, 2017)[36].

The U.S Navy, U.S Coast Guard and other navies have undertaken a number of studies for the installation of fuel cells. An additional benefit for the military is that fuel cells are very quiet compared to diesel engines. A detailed concept study was conducted into replacing a diesel generator set for the U.S Coast Guard's USCGGC *Vindicator* by a 2.5MW MCFC fuel cell[37]. The package included a fuel reformer for low sulphur NATO standard F-76 distillate fuel: the reformer separated the fuel into hydrogen and carbon dioxide. The US Office of Naval Research developed a 2.5MW ship service fuel cell which was based on a MCFC and will reform naval fuel. The goal was to achieve their objective using commercial or near commercial technologies and for it to be highly reliable, maintainable and self-contained with respect to water and energy balance. The steam reformation of NATO F-76 was demonstrated for over 1,400 hours and has fueled a subscale MCFC for 1, 000 hours.

Based on the USA example, it is worthwhile considering what capabilities the Navy might gain taking into account technological change in the way that private industry does. LPG, LNG, and hydrogen would enjoy weight advantages over fuel oil, allowing for vessels to operate without refueling for even more extended periods of time or affording space aboard for other mission-relevant payloads. Since 2016, General Motors, the Office of Naval Research, and the US Naval Research Laboratory have partnered on a research project regarding unmanned undersea vehicles (UUVs) using hydrogen fuel cell technology, with the higher efficiency of hydrogen intended to allow these vessels to conduct surveillance for vastly longer periods of time than would be possible with conventional fuels. LPG prices are also considerably lower than diesel or LNG in the USA or elsewhere.

Fuel cells have come a long way in technology maturity. Still large scale exploitation in both, domestic and industrial segments has not taken place, at the expected pace. Other forms of energy conversion are still remaining competitive. Defence sector stands to gain significantly from the unique features of fuel cells. The challenges in design and engineering to meet the stringent military standards in reliability, environmental

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[35] O' Rourke, R (2007), "Navy Ship Propulsion Technologies; Options for reducing Oil use – Background for Congress", Congressional Research Service.

[36] Narayana Das, J (2017), Chapter from book "Energy Engineering proceedings of CAETS 2015 Convocation on Pathways to Sustainability", pp 9-18.

[37] MCFC - Molten carbonate fuel cell uses a molten carbonate salt suspended in a porous ceramic matrix as the electrolyte. Salts commonly used include lithium carbonate, potassium carbonate and sodium carbonate.

qualification, life cycle management, etc., are to be addressed through a comprehensive approach. There is strong interest in Europe, Japan, and the USA in developing shipboard fuel cell technology for both powering shipboard equipment and ship propulsion. In Europe, fuel cell technology has been incorporated into non-nuclear-powered submarines, such as the German Type 212 submarine, and is starting to be applied to civilian surface ships.

The main question remains which alternative fuels and at which conditions can be feasible in the militaries, for example the Netherlands Defence Academy experts (Geertsma, Krijgsman, 2017)[38] studied power systems design and alternative fuels based on the case study of support vessels of 1000 to 2000 tons, taking into account technology readiness, logistic availability of the fuel; and the estimated yearly CO_2 emissions. The analysis concluded that batteries are unfeasible, and solid oxide fuel cells (SOFC) and hydrogen fuels are currently insufficiently mature. Methanol, in particular when produced from renewable feedstock, appears to be a logistically and technically mature fuel. Methanol as a fuel for internal combustion engines can reduce CO_2 emissions by 70% for 10% higher capital cost and 100% increased fuel cost. The feasibility of alternative fuels for frigates and other vessels appears to be ultimate challenge as these ships are volume critical.

However, it is difficult to say how military vessels using such alternative fuels would perform in combat. In recent years, there have been several incidents involving LPG tankers that resulted in the loss of life. In January, 2019, two Tanzanian-flagged LPG tankers collided in the Kerch strait - a disputed waterway that links the Black sea and the Sea of Azov - leading to an explosion aboard one of the vessels that killed 11 persons. At least one of the two tankers had reportedly failed safety inspections, with corrosion rife on her bulkheads and decks (Pryce, 2019). LNG cannot burn in its cryogenic liquid form, which could give some momentum toward the use of LNG as an alternative marine fuel. However, the new interest in transitioning commercial power generation from coal to natural gas could drive LNG prices globally to levels unattractive to most militaries. The safety concerns presented by LPG and by hydrogen could, therefore become an obstacle to their adoption by naval forces until designs can be presented, which demonstrate the survivability of vessels powered by such fuels.

CHAPTER 4 LIQUEFIED NATURAL GAS (LNG) AS A MARINE FUEL - OVERVIEW OF THE TECHNICAL PROPERTIES

Gas is set to become the second largest source of energy by 2025, with renewables and natural gas accounting for 85% of energy growth. Natural gas is a mixture consisting primarily of methane (CH_4), but commonly including varying amounts of other higher alkanes (e.g ethane, propane), and sometimes a small percentage of carbon dioxide, nitrogen, hydrogen sulphide, or helium. Biomethane, synthetic natural gas from biomass (Bio-SNG) or synthetic power-to-Gas (PtG) are renewable alternatives to fossil natural gas.

Biomethane is produced by fermenting biomass to create biogas. The composition of biogas varies considerably depending on the type of biomass used (the substrate). The methane content varies between 50-75%. Biogas has a high CO_2 content (25-45%) and a relatively high water content (2-7%) and contains hydrogen supplied, oxygen, nitrogen and other components and impurities such as siloxanes. Biogas is cleaned and treated to obtain network quality gas with a high methane content so that it can be fed into the natural gas network or used by consumers.

One of the reasons why ship owners opt for LNG is its CO_2 mitigation potential. It is proven to be substantial as the CO_2 reduction of LNG ranges between 5-30% compared to the heavy fuel oil (HFO) (Bouman et al., 2017)[39]. Different carbon emissions abatement techniques (e.g low sulphur fuels or the installation of scrubbers) have its ad-

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[38] Cdr (E) dr.ir Geertsma, ir Krijgsman (2018), "Alternative fuels and power systems to reduce environmental impact of support vessels", Netherlands Defence Academy, Delft University of Technology; MARIN.

[39] Bouman, E., Lindstad, E., Rilland, E., Stromman, A. (2015), "State-of-the-art technologies and potential for reducing GHG emissions from shipping – A Review", in Transportation Research part D, Vol. 52, pp. 408-421.

vantages and disadvantages. The switch to LNG for example, necessitates high investments in the building and retrofitting of (LNG) vessel engines. The potential of LNG is however also recognized by the European Commission that therefore composed an LNG strategy with the aim to have a core network of LNG availability by 2025 (EU, 2016)[40].

Methane transported by pipeline in gaseous form or by tanker in a compressed liquefied form is known as liquefied natural gas (LNG). LNG carriers have been using liquefied natural gas for several decades, therefore it is both technically proven and a commercially viable solution for shipping today.

Figure 5 LNG carrier

Source: GIIGL (2016)

LNG can be classified into three groups, according to its density: heavy, medium or light. Their composition is depicted in Figure 6.

The number of LNG-fueled ships is growing and based on the estimates provided by Clarksons (2019), the existing world fleet is made up of 668 LNG-fueled and LNG-ready ships with an additional 409 in the order book.

Norway has pioneered the use of LNG as a ship fuel - outside of LNG carriers - in ferries and offshore service vessels for the oil and gas industry. Other vessel types have been added, including tugs, fish feed carriers, wind farm support vessels, cruise ferries, small chemical tankers and container feeder vessels. More recently, large vessels, including bulk carriers, container vessels, oil tankers, car carriers and cruise ships, have been added to the order book which indicates that almost all vessel types are now possible to be fueled with LNG.

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[40] European Commission (2016), "Communication from the Commission, the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions: on an EU Strategy for liquefied natural gas and gas storage" COM (2016) 49, Brussels.

Figure 6. LNG classification based on density and composition

Molar composition (%)	Light LNG	Medium LNG	Medium LNG
Methane (CH_4)	98.60	92.30	85.87
Ethane (C_2H_6)	1.18	5.00	8.40
Propane (C_3H_8)	0.10	1.50	3.00
Butane (C_4H_{10})	0.02	0.60	1.20
Pentane (C_5H_{12})	-	0.10	0.23
Nitrogen (N_2)	0.10	0.50	1.30
Density kg/m^3 (-162 ^{o}C/1.3 bar)	427.58	451.58	474.87
LHV (kJ/kg)	49.935	49.557	48.984

Source: adapted from the article by Fernandez et al "Liquefied Natural Gas", published in Renewable and Sustainable Energy Reviews 67 (2017) 1395-1411.

However, handling and combustion of LNG involves the release of unburnt methane, also referred as methane slip, which can diminish its overall environmental advantages depending on the volume of the methane emissions. Methane is a very potent GHG with global warming potential 28 times higher than CO_2 over a period of 100 years and 84 times higher over a 20 years period (Anderson et al., 2011)[41].

Methane emissions can differ significantly depending on ship, engine types and loads. Manufacturers claim that efficient engines can emit less than 1 g/kWh while others might have emissions close to 6 g/kWh (Verbeek, 2013). It is also important to take into account that methane slip can also occur during bunkering phase as well as upstream in the fuel production, processing and transmission, which also further lowers its GHG mitigation potential. When the methane emissions are higher than 5.8 g/lWh, the use of LNG will lose its mitigation potential and even lead to higher overall GHG emissions (Verbeek, 2013)[42].

Engine manufacturers and shipyards state that the "methane slip" from burning natural gas is small and that they are working to produce cleaner burns. Proposed power solutions like batteries, hydrogen, and ammonia are still years away from proving out, and many industry executives say privately that meeting the IMO's 2050 target will be difficult. It is believed that LNG could become the default fuel over the near term as the industry looks for cleaner alternatives. Hydrogen which must be compressed or liquefied, will need 6 times the space and 4 times the weight of the current fuel storage. This in turn will cut the ship's capacity by more than a third.

The technical characteristics of LNG are described below, beginning with an explanation of the technical liquefaction process which converts natural gas into LNG. Followed by the main physical and chemical characteristics of LNG that affect combustion are also touched upon.

4.1 BASIC CHARACTERISTICS OF LNG

LNG is odorless; in fact, odourants must be added to methane before it is distributed by local gas utilities for end users to enable detection of natural gas leaks from hot-water heaters and other

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[41] Bengtsson, S., Andersson, K., Fridell, E. (2011), "Life cycle assessment of marine fuels. A comparative study of four fossil fuels for marine propulsion" Chalmers University of Technology of Shipping and Marine Technology.

[42] Verbeek et al. (2013), "GHG emission reduction potential of EU related maritime transport and on its impacts", Delft University, the Netherlands

natural gas appliances. Natural gas (methane) is not toxic. However, as with any gaseous material besides air and oxygen, natural gas that is vaporised from LNG can cause asphyxiation due to lack of oxygen if a concentration of gas develops in an unventilated, confined area.

Figure 7. Physical properties of methane

Property	Value
Molar mass	0.017 kg/mol
Atmospheric boiling point	-162 °C
Liquid density relative to water	0.42-0.45
Vapor density relative to air at 1 atm and 20°C	0.6
Auto-ignition temperature at 1 atm	530 °C
Flammability limits in air at 1 atm and 20°C	4.5-16.5 volume %
Minimum ignition energy at 1 atm and 20 °C	0.28 MJ
Combustion energy at 1 atm and 20 °C	50 MJ/kg

Source: Adapted from Vanderbroek & Berghmans article "Safety aspects of the use of LNG for marine propulsion" (2012).

Density is a measurement of mass per unit of volume, and it is an absolute quantity. The density of a gas depends on the pressure and temperature conditions. The density of methane, the main constituent of LNG, is 0.7 kg/m^3 under standard conditions, making it lighter than air (approximately 1 kg/m^3) and it rapidly evaporates in the open air. As LNG is not a pure substance, the density of LNG varies slightly with its actual composition. Its density falls between 430 to 470 kg/m^3 and an average density of LNG is 450 kg/m^3. LNG is therefore less than half as heavy as fuel oil (832 kg/m^3) or synthetic Fischer-Tropsch diesel produced from natural gas, also called Gas-to-Liquids (GTL) respectively (780 kg/m^3).

A transition from the gas to the liquid phase, or the reverse, occurs at the boiling point and is characterized by a sudden change in density. The normal boiling point of methane is 161.5 degrees Celsius and its normal pressure is 1.013 bar. Methane has a very low boiling point: if it is cooled to below -161 degrees Celsius under atmospheric conditions (1 bar pressure), it condenses and passes from the gas to the liquid phase. Very few gases have a lower boiling point than methane, but those that do not include hydrogen and nitrogen. Methane at 1 bar pressure and ambient temperatures (20°C) has a volume of approximately 1,500 l/kg; thus the volume of liquid methane is actually 600 times smaller than that of gaseous methane.

These low temperature gas condensates are also called cryogenic liquids because they can be used for special cooling purposes. For each gas there is a temperature at which the gas can no longer be liquefied by increasing the pressure, or there is no longer a transition from the gas to the liquid phase (supercritical state). This temperature is called the critical temperature, which in case of methane is -82.6 degrees Celsius.

Relative density or specific gravity of a gas is the ratio of the density of that gas to the density of air (at 15.6 °C). Any gas with a specific gravity of less than 1.0 is lighter than air (buoyant). When specific gravity or relative density is significantly less than air, a gas will easily disperse in open or well-ventilated areas. On the other hand, any gas with a specific gravity of greater than 1.0 is heavier than air (negative buoyant). The specific gravity of methane at ambient temperature is 0.554, therefore it is lighter than air and buoyant.

Under ambient conditions, LNG will become a vapor and as it vaporizes, the cold vapors will condense the moisture in the air, often causing the formation of a white cloud until the gas warms, dilutes and disperses. Cold LNG vapors (-110°C) are negatively buoyant and more likely to accumulate in low areas until the vapors warm. Therefore, a release of LNG that occurs in an enclosed space or low spot will tend to replace the air (and oxygen) and make the area a hazard for breathing.

The flammability range is the range between the minimum and maximum concentrations of vapor (percent by volume) in which air and LNG vapors form a flammable mixture that can be ignited and burn. LNG has a higher flammability range in the air (see Figure 6) and higher auto-ignition temperature.

The ignition temperature is the temperature to which a substance must be heated before it auto-ignites in the presence of oxygen. *The auto ignition temperature* is the lowest temperature at which a flammable gas vapor will ignite spontaneously, without a source of ignition, after several minutes of exposure to sources of heat. With very high temperatures, and within the flammability range, ignition can be virtually instantaneous. For methane vapors derived from LNG, with a fuel-air mixture of about 10 percent of methane in air (about the middle of the 5-15 percent flammability limit) and atmospheric pressure, the auto ignition temperature is above 540 degrees Celsius. This extremely high temperature requires a strong source of thermal radiation, heat, or hot surface.

If LNG is spilled on the ground or on water and the resulting flammable gas vapor does not encounter an ignition source (a flame or spark or a source of heat of 540°C or greater), the vapor will generally dissipate into the atmosphere, and no fire will take place. This indicates that the ignition temperature of methane is relatively high, and thus around twice as high as that of diesel fuel, for example. However, when the share of higher alkanes in the LNG fuel rises (due to evaporation, for example), the ignition temperature falls. Methane gas will ignite only if the ratio or mix of gas vapor to air is within the limited flammability range. An often expected hazard is ignition from flames or sparks. Consequently, LNG facilities are designed and operated using standards and procedures to eliminate this hazard and equipped with extensive fire detection and protection systems should flames or sparks occur.

When compared to other liquid fuels, LNG vapor (methane) require the highest temperature for auto ignition, as shown in the Figure 8.

Fuel	Auto-ignition temperature (Celsius)
LNG (primarily methane)	540 °C
LPG	454-510 °C
Ethanol	423 °C
Methanol	464 °C
Gasoline	257 °C
Diesel Fuel	Approximately 315 °C

Source: New York Energy Planning Board, Report on issues regarding the existing New York Liquefied Natural Gas Moratorium, November 1998, modified by the author.

Below the ignition temperature, a gas/air mixture can only be ignited by an ignition source such as a naked flame, spark, plug or an electrostatic charge. LNG cannot be ignited as long as it is kept in closed, oxygen-tight containers. The explosion limits of methane/air mixtures (4.4 to 17% are slightly wider than those of liquefied petroleum gas (auto gas) and far higher than those of diesel (0.6 to 6.5%). Natural gas and LNG have a high flame temperature; they burn faster and generate more heat than liquid fuels (GIIGNL, 2015b).

In summary, LNG is extremely cold, non-toxic, non-corrosive substance that is transferred and stored at atmospheric pressure. It is refrigerated, rather than pressurized, which enable LNG to be an effective, economical method of transporting large volumes of natural gas over long distances. LNG itself poses little danger as long as it is contained within storage tanks, piping, and equipment designed for use at LNG cryogenic conditions (Moss, 2003). However, vapors resulting from LNG as a result of an uncontrolled release can be hazardous, within the constraints of the key properties of LNG and its vapors - flammability range and in contact with a source of ignition - as described above.

CHAPTER 5 NATURAL GAS SECTOR

With economies worldwide grinding to a halt as virus-containment measures take their toll, oil is not the only fossil fuel to have suffered a steep decline in prices. Demand from the world's biggest buyers of liquefied natural gas (LNG) has plunged, dragging Asia's spot prices to record low levels and forcing some suppliers to start cutting output. The world's biggest LNG markets - Japan, China, and South Korea - are all seeing a drop in demand for gas used in power generation, heating, vehicles and chemical manufacture.

LNG industry has witnessed its third and most significant expansionary phase lately, in which supply is racing ahead of demand. The industry's expansion is part of two overarching trends: the gradual spread of gas-on-gas competition that has emanated from both the US and Northwestern Europe for more than a decade, and the global transition to lower emission energy sources, which is making LNG a key fuel of choice for many countries.

Gas pricing is directly influenced by the maturity of the national market and by the degree of its liberalization. A growing liberalized market with a large international LNG trade results in a fast evolution of gas pricing. This tendency of the market is to switch from oil indexed pricing of long term contracts to a price determined by market forces. In different countries, short term markets and spot markets for natural gas are developing, so that gas price has daily quotation resulted from the competition of more suppliers.

A gas on gas competition is a type of LNG price formation mechanism where the price is determined by the interplay of supply and demand - gas-on-gas competition - and is traded over a variety of different periods (daily, monthly, annually or other periods). Trading takes place at physical hubs (e.g Henry Hub) or notional hubs (e.g National Balancing Point in the UK). What role could natural gas, the cleanest fossil energy source with the lowest carbon content, and its liquefied derivative LNG, play in the future global energy mix?

The present chapter will touch upon the latest developments at the global gas markets that also provides an overview about the latest developments with regard to natural gas demand and supply. Major trends in the global natural gas and LNG trade as well as LNG pricing mechanisms are also discussed.

5.1 GLOBAL ENERGY DEMAND, NATURAL GAS AND LNG

The first quarter of 2020 has proven to be very challenging for natural gas and LNG producers, as historically low gas prices have prevailed throughout the winter season. First, the increase in LNG exports combined with a mild winter across the Northern Hemisphere lead to a counter-cyclical drop in international gas prices. The bearish tone continued throughout February and March as markets around the world started to announce lockdown in order to control the spread of the Covid-19 virus.

Oil prices that hit two-decade lows in April and are down more than 50 percent since the end of 2019 have exacerbated the problem. The prospect for sustained lower oil prices has the potential to impact the global gas industry directly through oil-based pricing and indirectly through associated gas production.

Gas prices will be influenced by oil prices for several years. If oil prices stay low, so will gas prices. The contracts linked to oil will have to be worked through first, but even if oil and gas prices are delinked after certain contracts are concluded, inexpensive oil could psychologically have a dampening effect on all energy prices. For example, Asia - which takes 70 percent of global LNG exports - still buys most of its LNG in long-term contracts linked to oil prices. There is typically a lag of three to six months before the drop in oil prices is felt by buyers and sellers.

On demand side, no new country joined the ranks of importers in 2019 but several countries made sound progress on infrastructure development and are set to begin importing in the coming years. Although, no new consumers joined the existing markets in the global LNG arena in 2019, the most recent new players have increased their intake in volumes - Bangladesh, Pakistan, Poland, and Panama. At the same time, mature markets like India, are adding new floating re-gasification capacity.

Floating Storage and Re-gasification Unit (FSRU) continues to be an exciting and growing segment, improving access to modern energy and security worldwide. FSRUs have recently enabled additional markets that import LNG to meet short-term gas demand when the LNG price is competitive with other fuels. They are attractive for those markets because of lower investment costs, shorter installation periods (around 18 months for FSRUs versus more than five years for onshore conventional re-gasification terminals) and greater flexibility in length of commitment than onshore re-gasification facilities (ICIS, 2018)[43]. FSRUs have therefore played important roles in overcoming the short-fall in gas production or meeting emerging gas demand quickly in recent years. The demand for LNG may increase as the market expands or decreases in response to higher LNG prices. Therefore, flexibility in the global LNG market will become more important for timely and adequate response to potential fluctuations in LNG demand among these markets. Recent countries to invest in FSRUs are Lithuania in 2014, Egypt and Jordan in 2015, and the United Arab Emirates in 2016. Of the 37 existing LNG import markets as of February 2020, 19 imported LNG with FSRUs, and 6 of those had onshore terminals as well (IGU, 2020)[44].

The drastic curtailment of global economic activity and mobility during the first quarter of 2020 pushed down global energy demand by 3.8% relative to the first quarter of 2019 (IEA, 2020). If lockdowns last for many months and recoveries are slow across much of the world, as is increasingly likely, annual energy demand will drop by 6% in 2020, wiping off the last five years of demand growth. The drop in global economic activity cut demand for some energy sources much more than for others, with impacts on demand in Q1 2020 going well beyond declines in gross domestic product (GDP) for certain sectors and fuels.

The IEA's full year projection indicates that global natural gas demand could decrease by 5% in 2020, based on their broad assumptions for the year. This decline is less than anticipated fall in oil demand, reflecting the fact that natural gas is less exposed to the collapse in demand for transportation fuels. Nonetheless it represents a huge shock to a gas industry that is used to robust growth in consumption. This drop would be the first in annual consumption since 2009, when it fell by 2%, and the largest recorded year-on-year drop in consumption since natural gas demand developed at scale during the second half of the 20th century. Based upon the above-mentioned trends, natural gas consumption is expected to fall in every sector and region in 2020 compared with 2019, but most of the declines are in power generation.

This also means that the future for gas and LNG is highly uncertain, particularly as new supply continues to come online in a market that may struggle to absorb it. In absolute terms, global gas demand is expected to be around 3,878 billion cubic meters (bcm) in 2020, down from 3,951 billion cubic meters last year. As compared to the pre-Covid-19 estimates this year's natural gas demand was expected to grow to 4,038 billion cubic meters.

Economic growth is becoming increasingly important proxy for greater gas usage globally. Industrial sector demand - including gas as a feedstock for petrochemicals and fertilizers - has increased in significance as a growth driver relative to gas consumption for power generation. There is now a huge question mark around economic growth moving forward due to the coronavirus pandemic.

Therefore, energy demand is set to decline in all major regions in 2020. Demand in China is projected to decline by more than 4%, a reversal

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[43] Independent Commodity Intelligent Services (ICIS), "LNG Year in Review 2018".

[44] IGU (2020), "World LNG Report".

from average annual demand growth of nearly 3% between 2010 and 2019. In India, energy demand would decline for the first time, following on from low demand growth in 2019. However, it is advanced economies that will experience the greatest declines in energy demand in 2020. In both the European Union and the USA, demand in 2020 is likely to fall around 10% below 2019 levels, almost double the impact of the global financial crisis in 2008.

In Asia, demand was characterized by two diverging trends: on the one hand, it continued to be boosted by China despite the US - China trade frictions and the slowdown of the coal-to-gas switch in the industrial sector. On the other hand, LNG demand declined in Japan and South Korea, where increasing levels of nuclear power generation and the pace of renewables deployment influenced the role of LNG in the power mix. In Europe, the absorption of surplus volumes was enabled by a combination of lower pipeline imports, declining domestic production, increased storage use and additional gas-fired power generation. Imports dwindled in the Middle-East as Egypt increased its exports. The same dynamic occurred in South America as Argentina started LNG production and exports.

Natural gas supply did not adjust to this drop in consumption, resulting in a considerable build-up of gas in storage. US dry gas production grew by 7% in Q1 2020 relative to Q1 2019, while global LNG trade in its sixth consecutive year of growth increased by an estimated 13%. Thus, global LNG trade set a new record last year, reaching 354.7 MT, up 13% on 2018. The US (+13.1 MT), Australia (+8.7 MT) and Russia (+11 MT) added the most capacity but Qatar managed to maintain its position as the largest exporter in the world (77.8 MT). China imported 7 MT and Europe 37 MT more while Japan and South Korea both imported less; and Egypt and Argentina swung from LNG imports to LNG exports. Re-exports fell 59% in 2019 as price difference between the Atlantic and Pacific basins fell.

Europe accounted for about 60% of the increase of LNG over this period. While pipeline imports decreased in both markets, underground storage inventories experienced a strong build-up. In the USA they rose by 77% compared with 2019, 17% above the five-year average as of the end of March. In Europe they rose 40%, to reach 80% above the five-year average. These increases were supported by exceptionally low spot prices, with the US Henry Hub price at its lowest Q1 average since its establishment in 2003.

For LNG sellers and buyers, business models and contractual arrangements are becoming increasingly diversified. Portfolio players - in the LNG industry in this century - have contributed and are expected to continue contributing to development of more flexible LNG markets by handing over and receiving cargoes at different locations around the world responding to market signals. An LNG portfolio player is defined as a company who holds a portfolio of LNG supply from different regions as well as various shipping, storage and re-gasification assets. LNG volumes controlled by portfolio players have increased not only in the short-term sales, but also in the long-term contracts markets (Hashimoto, 2018)[45].

At the LNG market there are large players with multiple supply sources and market positions, as well as an increasing number of smaller end-use LNG buyers in different regions in the world. Traders continue to take advantage of seasonal and local supply tensions and integrated portfolio players are displaying impressive growth. Competing interests can be seen, a world in which sellers require long-term commitments to support their investments, whereas buyers need shorter contracts durations, diversified pricing structures, increased destination flexibility in order to manage demand uncertainty. The presence of LNG hubs and the increase in available natural gas supplies have attracted new buyers from afar as the Middle-East and North Africa - among them, Jordan, Pakistan, and Egypt. The evolution in global trading is producing more natural liquidity, price transparency, longer-term contracts, and gas-on-gas competition, which ultimately reduces contractual risk and facilitate hedging. By globalizing the LNG market, these hubs could increase commoditization.

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[45] Hashimoto, H. (2018), "Emergence of LNG Portfolio Players" in IEEJ, March 2018.

Looking further ahead, LNG will continue to be a flexible, reliable and cleaner energy source to meet ever more flexible and climate-conscious demand. To allow natural gas to penetrate new markets, prices need to remain at levels that make gas competitive with alternative fuels in downstream power and gas markets but, at the same time, support the significant investments needed in production, liquefaction, transportation and downstream infrastructure. Natural gas's effective contribution in quickly improving air quality and curbing carbon emissions should be key in positioning LNG as an enduring part of the energy mix and as a pragmatic and lower-carbon solution for the future, while new gases will begin to take advantage of the versatility of LNG infrastructure.

5.2 GLOBAL GAS RESOURCES AND GLOBAL GAS SUPPLY

At current global consumption levels, the discoverable conventional natural gas reserves will last for just under 60 years. Global natural gas resources, currently estimated at around 800,000 billion m^3, are a better indicator of future natural gas production. According to current estimates, global natural gas remaining proven recoverable natural gas reserves are approximately 186 trillion m^3. Over the past 30 years, proven recoverable natural gas reserves have grown by 3-4 trillion m^3 a year and the reserve-to-production ratio has stayed steady at close to 60 years.

Advances in exploration and production technologies have increased our ability to develop gas resources, particularly from unconventional gas resources. Unconventional gas resources that currently account for approximately 46% of global natural gas reserves include shale gas, tight gas (from rock formations with low permeability) and coal bed methane (CBM); shale gas accounts for around 70% of the unconventional gas reserves. Coalbed methane, also known as coal seam gas is a form of natural gas extracted from coal beds. In recent decades it has become an important source of energy in the USA, Canada, Australia and other countries. The presence of this gas is well known from its occurrence in underground coal mining, where it presents a serious safety risk (IEA, 2018).[46]

Natural gas resources are distributed geographically across large parts of the world, and much more widely than oil reserves. The largest conventional gas resources are in Iran (18%), Russia (17%) and Qatar (13%). 70 per cent of the reserves in Iran and Qatar refer to a joint deposit with the size that was estimated with a small number of exploratory drillings several decades ago. An approximated 4.3% of global natural gas reserves are located in the USA, with half of the deposits in form of coal bed methane and shale gas. However, US natural gas reserves are depleted disproportionally quickly due to the fact that the country is the world's largest producer of natural gas.

Confirmed unconventional natural gas reserves account for approximately three-quarters of global technically minable reserves. In a 2012 report, the IEA estimated that global confirmed technically mixable natural gas reserves amounted to 420 trillion m^3, with 331 trillion m^3 recoverable with unconventional technology. The unconventional resources were 208 trillion m^3 in shale natural gas, 76 trillion m^3 in tight natural gas sand 47 trillion m^3 of coal bed methane. In a separate report, the U.S. Energy Information Administration (EIA) assessed the world's recoverable reserves of shale natural gas at 7299 trillion cubic feet, of which China's share was the largest, followed by Argentina, Algeria, the United States and Canada.

According to IEA estimates, global unconventional natural gas total production volume will reach 928 billion m^3 in 2020, including 454 billion m^3 of shale natural gas, 148 billion m^3 of coal bed methane and 294 billion m^3 of tight natural gas.

Despite the optimism, there nonetheless remain significant uncertainties about how quickly unconventional resources can be brought online outside the US, especially in countries where

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[46] IEA (2018), "Gas 2018: Analysis and Forecasts to 2023" Paris.

little or no production has been taken place. Although China is estimated to have unconventional resources totaling about 32 trillion m³, the government recently reduced its near-term outlook for reaching theses reserves. Problems cited included that the resources were spread across more than 500 basins and the geography was difficult, as well as cost, inadequate infrastructure, water disposal concerns.

World gas production is dominated by conventional gas, with a share of just under 80% of total production (IEA, 2018)[47].

Figure 9 Gas production in 2018

Country	Volume in billion cubic meters
United States	864
Russia	741
Iran	232
Canada	188
Qatar	168
China	160
Norway	127
Australia	125
Saudi Arabia	98
Algeria	96
Turkmenistan	85
Indonesia	75

Source: Modified from Enerdata diagram (2018).

5.3 NATURAL GAS TRADE AND LNG MARKET

Global natural gas trade has expanded rapidly, driven by significant demand growth in Asian markets and ample natural gas resources in Qatar, Australia, the USA and the Russian Federation. The LNG trade, which is the only viable option to connect demand and supply for long-distance trade between continents, has experienced impressive growth over the past two decades. This is based on successive waves of investment in natural gas export and import infrastructure.

LNG markets have grown in volume and also in the number if market participants. The USA played a crucial role in the structural change of the LNG market more than a decade ago. The country emerged as a potential importer which triggered large investments in liquefaction infrastructure, especially in Qatar. It also introduced technical means to provide rapid and flexible import solutions, such as floating storage and re-gasification units (FSRUs).

Traditional elements of natural gas sales agreements were challenged. This was because of oil-indexed gas sales agreements did not reflect competition with coal as an alternative in the power sector. In addition, the long-term nature of existing contracts was unacceptable against the background of existing liquid markets in the USA.

The shale gas revolution in the USA overturned demand projections for the LNG market in the 2000s, after Qatar took final investment decisions (FIDs) for LNG export infrastructure. The USA did not become a major LNG importer but rather a future competitive exporter owing to the vast and cost-competitive potential of its shale gas reserves. The LNG terminals that were planned as re-gasification facilities were thus converted to liquefaction plants, ready to supply the global market with LNG originating from the USA.

With imports of around 350 billion m³, the European Union is now the largest gas importer, followed by China, Japan and Korea. Russia, the Middle East, the Caspian region and Australia, on the other hand, are major gas exporters. The EU will remain the world's largest gas importer in the future, not least because of its own natural gas production continues to decline. Within the next decade, China will become the second largest gas importer. The USA, in particular, is expected to become a major gas exporter in the future because of the shale boom (IEA, 2018c).

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[47] Ibid 2018.

In 2018, global LNG trade reached 316, 5 tons, according to the 2019 World LNG Report prepared by the International Gas Union. The number of LNG exporting countries increased to 19 last year, with 2.4 million tons per annum (mtpa) Kribi FLNG project coming online in Cameroon.

Qatar has traditionally held the title for over a decade, producing some 75 million tons per year. Despite stable production rates, Qatar's market share has fallen to 24.9% in recent years due to a fixed liquefaction capacity from 2011 and exponential growth from international competitors. For example, in 2013 Qatar's contribution to China's supply was 37%, whereas the figure declined to just 20.7% in 2017 (ERCE, 2020). Last year Qatar exported 104.8 billion cubic meters (BP Statistical Review of World Energy). It also plans to increase its LNG exports capacity by 43%, and develop its North Field Expansion project, adding about 32 mtpa of liquefied gas to the market from 2024.

LNG market continues to grow in response to strong Asian demand. Over one hundred billion cubic meters of new LNG supply capacity is to be commissioned between 2018 and 2032, with the bulk of these additions coming from Australia and the USA. So far, this wave of new liquefaction capacity has been absorbed without any signs of looming oversupply, mostly by Asian importers. Both mature and fast-growing emerging markets strongly have contributed to this growth.

While China is expected to be the main driver of natural gas demand growth for the near future on the back of continuous energy consumption growth and strong policy support to curb air pollution, more mature Asian markets are likely to follow different paths. LNG imports are expected to gradually decrease in Japan in the longer term as further nuclear capacity restarts, while in South Korea natural gas demand benefits from changes in energy policy orientations and the implementation of nuclear phase-out and the curtailment of new and existing coal-fired power generation plants. Other developing Asian economies expect to have strong population growth, which supports further electrification in this region. Additional power demand will create opportunities for natural gas growth in the region, although the sensitivity to policies and price levels remain uncertain.

Natural gas markets are transitioning from local to regional and global markets, with increasing competition and diversity among suppliers and customers. LNG is the driving force to further enhance competition and market integration in international gas markets. Its development is favored by the state of the well-supplied market that is assumed to continue over the coming five years. The expansion in supply capacity (nearly 200 bcm) will exceed expected LNG demand growth (forecast to be closer to 100 bcm by 2022).

While overall LNG consumption is expected to be further concentrated in the Asia-Pacific region, the trend towards diversification of consuming countries will continue. Further diversification also happens on the supply side - apart from the USA and Australia, both traditional and new suppliers develop new liquefaction projects to capture this additional demand originating from the Asian region. While the Russian Federation is steadily adding new liquefaction trains, Qatar prepares to expand its export capacity in order to retain its leading position. Recent final investment decisions in Canada and offshore Mauritania and Senegal further reinforce the future diversity of suppliers.

The number of countries that import LNG has now increased to 37. The largest LNG importer is Japan with 85 million tons -about the same as Qatar's exports. Overall, LNG imports are dominated by Asian countries: Japan, followed by China and South Korea. By 2040, emerging countries in Asia will have absorbed over 80% of the growth in the international LNG trade (IEA, 2018c).

But Europe as a whole (including Turkey) is now also importing substantial LNG volumes - around 47 million tons in total. Spain is the major LNG importer in Europe, followed by Turkey and France. The LNG share of the EU's natural gas imports is currently 15% and is expected to increase further by 2040 (IEA, 2018)[48].

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[48] Ibid 2018.

5.4 NATURAL GAS AND LNG PRICING MECHANISMS

Historically, international trade in gas was quite limited, as gas was produced and consumed locally or regionally. Pricing mechanisms ranged from regulated prices set by governments, prices indexed to competing fuels, or spot market pricing in competitive markets. Contracting structures in each of the major market areas evolved independently of the others and there was little reason for the pricing structures to be linked because gas was not a fungible international commodity like oil. Not all gas is bought and sold on a short-term fixed price basis and there will be longer term contracts but these will use gas price indices to determine the monthly price, for example, rather than competing fuel indices. Also included in this category is spot LNG, any pricing which is linked to hub or spot prices and also bilateral agreements in markets where there are multiple buyers and sellers (IGU, 2018). Spot markets and spot prices are a wide range of gas commodity markets and dynamic pricing systems that include formal and informal quotes, spot and future trades, virtual and physical trades, and over the counter and bilateral contracts.

The physical characteristics of natural gas, which create a strong dependence on pipeline transportation systems have led to local markets for natural gas - in contrast to the global markets for oil. The local markets are characterized by different pricing mechanisms, different gas resource availability, political interests and technology developments. The emergence of LNG trade aims to link the regional markets, bringing them towards a more global approach.

The natural gas market can also be influenced by the oil market, as gas is extracted along with crude oil. Changes to the demand and supply of oil have a knock-on effect on production of gas. So, although a fall in demand for gas would push down prices, if lower oil demand results in production cuts then resulting drop in natural gas output would reduce supply. The markets are not as closely correlated as they once were, when more electricity generation switched between using fuel oil and natural gas depending on prices.

The reconfiguration of supply and demand in the LNG industry is on course to change the nature of global trading drastically and permanently. The traditional ways of doing business, based on destination-restricted, oil-indexed long-term contracts, are disappearing, making room for enhanced flexibility and interconnectivity, promoting a more liquid, competitive and transparent marketplace.

Suppliers, challenged with high production costs or waiting to come on stream once the surplus erodes and prices recover, may see this as a negative. But new opportunities are also available for those able to respond fast. Accepting that buyers' willingness to sign long-term deals largely depends on their ability to reduce risk through destination flexibility is a step towards securing new contracts and project final investment decisions (FID) into the 2020s. Continued investment in emerging markets should help producers diversify downstream portfolios and create outlets to absorb growing global supplies. Entering further into the value chain would boost their ability to optimize cargoes and capture spot value, while supporting the development of the LNG derivatives market could help limit future exposure to price volatility.

Increasing physical LNG trading volumes is considered to be an important factor that leads to improving liquidity for spot trading and consequently to the development of a marketplace for LNG. In the traditional LNG market, however, supply originated from certain limited regions and from certain limited players with large financial resources, since large development costs were required. Spot and short-term LNG recorded an impressive increase in 2018 - rising from 27% of global physical trade the previous year to 32% the latest annual report from LNG importers' group GIIGNL shows that true spot trading has been rising rapidly since 2016. And the signs are that this surge is set to continue for at least another couple of years as additional more flexible production.

There has been a growing debate about whether LNG would eventually become fully commoditized given the inevitable rise of spot LNG trading. This has been spurred on by the numerous attempts to create a gas/LNG trading hub in Asia as well as LNG futures markets, the rise of aggregators, a growing number of so-called portfolio contracts, traders entering the world of LNG and increasing amounts of flexible US LNG.

LNG is often compared to oil when the debate about commoditization comes up. The fact is that global LNG markets have been changing and yearning to look like oil markets, but they are not quite there yet. Selling an oil cargo is considerably easier than an LNG cargo. Oil markets are liquid and a seller will always find a buyer at given price; the cargo will probably change hands several times before it is unloaded. Sellers can also opt to store the oil cargo and sell it later.

5.4.1 LNG PRICING MECHANISMS

Natural gas prices and price-setting mechanisms have evolved over time. While long-term contracts linked to oil were once dominant, now price setting is taking different forms across markets, and prices vary by region. Natural gas prices generally fall into 3 categories depending on the degree of regulation, the competitiveness of the market, and market liquidity: (1) government regulated prices, based on cost of services, (2) price indexation to competing fuels (commonly known as oil-indexed pricing) and (3) spot market pricing in competitive gas markets.

The development of a global natural gas market is limited by geography, with most international trade being over natural gas pipelines or by LNG shipping. Geographical limitations and high shipping costs - the construction of international long-distance pipelines, as well as the costs of shipping and storing LNG - restrict trade between different regions, causing the natural gas market to develop distinct regional characteristics, particularly, regarding how prices are established. Unlike other internationally traded commodity markets, natural gas has disparate regional benchmark prices. Despite the fact that natural gas and oil share many characteristics (both are hydrocarbons, both are found and produced using similar methods and equipment), they contrast in the way they are sold and priced.

Oil is sold by volume or weight, typically barrels or tons. By contrast natural gas is sold by unit of energy[49]. A large majority of crude oil is bought and sold directly or indirectly through highly liquid global markets. Quoted oil prices usually refer to a specific type of crude oil (with unique characteristics) at a specific delivery location. For example, in the USA, crude oil price usually refers West Texas Intermediate, a specific type of oil, sold at a defined location in Oklahoma. Any oil traded in the USA would "benchmarked" against this value, and be sold at a premium or discount to this benchmark price.

In contrast to oil markets, because natural gas is difficult to transport, natural gas prices tend to be set locally or regionally. The large majority (over 90%) of traded natural gas is transported by pipeline. A pipeline may connect a single producer with a single buyer of gas - such as of a gas field supplying to a dedicated power plant - or may consist of a sophisticated grid connecting thousands of individual gas producers and thousands millions of gas consumers. Natural gas prices in the first place, involving a single producer and a single buyer would be negotiated between the parties. In the second case, where there are many buyers and sellers of gas, traded prices are most influenced by supply and demand.

The practice of indexing gas prices to competing fuels - specifically oil products - gained favour early ion in Europe and thereafter in Asia. The very growth of these markets rested on increasing international trade in natural gas that was contractually based on linking gas prices to oil product prices for both pipeline gas and its liquefied natural gas (LNG) counterpart. The USA, by contrast, pioneered commodity markets based on hub trading.

The landscape began to change in Europe in the 1990s. The USA decided to introduce a liberalised market in natural gas and the industry began developing traded markets based loosely on the U.S

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[49] Common energy units include British thermal unit (Btu), Therms, and Joules (J).

model. In 1998, the UK gas network was linked to Belgium, causing commodity markets to spread into continental Europe. The European gas market split, with oil indexation dominating the continent while competitive hub pricing - centred in the UK - made inroads into Northwestern Europe.

Most gas markets in the world can be divided into 4 groups: (1) gas-on-gas markets, (2) price indexed to substitute energy prices, (3) oil linked price markets, and (4) regulated markets.

Gas-on-gas pricing is a characteristic feature of the gas markets in the USA, UK, and Canada that are definitely the most liberal and traded gas markets in the world. Northwestern Europe has been added to this group owing to the remarkable transition towards hub pricing that has taken place since the early 2010s in a relatively short period of time, much of the gas sold and consumed in Northwestern Europe has switched from formula-based oil product-linked prices to hub gas-on-gas prices. This transition has resulted largely from the development of common regulations, standardized contracts, increased infrastructure, government support, and general market liberalization. Remarkably, this transition has occurred despite the resistance of major gas suppliers, Russia and Norway in particular, who had benefitted from it. In these markets gas prices are set in relation to regional gas supply and demand, where gas competes with other gas - hence the term gas-on-gas pricing. There are large number of buyers and sellers largely competing without governmental intervention. Gas is traded on open exchanges such as NYMEX, and there are established benchmark or hub prices where pricing information is transparent, readily available, and updated regularly. Infrastructure is openly accessible, and usage fees are either regulated or fairly priced.

Price-indexed to substitute energy prices is a common feature of the gas markets in Central and Southern Europe, South Africa, and to a lesser extent Southeast Asia. Whereas many countries in Northwestern Europe have rapidly evolved to gas-on-gas pricing with robust gas pricing hubs, much of Central and Southern Europe has yet to evolve towards gas-on-gas characteristics. In these countries, there is a limited but growing gas grid. There are some gas storage facilities, and an emerging traded gas market. However, in these markets, most gas remains priced in relation to other energy such as oil products, coal, or even electricity, explicitly linked by formula under majority long-term contracts.

Oil linked price markets are typical in the traditional LNG markets of North Asia - especially Japan, Korea ,and Taiwan - and emerging LNG markets, such as India and China. The North Asia region, with the exception of China, has limited domestic energy resources and does not have the infrastructure to import gas by pipeline. Thus, essentially all of their gas is delivered via LNG imports. firstly, oil linked contracts provide the guarantee of demand needed to by developers to launch new LNG projects and are not as vulnerable to the volatile spikes as the spot market would be. Secondly, apart from providing stability, these contracts offer forward visibility on future pricing and supply security. Nonetheless, some 32% of the entire LNG trade is currently conducted on a spot basis, implying that LNG prices are slowly but increasingly reflective of the supply and demand of the commodity itself.

The common types of LNG sale and purchase agreements are short term sales agreements, master- and long-term agreements. Short - term sales agreements are 1 to 5 year bilateral agreements, often with little flexibility of terms. Master agreements, a popular arrangement under which seller and buyer sign an agreement that sets out the general terms according to which they will sell and buy LNG without the committing the parties to an obligation to actually buy and sell specific quantity of LNG. In case the parties will to transact, they will complete a supplementary “confirmation notice” deemed to include the general terms of the master agreement and the transaction - specific terms such as contract price, contract quantity and LNG specification. Long-term sales agreements, are typically for a term of 20 years, the long-term sales agreement remain the traditional collateral for financing the capital-intensive LNG value chain.

There is criticism that the oil-indexed price mechanism adopted in long-term LNG purchase contracts does not properly reflect the supply and demand of LNG. Moreover, since price formulas vary by contrast and are decided bilaterally, transaction prices are unknown except to the parties of the contracts, and even if the formulas were disclosed to third parties, it would be difficult to evaluate contracts without understanding the factors that determine the price. Until now, this opaque price-setting method has been considered normal market practice in the LNG market.

What used to be a "linear trade" -with ships plying between a given liquefaction plant and a given re-gasification terminal - has given way to more complex patterns of LNG trading. For decades, LNG sales and purchase agreements (SPA-s) were long term, with pricing mechanisms tying the price of LNG to that of crude oil, and destination restriction clauses that forbade buyers from reselling cargoes The terms of these contracts were so rigid that LNG projects were sometimes described as "virtual pipelines".

Natural gas hubs (e.g Henry Hub) are an important factor natural gas pricing mechanisms, given that their core function is to provide a physical connection within the natural gas system and to facilitate competitive pricing. Natural gas hubs break the link between the price of natural gas and oil prices. North American gas is usually priced at liquid trading hubs, of which the biggest and most significant is Henry Hub. It is an interstate pipeline that is certified as an open-access gas transporter, and it is directly connected to four industrial consumers and one producer. Due to its central location and high degree of interconnectedness, the Henry Hub is used as the delivery point for New York Mercantile Exchange's (NYMEX) natural gas futures contract.

The United Kingdom uses the National Balancing Point (NBP), which is unique in that it is a virtual trading location. Both determine and publicly report price indices that some market participants view as global benchmarks for the value of natural gas. However, Asia does not have a unified pricing benchmark that reflects local market forces, having no suitable location with sufficiently developed physical infrastructure nor regulatory framework in place to accommodate the creation of natural gas trading hub. The most commonly used reference for spot physical cargoes within Asia is the S&P Global Platt's Japan Korea Marker (JKM), which reflects the spot market value of cargoes delivered ex-ship (DES) into its eponymous markets, as well as deliveries into ports in Taiwan or China with the same minimum cargo size of 135,000 cu m as these countries equate to the majority of global LNG demand.

While hubs in North America and Europe are pipeline-based (for example, Louisiana's Henry Hub has access to natural gas infrastructure on the U.S Gulf Coast), many countries in Asia rely on LNG as the primary source of natural gas. Asian LNG import terminals are at a distinct disadvantage in this regard due to the limited pipeline interconnectivity and the inevitable time lag between contracting and delivering large LNG cargoes. The competitive pricing that the formation of hubs allows becomes a kind of substitute plan for controlled prices linked to oil prices. In addition, natural gas hubs also form an important component of natural gas downstream markets.

Price levels across the regions have also varied significantly, reflecting the changes to the supply and demand for each market (see figure 8). In North America, the influential Henry hub price generally reflects the supply and demand dynamics in the United States, for example by reflecting seasonal variations and longer term trends (such as shale gas revolution). Indeed, there were periods when US natural gas prices were higher than the average LNG import price in Japan, for instance when the market expected the United States to need substantial LNG imports.

Figure 10 Regional market pricing characteristics

Region	Market description	Method of price formation
North America	Natural gas market with competition-based natural gas pricing. Interconnected infrastructure linking storage, supply and demand hubs	Multiple natural gas indices, with Henry Hub the dominant openly-traded LNG index.
Europe	Multiple natural gas markets with varying degrees of competition-based pricing. Markets operate and regulations are developed under a framework established under the European Union, but strong national interests remain. Infrastructure is primarily interconnected, with some bottlenecks.	Long-term contracts connected to oil price or oil product prices are being increasingly challenged by competitive pricing, for example from NBP in the UK and Title Transfer Facility (TTF) in the Netherlands.
Japan, South Korea, and Taiwan	Markets primarily based on national monopolies and supply in the region primarily under long-term contracts, with some active spot LNG buying to manage supply and demand or some portfolio optimizing.	Strong oil indexation for long-term contracts to the Japan Crude Cocktail (JCC), which is generally defined within individual contracts and lags current oil prices because they are typically based on recent average prices of crude imports into Japan.
China	Market dominated by state-owned enterprises. Supply based on a mix of domestic production, pipeline imports from central Asia, Myanmar and, soon Russia.	Natural gas supplied under a mix of cost-plus for domestically produced natural gas and oil-indexed pricing, primarily for imports.

In the past, the Henry Hub price was widely seen as a benchmark for the US market, and many natural gas liquefaction projects around the world were begun targeting exports to the USA based on these prices, relying on the Henry Hub price for their export plan pricing, along with the belief that the United States would be a long-term LNG importer.

As North America and, to a lesser extent the United Kingdom and Northwestern Europe have extensive pipeline and gas storage systems with opportunities to both export and import gas from outside the markets, gas can be traded on both current and future contracts. This makes it possible for a buyer to purchase a defined volume of gas, to be delivered at a specified location on the gas grid, at a date in the future, at a price established today. This sophistication allows the gas market to be very efficient by maximizing usage of infrastructure and allowing both buyers and sellers to plan their financial future. Risks can be managed; however, short-term gas price tends to be volatile, continuously reacting to supply and demand.

An added advantage of a highly traded system is the spread of infrastructure over the entire network, not just at gas producing or consuming regions. A newly discovered gas field can be developed and marketed relatively easily, assuming that the pipeline grid is within a short distance, because there is confidence that produced gas can be sold at an established price. No prolonged gas marketing efforts are needed because the market has an established price-setting mechanism and all new gas consumes can usually be absorbed by the system without requiring that new purchase agreements be negotiated with individual buyers. Different parties can own different parts of the chain -from upstream to gas processing to pipelines, storage, and local distribution - because pricing is transparent and all services are competitive. In theory, no individual supplier or buyer is able to control prices, and the presence of intermediary parties, such as gas traders, usually results in more efficient markets and lower prices.

CHAPTER 6 SUPPLY CHAIN AND LOGISTICS OF LNG AND INFRASTRUCTURE

The reasons for the resurgence and growth of the LNG industry are a combination of the increased demand for energy, the availability of natural gas reserves in locations around the world that provide new supplies, and advancements in LNG technology which lower the cost of the LNG value chain.

The global LNG business has been described as a value chain containing 5 components: (1) exploration and natural gas production, (2) liquefaction, (3) shipment of LNG in special purpose ships for delivery to markets, (4) storage and re-gasification and (5) distribution and delivery of natural gas through the national gas pipeline system and its distribution to end users. The largest component of the total cost of LNG value chain is usually the liquefaction plant, while the production, shipping, and re-gasification components account for nearly equal portions of the remainder (Mutaz et al, 2016).

LNG infrastructure can be separated into two main elements: (1) Full-scale, spanning from the large liquefaction facilities to big import terminals, with tanks holding hundreds of thousands of cubic meters. This part of the infrastructure is well established both commercially and in terms of the technology, (2) small-scale, starting at LNG distribution sources such as import terminals through to the end consumer of LNG.

The emergence of small-scale LNG in the form of floating terminals (Floating Liquefaction Unit, Floating Storage Unit (FSU), Floating Re-gasification Unit (FRU) or Floating Storage and Re-gasification Unit (FSRU) can be seen. Floating Units (ships or barges) which generally require lower capital expenditures but may entail higher operating costs.

Although LNG has a good safety records as there have not been many accidents, still some hazards (e.g LNG spills, leakages and embrittlement of steel on board of the vessel) can occur resulting from its cryogenic temperature, flammability, and vapor dispersion characteristics. Safety aspects of LNG handling as a fuel are important. Even uninsulated LNG pipes can become cold enough to cause serious injury to personnel. Because of these issues, the piping system, material requirements, and safety issues are much different than for a fuel oil system. The hull or deck structures in areas when LNG spills, leaks or drips may occur must be either suitable for the cold temperatures or protected from the cold temperatures.

The stages in the LNG supply chain will be described in general below. This will be followed by a description of the elements of the supply and value chain for liquefied natural gas, from liquefaction to possible special uses of LNG as final energy.

6.1 NATURAL GAS LIQUEFACTION

Liquefaction is the process of cooling natural gas to very low temperatures, i.e. below the boiling point of natural gas. This results in a phase transition which changes the physical state of the gaseous natural gas to liquid. An important objective of natural gas treatment and liquefaction is to provide a product (LNG) with consistent technical characteristics and to make it easier to transport. Liquefaction process is essentially about the removal of the heat from natural gas. The basic principles for cooling and liquefying the gas using refrigerants involve matching as closely as possible the cooling/heating curves of the process gas and the refrigerant, as this results in a more efficient thermodynamic process requiring less power per unit of LNG produced. This applies to all liquefaction processes. Thus, the liquefaction cooling curve performance is a benchmark used to compare competing processes when a new LNG project is being developed (Mutaz et al, 2016)[50].

The liquefaction of natural gas is basically mechanical refrigeration, where the gas is cooled and liquefied by heat exchange with a separate refrigerant. Liquefaction takes place through cooling of the gas using heat exchangers. In these vessels, gas circulating through tube coils is exposed to compressed pure or mixed refrigerants. Heat transfer is accomplished as the refrigerant vaporizes, cooling the gas in the tubes before it returns to the compressor. The liquefied natural gas is pumped to an insulated storage tank where it remains until it can be loaded onto a tanker.

Natural gas liquefaction processes can be characterised by the number of process stages and the refrigerant used (Uhling/Wohlegemuth, 2012)[51]. The process uses either simple (single-component) or mixed refrigerants. The refrigerants must be cold enough to liquefy the natural gas at the end of the process. Propane (for pre-cooling), ethylene, methane itself and nitrogen are the main refrigerants. Mixed refrigerants do not have a boiling point but a boiling curve. The liquefaction process can have variations. A number of licensed processes have been developed over the last decades based upon mechanical refrigeration. Besides seeking to reduce unit investment and operating costs, the primary objectives of these technological innovations are to increase the capacity of LNG production and optimize the efficiency of the refrigeration process.

Liquefaction plants vary in size depending on whether they are centralized plants liquefying gas on a large-scale at the place of production, or decentralized plants liquefying gas from the natural gas network close to the point of consumption or from smaller scale local natural gas resources.

Figure 11 Liquefaction equipment

Source: Liquefaction-Equipment-Emerson, LNG Facts (2020)

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[50] Al Mutaz et al. (2016), "Natural Gas Liquefaction Technologies", in Oil & Gas Europe Magazine No 4/2016.

[51] Uhlig, B., Wohlgemuth, S. (2012), "LNG – Liquefied Natural Gas. Förderung Transportkette und motorische Verbrennung", Munich.

At present the dominant LNG supply model is the hub-and-spoke one, which involves centralized liquefaction in large industrial facilities, transport and onward distribution (GIIGNL, 2020)[52]. The large LNG liquefaction facilities are called LNG trains. Two, or even more LNG trains are often built alongside each other to ensure continuous and safe operation.

The LNG trains are either large-scale base-load plants with a liquefaction capacity of 3 to 8 million tons of LNG a year, medium-sized plants with the capacity of 0.5 to 2.5 million tons a year or small plants with a capacity of 0.3 to 0.5 million tons a year. The latter are often used as peak shaving plants which are used in case of fluctuations in consumption in the natural gas network. An even new category is mini or micro liquefaction plants, which are used for local liquefaction of biogas or biomethane or to supply LNG in isolated areas to which it cannot be transported (Wärtsilä, 2016).

6.1.1 INNOVATIVE OFFSHORE NATURAL GAS LIQUEFACTION

Floating liquefied natural gas (FLNG) is used to describe an offshore facility floating above a natural gas field. Floating liquefaction is a relatively new technology, compared to floating regasification which has quickly established itself as a standard approach. There are FLNG facilities both for natural gas production sites and for LNG receiving terminals. Floating units which can take natural gas from current production, liquefy it in order to produce LNG and store it onboard, are called Floating Production Storage and Offloading Units (FPSOU).They have been used in oil production since the 1980s and 1990s. In gas production this is still a new technology, which allows smaller, more remote natural gas resources to be developed more cost-effectively. The first FPSOU began to export LNG in 2017 (IEA, 2017; IGU, 2018). From technological point of view, floating liquefaction should not present any excessive technical challenges.

However, it does require a specialized LNG containment system to prevent sloshing; topsides modules including gas pre-treatment and liquefaction, safe systems for offloading cryogenic liquid in potentially difficult sea conditions. Production processes have to be kept away from living quarters - sharing experiences from onshore LNG plants in confined sites such as British Columbia in Canada. Weather conditions will have to be factored into installation and operational schedules.

This technology can unlock gas resources from underwater gas fields that may once have been economically or environmentally challenging to obtain. Many natural gas resources are located in offshore fields, but geographic, technical and economic limitations make a number of these difficult to develop.

Experimental development of offshore LNG production began in the mid-1990s. Mobil developed a FLNG production concept based on a square structure with a moon pool in the centre. Following that major projects conducted by the EU and major oil and gas companies made great progress in steel concrete hull design, topside development and LNG transfer systems. The FLNG project “Prelude” started operations in 2018. It is one of the world's first offshore LNG plants, and currently the largest. Prelude produces and liquefies natural gas around 300 miles off the coast of Western Australia. The floating platform operates at a sea depth of 250 meters and is 488 meters long by 74 meters wide, making it the size of four football pitches. The Prelude FLNG facility has the capacity to produce 5.3 million tons of liquids and condensate a year (Mtpa), including 3.6 Mtpa of LNG.

There are two scenarios for the future development of floating LNG. It may become a niche technology that is applied by few companies to solve specific problems, with land-based configurations remaining the default. This could happen if the first FLNG plants encounter cost or operational difficulties or if land-based costs fall as the current construction boom ebbs. For smaller offshore gas fields, compressed natural gas or small-scale gas-to-liquids may become viable competitors. However, in the second scenario, if the first

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[52] GIIGNL (2015), “The LNG Industry in 2014. Annual Report”.

few projects are successful, FLNG can emerge as a standard approach that eases the industry's problems with cost inflation and opens it up to a much wider range of fields and companies. The concurrent development of floating re-gasification giving access to a range of smaller markets, and the development of new pricing methods and unconventional gas-to-LNG projects, may lead towards a faster-moving, more diverse - and more flexible global LNG industry.

The FLNG facility is moored directly above the natural gas field. It routes gas from the field via risers. The gas is then processed and treated to remove impurities and liquefied through freezing, before being stored in the hull. Ocean-going carriers will offload the LNG, as well as the other liquid by-products, for delivery to markets worldwide. The conventional alternative to this would be to pump gas through pipelines to a shore-based facility for liquefaction before transferring the gas for delivery.

Designers optimize safety on the facility by locating storage facilities and process equipment as far from crew accommodation as possible. The accommodation areas of visiting LNG carriers are also at maximum distance from critical safety equipment. Safety gaps have been allowed between modules of process equipment so that gas can disperse quickly in the event of a gas leak.

Figure 12. Key attributes of FLNG facilities

- Using higher strength materials to survive the forces from vessel motion;
- Minimizing or eliminating either propane or all flammable components;
- Limiting and minimizing weight, plot space, and environmental footprint;
- Using chloride resistant stainless steel to construct exposed equipment;
- Less environmental impacts during decommissioning.

Source: Modified from Mutaz et al article "Natural Gas Liquefaction Technologies: An Overview".

6.2 RE-GASIFICATION

A Floating re-gasification Unit (FSRU) is a vital component required while transiting and transferring liquefied natural gas (LNG) through the oceanic channels. Therefore, FSRU can be termed as a special type of ship used for LNG transfer. FSRU vessels can be classified either as ships or offshore installations depending upon design they incorporate. The FSRUs have been developed since the beginning of this century and they are significantly cheaper and quicker to build. The first FSRUs were converted LNG carriers but there are now purpose-built carriers, which can be modified in different ways. There are also floating storage units (FSUs), most of which are old LNG tankers not equipped for re-gasification or smaller floating storage re-gasification barges.

Floating Storage Re-gasification Unit (FSRUs) can be equipped in two ways:

- either they can be installed as a separate unit aboard the LNG carrier itself or;
- An old gas carrier can be converted into an independent unit and placed in a particular destination as an offshore installation.

When the FSRU unit is installed in the ship itself, the construction of the vessel is similar to other LNG ships undergoing LNG trading operation with regular dry docking and complying with all the required international maritime safety standards. The major advantage of such installation is that the heating and liquefaction process can be carried out within the vessel itself without having to unload the fuel in its semi-frozen slouchy state. For the second method, an old tanker is modified with offshore installations as floating LNG unit, which can be either with the propulsion unit (mobile) or without the propulsion unit (fixed offshore unit). The former gives the flexibility to operate the unit as an LNG tanker when required.

Since the refurbished Floating Storage Re-gasification Unit (FSRU) would also be able to provide storing feasibilities of LNG, constant transference of the LNG cargo from LNG vessels would ensure that there is no storage depletion whatsoever. Generally, such kinds of Floating Storage Re-gasification Units are found near the harbor to prevent time-consumption. While utilizing a refurbished gas carrier as a floating Storage Re-gasification Unit (FSRU), care needs to be taken to suitably positioning these refurbished vessels to prevent any emergency arising near a particular port or harbor.

To sum it up, Floating Storage and Re-gasification Unit (FSRU) continues to be an exciting and growing segment, improving access to modern energy and security worldwide. FSRUs have recently enabled additional markets that import LNG to meet short-term gas demand when the LNG price is competitive with other fuels. They are attractive for those markets because of lower investment costs, shorter installation periods (around 18 months for FSRUs versus more than five years for onshore conventional re-gasification terminals) and greater flexibility in length of commitment than onshore re-gasification facilities (ICIS, 2018). FSRUs have therefore played important roles in overcoming the short-fall in gas production or meeting emerging gas demand quickly in recent years. The demand for LNG may increase as the market expands or decreases in response to higher LNG prices. Therefore, flexibility in the global LNG market will become more important for timely and adequate response to potential fluctuations in LNG demand among these markets. Recent countries to invest in FSRUs are Lithuania in 2014, Egypt and Jordan in 2015, and the United Arab Emirates in 2016. Of the 37 existing LNG import markets as of February 2020, 19 imported LNG with FSRUs, and 6 of those had onshore terminals as well (IGU, 2020)[53].

6.3 LNG TRANSPORT AND STORAGE

Primary modes of LNG transportation are by sea and truck and in a few locations by rail (e.g Japan). When LNG is to be transported any great distance, it is most often transported by sea in specialized LNG Carriers that are a blend of conventional ship design with specialized materials and advanced systems for handling cryogenic cargoes. The containment tanks have layers of insulation which isolate the LNG cargo from the hull by ensuring a minimum distance from the sides and bottom of the hull per the IGC (IMO International Gas Codes) and add layers of protection in the event of grounding or collision. Additionally, this insulation system limits the amount of LNG that boils off or evaporates during the voyages. On many LNG vessels, boil-off gas is used to supplement fuel during the voyage.

In areas around the world where a liquefaction plant is in the vicinity of re-gasification facilities, the most cost-effective transportation mechanism of LNG is by tank truck. Using specialized, double-skinned tank trucks, liquefied natural gas can be transported to a re-gasification facility quickly and effectively. In many parts of the world, trucking has been used for the transportation of LNG since 1968. LNG trucking is now a mature industry, using tanker trucks of 6 to 20 tons which meet industry requirements. LNG is regularly transported by tank truck in several countries, including, but not limited to the US, Japan, Korea, the UK, Norway, Germany, Belgium, Spain, Portugal, China, Brazil, Turkey and Australia.

After unloading, LNG is transferred via cryogenic pipelines to insulated storage tanks specifically built to hold LNG. There are three kinds of facilities where LNG can be stored: onshore import terminals, offshore import terminals and peak-shaving terminals. LNG carriers deliver the LNG to a marine terminal where the LNG is stored before undergoing re-gasification, which converts the LNG back into its gaseous form. LNG cans also be delivered to offshore terminals which are LNG ships constructed to function as Floating Storage and Re-gasification Units (FSRU), or if no storage is needed Floating Re-gasification Units (FRU). Floating facilities allow LNG terminals to be sited offshore. Re-gasification ships are operating in Argentina, Brazil, the UK and the US.

Another type of facility which may receive LNG by ship is known as peak-shaving facility. These plants, which may be operated by utilities, store LNG in tanks until it is needed at times of peak demand. An LNG peak-shaving facility is nor-

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[53] IGU (2020), "World LNG Report".

mally connected to the gas-supply system and may consist of LNG liquefaction equipment to convert the natural gas into LNG.

Cryogenic liquefied gases must be stored in well-insulated tanks in order to prevent pressure increases. Most of these double-walled storage tanks have three-foot concrete exterior walls and an inner tank that is constructed from a steel-nickel metal alloy specifically designed to accommodate the cold LNG. Should a leak develop in the inner wall, all of the LNG would be contained by the outer walls. Sophisticated monitoring systems provide constant surveillance for any internal leaks.

The physical characteristics of natural gas also determine the behaviour of liquefied natural gas during storage. However, the heat ingress from the tank's surroundings will increase the temperature inside the tank, causing the liquid to evaporate, generating boil-off-gas (BOG). It needs to be managed to prevent fuel tanks becoming over pressurized, which can lead to gas venting. The boil-off rate for large tanks is generally 0.1% per day; for smaller, poorly insulated LNG tanks it will be 1% per day (EU Commission/DGM 2017b)[54]. If heat ingress into the LNG fuel tanks is not controlled, venting of harmful gas can occur, causing a health and safety risk to crew and the surrounding area. There are ways of handling BOG or finding other ways of sub-cooling the fuel through a facility onboard the ship. These options need to be considered during the ship design to best suit the ship's operational profile.

Evaporation causes evaporative cooling so the boil-off gas is used to cool the rest of the liquid. The tank insulation is so effective that only relatively small amounts of boil-off gas are needed to maintain the temperature. As LNG is a mixture of substances, the composition of the liquid phase varies depending on the boiling point of its individual components. Components with a low boiling point, like nitrogen and methane, evaporate first; heavier hydrocarbons like ethane, propane and butane evaporate later.

As a result of heat-in leak of the LNG tanks, evaporation takes place of the more volatile components (N_2 and CH_4). This process is known as "weathering" Normally weathering is a fairly slow process. Typically, an LNG tank will lose about 0.05% of its contents per day in boil-off gas to absorb the heat input and keep the remaining liquid cold. The weathering process therefore causes the composition of LNG to evolve over a period of time thus altering the density of the LNG. Generally, LNG of different densities can form separate layers within a storage tank.

This layering is referred to as "stratification" and can also be formed during filling an LNG tank with LNG of different densities (commonly referred within the industry as "light" and "heavy" LNG). For the rollover to occur, a stratification of two layers is created as a result of density differentiation. When there is little vertical heat or mass or heat transfer, both layers establish their own convection currents. The lighter upper layer releases vapor and loses heat, its density increases and equalizes to the lower layer. The lower layer, having a higher temperature, will roll over the upper layer resulting into the release of superheat and thereby generating large volumes of boil-off gas in a short period of time. An over-pressurization of the tank can occur, causing some structural damage (Miller, 2019)[55].

Refrigeration associated with continuous pump-out cancels a major proportion of the heat leak or driving force for weathering and as a result the change in liquid composition during pump-out is minimal. Other options include refilling the LNG tanks with cold LNG or re-liquefying the boil-off gas. Another renewable alternative is biogenic LNG (Liquefied biogas/LBG), which does not age because, besides methane, it contains only small amounts of nitrogen and oxygen and none of the heavier hydrocarbons. Historically, there were a few occasions of rollover occurring ashore and on-board LNG tankers. The La Spezia incident in 1971 is probably one of the most significant. In 2008, a Moss-type LNG carrier experienced an increase in pressure in some of the cargo tanks.

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[54] European Commission (EU-COM/DG MOVE) (2017b), "LNG Blue Corridors. Studies regarding Aging of Fuel", Brussels, 2017.

[55] Miller, D (2019), "Outside-in risks for LNG storage" in LNG Industry, March 2019, Energy Global.

The phenomenon is more likely to occur in large tanks. However, there is potential for this phenomenon to develop during LNG bunkering operation, if the receiving tank is partially filled with aged LNG material.

Re-gasification is a process of converting LNG gas from liquid state to a gaseous state. Heat exchangers are used to re-gasify the LNG after it is removed from the tanks and pressurized between 70-100 bars. There were 148 LNG import terminals (re-gasification plants) located worldwide in 2018. In industry, LNG is used at different pressures. Different types of LNG are used: Cold LNG and saturated LNG. Cold LNG, at approximately 3 bar and -150°C is close to the normal boiling point of methane. Its liquid phase is colder than the gas phase and it has a higher energy density. With saturated LNG, the gas and liquid phases are at the same temperature; although a higher temperature of approximately -130 °C at a pressure of 8 to 10 bar is possible, this requires a more expensive, pressure-resistant tank design.

Re-gasification process involves raising the temperature of the LNG using sea water. The LNG is passed through a heat exchanger using sea water. Some LNG terminals also use turbine flue gases from their energy recovery systems. LNG is thus converted into gaseous state by heating at a temperature greater than 0 degree Celsius.

Some LNG terminals also have underwater burners which are also used to heat the LNG to convert it to gaseous form. Such burners use natural gas as fuel and are generally used during peak demand period. Such vaporizers are called submerged combustion vaporizers. Once it is turned back to the gaseous state, the natural gas undergoes metering, odorizing, analysis before it is fed to the natural gas transmission system.

6.4 LNG HAZARDS AND SAFETY ASPECTS

Compared to other fuels, there have been few LNG accidents in production and storage sites, with four major incidents till 2005 worldwide reported[56]. It is the cryogenic nature of LNG that introduces new hazards that differ to those of conventional oil-based marine fuels. The most important safety requirements for the industry is to safely process, store, and transport LNG.

The LNG tanker industry claims a record of relative safety over the last 50 years; since international LNG shipping began in 1959, tankers have carried over 45, 000 LNG cargoes without a serious accident at sea or in port. LNG tankers have experienced groundings and collisions during this period, but none has resulted in a major spill. The LNG marine safety record is partly due to the double-hulled design of LNG tankers. This design makes them more robust and less prone to accidental spills than old single-hulled tankers like the Exxon Valdez, which caused a major Alaskan oil spill after grounding in 1989.

The safety record of onshore LNG terminals is more mixed. Since 1944, there have been approximately 13 serious accidents at these facilities directly related to LNG. The largest LNG accident occurred on 20 October 1944 in Cleveland, Ohio, when one of the four storage tanks failed and rapidly released 4250 m^3 of LNG. The most probable cause was the use of a 3% nickel steel alloy for the tank construction. The metal became brittle at low temperatures and collapsed. Therefore, extreme care must be taken to endure that LNG does not drip or spill onto ship hulls or decking because it could lead to brittle fracture, seriously damaging the ship or bunkering barge.

Despite considerable technological improvements and standards since the 1940s that have made LNG facilities much safer, but serious hazards remain since LNG is inherently volatile and is usually shipped and stored in large quantities. Experience in handling other cryogenic liquids has led to increased LNG safety, and considerable research has been undertaken to determine the properties of LNG. Although LNG has been transported safely across the world's oceans for around 50 years, but it has not been used widely as a fuel, except in LNG carriers. Consequently, neither potential users nor the wider public know very much about its hazardous characteristics or how to handle it safely.

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[56] SANDIA National Laboratories (2004), "Guidance to Risk Analysis and Safety Implications of a Large Liquefied Natural Gas (LNG) Spill over Water", California, USA.

As natural gas is combustible, an uncontrolled release of LNG poses a hazard of fire or, in confined spaces, explosion. LNG also poses hazards because it is so cold. As a cryogenic fluid LNG will give rise to frost burns when it comes into contact with the human skin. To prevent this, suitable protective clothing should be worn when handling LNG. An LNG spill may give rise to metal embrittlement and metal cracks which may lead to structural failure. To avoid LNG spillages in contact with decks or other exposed parts of the ship structure, from becoming structural failure hazardous events (with cryogenic cracking associated to carbon-steel embrittlement) two possible solutions may be possible: (1) design for local cryogenic resistant structure and (2) use of stainless steel drip trays.

Drip trays are in fact, today, the most commonly used solution to contain LNG leakage and prevent damage to the ship's structure, being featured in the IGF code as an actual requirement for the bunkering station[57]. This includes the location below any flanged connection, typically fitted with spray shields, in the LNG piping system or where leakage may occur.

Drip trays should be sized to contain the maximum amount of leakage expected and made from suitable material, such as stainless steel. Cryogenic pipes and equipment are typically thermally insulated from the ship's structure to prevent the extreme cold from being transferred via conduction. These requirements are especially important at the bunker station because this is where LNG leaks or spills are most likely to occur. Special steels have been developed which do not suffer from cryogenic embrittlement. They can be applied to protect LNG sensitive areas such as LNG loading areas.

Methane does not sustain breathing such that large concentrations of this gas in air may give rise to asphyxiation. It refers to a condition of a deficient supply of oxygen to the body that arises from abnormal breathing. In a large-scale LNG release, the cryogenically cool liquid LNG would begin to vaporise upon release from the breach of an LNG cargo tank. If the vaporizing LNG does not ignite, the potential exists that the LNG vapour concentration in the air might be high enough to present an asphyxiated hazard to the ship crew, pilot boat crews, emergency response personnel, or others that might be exposed to an expanding LNG vaporization plume. Although oxygen deficiency from vaporization of an LNG spill should be considered in evaluating potential consequences, this should not be a major issue because flammability limits and fire concerns will probably be the dominant effects in most locations (Sandia, 2004)[58].

Almost all LNG-based safety incidents will start with a spill of LNG or an escape of cold gas. For very small LNG spills, particularly onto water, the LNG may vaporise very quickly and become a cold gas. This gas may disperse into the atmosphere. If the LNG leak is larger than the rate of vaporization it can immediately dissipate. In this case a pool of LNG will be formed that may stay in one place or spread out, depending on the physical obstructions in its vicinity and the degree of movement of the vessel involved. Cold gas is heavier than air so leaks will roll along a deck or flow downwards to lower levels or the water surface. They are usually very apparent as the cold gas condenses water vapour in the air to form a white cloud. As it spreads, the cold gas starts to warm. Its density therefore decreases and the gas becomes more buoyant, at about -110°C the cold gas becomes lighter than air and starts to rise. The direction and speed of gas dispersion is highly dependent on prevailing weather conditions. If the gas does not ignite, it should safely disperse in the atmosphere.

LNG spilled onto water can pose a more serious hazards as it will rapidly and continuously vaporise into natural gas, which could ignite. The resulting "pool fire" would spread as the LNG spill expands away from its source and its evaporation is continued.

The most important hazards of LNG have to do

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[57] IGF is the International Code of Safety for ship Using Gases or Other flashpoint Fuels. It provides an international standard for ships, other than vessels covered by the IGF Code, operating with gas on low flashpoint liquids as fuel.

[58] Ibid 2004.

with flammability. There are different scenarios which may develop when a spill of "cold LNG" (LNG at -162°C i.e. at atmospheric pressure) occurs.

A pool fire is intense, burning far more hotly and rapidly than oil or gasoline fires. It cannot be extinguished - all LNG must be consumed before it goes out. Because of LNG pool fire is so hot, its thermal radiation may injure people and damage property a considerable distance from the fire itself. If LNG spills but does not immediately ignite, the evaporating natural gas will form a vapour cloud that may drift some distance from the spill site. If the cloud subsequently encounters an ignition source, those portions of the cloud with a combustible gas-air concentration will burn. Because only a fraction of such a cloud would have a combustible gas-air concentration, the cloud would not likely ignite at all at once, but the fire could still cause considerable damage. An LNG vapour cloud fire would gradually burn its way back to the LNG spill where the vapours originated and would continue to burn as a pool fire.

The rate of LNG vapour ascent depends upon the quantity of LNG released, ambient weather conditions, and where the LNG is released, e.g confined or unconfined, low or elevated area, on land or on water. One strategy to manage the vapours is to create a downward water curtain which helps block and/or divert the vapours away from possible ignition sources until the vapours warm and become buoyant, and/or dilute to a lesser concentration outside the flammable limits.

Heat input to LNG in any form will enhance vaporization and dispersion. Such heat may be transferred from passive sources such as atmospheric humidity, the ground or spill catchment areas, impoundments, pits and structures. LNG vaporizes up to 5 times more quickly on water than on land, depending upon the soil condition. In fact, another strategy for managing the flammability hazard of LNG vapours is to use a water hose to warm the liquid more quickly (while avoiding contact with the super-cold LNG), increase vaporization rates, and make the vapours buoyant sooner, rising away from ignition sources at ground level.

Vapours released from LNG as it returns to a gas phase, it is not properly and safely managed, can become flammable but explosive only under certain well-known conditions. Yet safety and security measures contained in the engineering design and technologies and in the operating procedure of LNG facilities greatly reduce these potential dangers.

Safety guidelines for application of gas fuel must be considered with reference to the following issues: location of fuel tank(s), applicable regulations and standards, machinery arrangement, bunkering requirements as defined by the ship owner, and fire and safety requirements related strongly to the ship type and the mode of operation.

6.5 INTERNATIONAL FRAMEWORK AND LNG STANDARDS

As the definition of a standard denotes it is a "document" established by consensus and approved by a recognized body that provides, for common and repeated use, rules, guidelines or characteristics for activities or their results.

There are many international codes and standards, particularly ISO standards, for the safe handling and storage of LNG in LNG plants and carriers. ISO 16903:2015 (Petroleum and natural gas industries - Characteristics of LNG, influencing the design, and material selection) deals with fundamental health and safety matters in the LNG industry. Standards for LNG infrastructure and LNG applications in the retail sector are often more recent or are still being developed. The comprehensive ISO 16924: 2016 (Natural Gas fuelling stations - LNG stations for fuelling vehicles), for example, deal with safe fuelling station design (GIIGNL, 2015)[59].

Being a gaseous fuel, of flashpoint lower than 60°C (actually -175°C) LNG could not be considered as fuel with SOLAS[60] frame. Building from the experience of the IGC Code and from the

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[59] GIIGNL (2015), "The LNG Industry in 2014. Annual Report".

[60] SOLAS – The International Convention for the Safety of Life at Sea that sets minimum safety standards in the construction, equipment and operation of merchant ships.

application of Interim Guidelines[61] the IGF Code was developed. Containing what is today the best collection of provisions for the design, construction and operation of LNG fuelled ships the IGF Code entered into force on 1 January 2017.

On its own the IGF Code represents a highly relevant instrument, defining the safety requirements for the construction and operation of LNG-fuelled ships and, at the same time, defining the level of ambition in terms of safety, relevant safeguards, control and associated procedures.

The LNG bunkering related provisions are significant. An international standard exists on LNG bunkering arrangements for vessels not covered by the IGC Code. ISO 20519:2017 Ships and marine technology - Specification for bunkering of liquefied natural gas fuelled vessels provides standards on hardware, procedures, record-keeping and training. Some standards already exist and new ones are being developed to ensure that the whole process of refuelling LNG powered ships and even evacuating LNG fuel from ships is safe to both the personnel and the environment. Some of the regulatory Organisation's include the Society of International Gas Tankers and Terminal Operators (SIGTTO), the International Organisation for Standardisation (ISO) and the International Maritime Organisation (IMO).

Thus, a whole raft of standards have been introduced for handling LNG as a substance, but there are not yet any specific LNG fuel standards. At the moment, there is no clear background for quality standards for maritime LNG as in the case of diesel fuels. Several manufacturers of heavy duty natural gas industrial engines use either the methane number (MN) or motor octane number (MON) for specification of gas quality requirements Both the MON and the MN are measures of the knock resistance of the fuel. It is fuel's ability not to self-ignite and burn in an uncontrolled way while the fuel is being compressed. This means that the air-fuel mixture in the engine is not ignited only by the ignition spark, but also by compression. An octane number describes this phenomenon under defined conditions. Natural "boil off" is to have MN at around 100 and calorific value (LCV) between 33-35 MJ/nm. The "forced boil off" gas will have MN in the range between 70 and 80. The LCV will be higher than for natural boil-off gas, and quite stable at around 38-39 MJ/nm.

Work is being carried out by ISO working groups to adapt standards in maritime area (already existing or being under development) from petroleum or gas industries. The example could be ISO 28460 standards "Petroleum and natural gas industries - Installation and equipment for liquefied natural gas -Ship-to-shore interface and port operations". That subject needs detailed exploration and summary of standardisation work, will be contained in IGF Code and related classification requirements.

6.6 LNG MARINE REFUELLING INFRASTRUCTURE AND VESSEL BUNKERING

LNG can be used in conjunction with electrical energy to create a hybrid fuel system and is set to disrupt the long-standing diesel and crude oil market that has fuelled the maritime sector for decades. Using LNG would eliminate sulphur emissions as well as reduce nitrogen emissions, this has been seen in the Port of Rotterdam, the largest port in Europe, opening a third berth for small LNG vessels and tankers. Liquefied Natural Gas (LNG) is a large development in sustainability for the maritime sector, as one of the largest barriers to implementing any new fuel is lack of infrastructure. Large-scale distribution of LNG will be made much easier when large ports adopt the fuel, leading the sector to follow suit.

LNG bunkering is the practice of transferring liquefied natural gas to a ship for use as a fuel. It is growing in popularity as it has a far better emissions profile than traditional petroleum-based sources of marine fuel, which has been particularly important since the International Convention for the Prevention of Pollution from Ships (ICPPS) came into force in 2015. In addition, although the Paris Agreement made no specific reference to shipping, there is a general movement towards a cleaner, greener future and a 20 per cent reduction in carbon dioxide from shipping

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[61] MSC 285 (86) - Interim guidelines on Safety for Natural Gas-Fuelled Engine Installations in Ships.

emissions (achieved by switching from marine fuel to LNG) is seen as a key component of the strategy to meet this aim. According to a recent DNV GL study, the number of non-LNG carrier vessels running on LNG will reach 1,000 by 2020. Whilst current low oil prices are expected to rise in the longer term it is likely that low priced LNG out of the US will be available to make the use of LNG as a bunker fuel competitive against heavy fuel oil, even factoring in the conversion costs. The ordering of LNG-fuelled ships is becoming a more common occurrence in Northern Europe - see for example the recent orders of LNG-fuelled ships from Tallink Grupp, an Estonia-based shipping company that provides shuttle ferry service between Tallinn and Helsinki.

One of the most important elements for the LNG market is the widespread implementation of LNG plants for production, liquefaction and transportation. LNG bunkering facilities will need to be installed in ports around the world to encourage and enable the sector to take LNG more seriously. Bunkering segment provides a link between LNG production and liquefaction plants and important terminals on the consumption side. The re-export and distribution of small quantities of LNG from import or export terminals to end consumers such as ships is not currently industrialised. Technically this can already be done and is carried out for individual projects (DNV GL, 2017b)[62].

First bunkering ships started operating in summer 2017 and since that time its number has considerably risen. In early 2019, there were only six bunkering vessels operational around the world. As of February 2020, there are 12 in operation with a further 27 on order or under construction. For example, a new LNG bunker vessel is being built by the Dutch shipyard Damen Group and it will be delivered late 2020 to the company Elenger that is a major LNG supplier in the Baltic region. The new ship will load LNG in the Baltic Sea region terminals for distribution in the Baltic area.

Although lack of re-fuelling infrastructure has frequently been identified as one of the major barriers to the development of this market, but the recent SEA-LNG report shows that many ports are investing heavily in LNG infrastructure. For example, Europe's largest bunker port, Rotterdam nearly doubled its LNG bunkering operations in the third quarter of 2019, compared to the previous three months. This year, Rotterdam will have seven or eight bunker vessels in operation. The port expects this growth to reach a million tons by 2025-2030, which would be around 10 per cent of all bunker fuels sold. Nauticor's 7,500 cbm Kairos, currently the largest operational LNG-bunkering vessel, started LNG bunkering early in 2019 in the Port of Visby, Sweden.

Current EU policy requires at least one LNG bunkering port in each member-state. About 10% of European coastal and inland ports will be included, a total of 139 ports. Coastal port LNG infrastructure will be completed by 2020 and for inland ports by 2025. There are several ports under development in North-America, mostly in the south east, the Gulf of Mexico and around the Great Lakes, but also for ferry and deep-sea operations in the Pacific Northwest. China is extending LNG bunkering infrastructure from inland waterways to coastal areas and is expected to be able to service the LNG demand of all vessel types. South Korea offers LNG bunkering in the port of Incheon and is considering a second facility in Busan. Elsewhere in Asia, in addition to Singapore, Japan and Australia are also working to develop LNG bunkering facilities.

The EU member-states currently have around 200 LNG refuelling stations. Most of these are located in Italy (50) and Spain (41), followed by France (31), the Netherlands (24) and the UK (13). The network is being developed under the EU Alternative Fuels Infrastructure Development (AFID) Directive and within EU- or government-supported projects such as Blue Corridors and the BioLNG EuroNet.

There are around 30 large-scale LNG import terminals in Europe, the country with the highest number of LNG terminals being Spain. LNG import terminals generally have the capacity to

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[62] DNV GL (2017b), "Uptake of LNG as a fuel for shipping", In Maritime Articles, 22 November 2017.

store several hundreds of thousands cubic meters of LNG. The largest import terminal, with a storage capacity of 1,000,000 m³, is on the Isle of Grain in the UK. There are more LNG import terminals at the planning or construction stage. As an example, there is also a large-scale export terminal with a capacity of 4.3 million tons in Hammerfest in the far north of Norway, and a growing number of unrecorded, small-scale LNG import, export and liquefaction facilities and bunkering stations and over 1,000 small storage facilities (GIE, 2018 newsletter).

The infrastructure necessary for refuelling LNG-powered vessels is currently limited, but expanding as new LNG bunkering projects come on stream across Europe, with more proposals for bunkering facilities under consideration. So far Europe's LNG bunkering activity has been focused in the north, notably Scandinavia and the Baltic countries. Pilot projects have been developed in northern Europe, boosted by strong government support, infrastructure already in place and the ICPPS. However, there is also a number of initiatives underway elsewhere in Europe, including the Poseidon Med II project and multiple studies focused on Greek waters.

The Port of Rotterdam was the first port of Europe to offer LNG bunkering in 2014. New facilities have been recently announced for the Port of Antwerp where it is possible for both seagoing and inland ships to bunker LNG, and the owners of many other European import terminals are considering similar expansion. A new add-on to traditional project models for LNG terminals can be seen, whereby bunkering vessels are granted rights to load LNG at existing terminals and then deliver LNG to arriving vessels. Such bunker delivery will be either at a berth, from road tankers (truck-to-ship) or via ship-to-ship transfer. There could also be huge potential to expand the sector in the Mediterranean for use in container vessels, tugs and other support vessels operating close to shore, as well as cruise liners and passenger ferries. A major change is imminent, and a number of independent industry forecasts indicate that the use of LNG as a bunker fuel offers opportunities for early movers to secure a market-leading position ashore and afloat as global LNG fuelling becomes a mainstream option.

Poseidon Med II LNG Bunkering Project commenced in 2016 as a continuation of the previous Poseidon Med and Archipelago LNG projects, this European cross-border project, co-financed by the European Union through the Connecting Europe Facility, aims to take all necessary steps towards adoption of LNG as marine fuel in the east Mediterranean and Adriatic Seas. It aims of making Greece an international marine bunkering and distribution hub for LNG in South-Eastern Europe. The Poseidon Med II LNG project encompasses three EU member states and its task is to prepare a detailed infrastructure development plan promoting the adoption of LNG as marine fuel for shipping operations. The final stage of the project (to be completed by 2020) is expected to include a detailed strategy plan for an LNG transport, distribution, and supply network, and define the framework for a well-functioning and sustainable market. The project is coordinated by the Public Gas Corporation of Greece (DEPA) and comprises 26 partners including DEFSA (the Greek gas system operator), Lloyd's Register, Ocean Finance, all major short sea shipping companies operating in Aegean, Ionian and Adriatic seas as well as several of the main seaports in the region such as the port of Piraeus, the Port of Venice and the Port of Limassol.

Increased use of trucks to transport LNG will enable suppliers to tap into industrial and domestic gas demand in places which are not connected to gas grids, such as Sardinia in Italy. Plans are underway for the construction of an LNG terminal and distribution facility, which will be located in the Port of Oristano, (on the west coast of Sardinia) and it will be operational since Q3 2020. One notable, specific spur of Italy's interest in small-scale LNG and its bunkering activities is the new generation of LNG-powered Mediterranean cruise vessels of 180,000 gt and above currently under construction. Such vessels are being provided with bunker tank capacities in the 3,000-3,500 m³ range.

Sardinia is an important focus for Italy's small-scale LNG ambitions. Subject to successful final investment decisions, the Mediterranean's largest island will play host to five of the anticipated 11 terminals. Three are planned for Oristano, one for Porto Torres in the north and one for Cagliari in the south. The other six proposed small-scale terminals are at Genoa and Livorno, on the Tyrrhenian Sea, Naples, Gela in southern Sicily and Porto Maghera and Ravenna in the Adriatic. Besides HiGas only Ravenna and a second Oristano project, tabled by Edison, have received the necessary authorisations, Genoa, Naples and Gela are still at the study stage while the other projects are at various points in the permitting process.The HiGas terminal, which is under construction in Oristano's Santa Giusta industrial port zone is poised to become the Mediterranean's first small-scale marine LNG terminal.

6.6.1 LNG BUNKERING MODES

During LNG bunkering ships take on LNG which is used as fuel and for the on-board energy supply. When considering any new or evolving technology, it is important to have a clear understanding of not only the benefits, but the challenges that may be involved. Loading LNG into fuel tanks is a different process from loading HFO due to some unique differences in the fuel characteristics.

Delivering LNG fuel to a ship can be done in different ways, following different methods, depending on different logistic and operational factors. Various LNG bunkering methods are available, with Truck-to-Ship (TTS) being the most commonly used. This bunkering method has been a result of different aspects and difficulties that concur in the development of the business case for bunkering LNG as a marine fuel. On one hand, the operational flexibility and limited infrastructure requirements for TTS and, on the other hand, relatively low initial investment to establish business readiness, have driven the option for this LNG bunkering method.

There are basically 3 different bunkering concepts for seagoing and inland navigation ships that can be used to develop the LNG bunkering infrastruc-

Figure 13 – The bunkering vessel ENGIE Zeebrugge is jointly owned by ENGIE, Mitsubishi Corporation, NYK Line, and Fluxys. With an LNG capacity of 5,000 m³, she will service all types of shipping customers in Northern Europe from her home port of Zeebrugge, under the brand Gas4Sea

Source: ENGIE (2017)

ture. These are truck-to-ship, ship-to-ship and shore-to-ship. Each of the bunkering concepts has a different capacity regarding bunkering volume or bunkering speed (EMSA, 2018).

Ship-to-ship bunkering (STS) is the transfer of LNG from one vessel to another vessel as seen in Figure 11. Some advantages of this bunkering method are that it allows for flexibility in bunkering and location, which can be at sea or at the port. However, bunkering at sea is restricted by weather conditions, such as waves, winds and currents. In addition, STS-bunkering allows for logistical flexibility as bunkering can happen at the same time as other activities, with the quay side free for cargo handling operation. This method is most favorable option for LNG bunkering, especially for ships with a short port turnaround. The disadvantages include limited size for bunker vessel, conditioned by port limitations.

STS-bunkering is a suitable method for vessels that have bunker volumes of or above 100m^3 LNG (basically all maritime vessels). The capacity of bunker vessels may range from 1,000 to 10,000 m^3 (although also smaller ships are currently used in some ports).

Loading the LNG feeder vessel often takes place at an import terminal or storage facility. LNG bunker vessels are smaller than LNG feeder vessels. Supplying the bunker vessel will be done at dedicated jetties that accommodate small size LNG carriers or feeders and bunker vessels. These jetties or quays can be constructed close to the import terminal or at intermediate LNG terminals.

Tank truck-to-ship bunkering (TTS) is the transfer of LNG from a truck to a vessel which is moored to a dock or jetty. A flexible hose or flexible connection arm is used in this bunkering option. A tank truck carry about 50m^3 of LNG and it can transfer this in approximately an hour. The loading of LNG can happen at any jetty thus it only requires a port that permits shore side LNG bunkering from a jetty. Transferring LNG via TTS for large volume transfers is limited by the transfer rate and number of trucks required (DNV GL, 2014).

This method's disadvantages include limited capacity of trucks (approximately 40-80m^3 is likely to dictate multi-truck operations) as well as limited movement on the quay side, mostly influenced by the presence of the bunker truck(s).

Tank trucks are flexible way of bunkering vessels with (very) small LNG bunker volumes. This option is suitable for receiving vessels with up to 200 m^3 given that the turnaround time is long enough.

LNG terminal-to-ship via pipeline bunkering (PTS) is the transfer of LNG from a fixed storage tank on land through a pipeline with a flexible end piece or hose to a vessel which is moored to a dock or jetty. Because onsite storage can be scaled, large volumes of LNG can be bunkered when compared to TTS. The transport of LNG to the storage tank can happen in several ways, for example by truck or bunker barge. It is also possible to allow for onsite production of LNG via a small-scale liquefaction facility. As there is a fixed location for bunkering, the receiving vessel will have to make arrangements to allow bunkering at the same time as other activities, to save time spent at the port.

An intermediate LNG storage location with bunkering capacity requires an LNG storage tank and supply of LNG to the onsite storage by a feeder vessel, tank trucks, pipelines or a small-scale liquefaction plant receiving natural gas (DNV GL, 2014). LNG storage tanks can vary from small (200 m^3) to quite large (100,000 m^3).

Storing tanks have to be placed close to the berths when bunkering operations are performed due to technical, operational and economic difficulties with long pipelines.

Depending on LNG quantity needed and potential time constraints for the operation, it is possible that different LNG bunkering modes are more applicable to different needs. For example if small quantity of LNG fuel is needed Truck-to-Ship method is more applicable or on the other hand if a great quantity of LNG fuel is needed and STS or PTS method is more applicable.

All LNG bunkering modes share several fundamental aspects of concern that need to be carefully addressed in order to have safe and successful operations:

- Risk(s) analysis and safety management, intrinsically different depending on the method chosen for bunkering;
- Permitting, which will be needed for the different operations, from the relevant competent authorities;
- Training of all personnel involved, both onboard and ashore.

6.6.2 TECHNICAL AND OPERATIONAL CONSIDERATIONS OF LNG BUNKERING

Methods of filling LNG storage tanks have been developed wherein there is no vapor emitted from the tanks, or the vapour is returned to the bunkering vessel or terminal. Lines used for bunkering must at the completion of bunkering be drained of LNG and the remaining gas vapours removed using nitrogen. Any liquid remaining in the pipes that is trapped between closed valves will boil and expand to fill the space available. If that space is small, the pressure developed by the expanding vapour can increase to dangerous levels and cause the pipes to burst or valves to be damaged. When there is a risk of natural gas pressure buildup, such as LNG storage tanks and piping systems, relief valves are required to safely allow the excess pressure to be released as a final safety measure. Relief valves should be properly located so the hazardous zone created by the release of vapour is not near any operational areas abroad the vessel. In general, relief valves should tie into a vent mast which directs the gas away from all critical areas.

The equipment required to support the bunkering operation on the receiving vessel includes bunker stations, bunker piping and storage tanks. While these are familiar elements, they have unique requirements when used with LNG. The bunker station provides connection to the ship's fuel gas system and fuel tanks allow loading of LNG fuel and, in some cases, return of displaced vapour from the fuel tanks. Due to the additional hazards present with LNG, the requirements and capabilities of bunker stations on LNG fuelled ships are more complex as compared to the oil-fuelled ships. The following highlights the primary considerations for LNG bunkering.

Bunker stations present risks for allowing LNG and vapour to escape into the atmosphere, potentially creating a flammable mixture with air. The location of the bunker station is critical factor for determining the level of risk associated with the ship's bunkering operation and arrangement. Depending on the location of bunker stations, certain additional outfitting requirements may exist. For example, on certain types of ships bunker stations are located below the weather deck. These normally require a suitable watertight door in the side shell, which prevents waves and weather from entering the space, but can be opened to allow the ends of the bunker hoses to enter the bunker station. Furthermore, an air lock may be required to separate the bunker station from adjacent non-hazardous areas.

LNG pipelines are increasingly important elements in the context of LNG bunkering. They allow the LNG fuel to be transferred from the storage location (pressure or atmospheric tanks) into the LNG bunkering location. The total length of the pipelines is limited to the efficiency of the insulation and, in principle, should not be longer than 250m. This will depend on many aspects which are mostly dependent from the location and the main question is whether the LNG distribution system has the ability to manage BOG generated during transfer. The pipeline layout design can consider different routing solutions, either by aerial route with supports or lay along a special trench, designed to keep the LNG pipeline offset from the risks associated to vehicle circulation hazards/accidents.

According to classification and regulatory requirements, LNG and vapour piping may not pass through accommodation spaces, service spaces, or control stations, but they can pass through certain enclosed spaces, such as machinery spaces, if the pipes are either double walled or installed in a ventilated pipe or duct. In the case of double-walled piping, the arrangements consist of two concentric pipes with the inner pipe used for LNG or vapour transfer. The space between the concentric pipes is pressurized with inert gas at a higher pressure than the maximum pressure in the inner pipe. A monitoring system with alarms is fitted to detect a loss of inert gas pressure, thus indicating a leak either of the concentric pipes.

The Emergency Shutdown System (ESD) is critical to the safety of the vessel and is typically a hardwired system. It is a method or a system that safely and effectively stops the transfer of LNG (and vapour as applicable) between the LNG bunkering facility and the receiving ship in the event of an emergency during the bunkering operation. The control system involved in the ESD, which is linked system, can be activated automatically or manually. The ESD may consist of two parts:

- ESD - stage 1, is a system that shuts the LNG transfer process down in a controlled manner when it receives inputs from one or more of the following; transfer personnel, high levels LNG tank alarms, cables or other means designed to detect excessive movement between transfer vessels or vessel and an LNG port facility, or other alarms.

- ESD - stage 2, is a system that activates decoupling of the transfer system between the transfer vessels or between a vessel and an LNG port facility. The decoupling mechanism contains quick acting valves designed to contain the contents of the LNG transfer line (dry break) during decoupling.

Typical reasons for activation of the ESD include gas detection, fire detection, excessive ship movement, power failure as to name some of them.

The use of safety and security zones around the LNG bunkering operation are necessary to prevent the creation and spread of hazardous situations that may result from the LNG bunkering. The intent is to prevent accidental gas release as a result of damage to the LNG bunkering system and to prevent ignition of any released gas. The two types of zones have different purposes and definitions. The purpose of a safety zone is to designate an area where only essential personnel with proper training are allowed to enter and where no sources of ignition are allowed. The extent of the zone is determined by various criteria depending on the regulation or reviewing authority.

The purpose of the security zone is to create an area of sufficient size that keeps other vessels, vehicles, equipment, and cargo operations far enough away so that they pose little risk of damaging or interfering with the LNG bunkering system and equipment. This zone is intended to keep non-essential personnel far enough away so that injury by any hazardous incident during the bunkering operation is unlikely, and to make it difficult for a person to intentionally damage or interfere with the bunkering system and equipment.

CHAPTER 7 GAS ENGINES AND EMISSIONS

Using engines that operate on gas are not new in shipping. In particular, the use of “boil off”, i.e. the hydrocarbon vapours generated when transporting LNG, is standard in LNG carriers and in much smaller engines compressed natural gas (CNG) has been used in canal boats and other small vessels.

Conventional ship engines have the potential to be converted to a lean gas engine or dual fuel engine design. The main issue is the supply of the LNG to the vessel. According to the MAGALOG report on maritime fuel gas logistics[63] there are 2 time-bound factors, which have an effect on the implementation of the lean gas driven engines:

- Introduction of LNG-fuelled ships is more likely to happen by building new ships equipped for this, than by converting existing ships from conventional fuel to LNG. Ships usually have economic lives of 30 years or more, and it should therefore take at least 30-40 years to fully convert an established shipping segment. However, one might see a more rapid switch to cleaner technologies within the ECAs, by transfer of more polluting ships to operation in outside waters.

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[63] MAGALOG (2008), “Maritime Gas Fuel Logistics: Developing LNG as a clean fuel for shipping in the Baltic and North Seas”.

- Some shipping segments will be better suited than others to introducing LNG early (long term contracts and fixed routes). An important reason for this is that the development of cost effective supply systems for LNG bunkering needs to be undertaken in steps over a length of time.

LNG has been used as a marine fuel more than 50 years but for most of the time it was as boil off gas from the cargo used to fuel the boilers for steam engines, its use in internal combustion engines at sea is more recent and dates to 2001. It was then that the Finnish company Wärtsilä equipped the FPSO Petrojarl I with a pair of its 18V32DF dual-fuel engines. This was followed by contracts for a series of LNG carriers built in France and two offshore ships. As there is not much information available about the use of LNG on board some other vessel types (e.g patrol boats, offshore vessels), then different gas engine technologies are viewed from the perspective of LNG carriers (tankers) that have been on the market for years. Nevertheless it is important to take into account some additional considerations such as reliability of the technology and safety (e.g patrol vessels used in performing some other functions in short-sea shipping).

Today the maritime sector is on the verge of major change, from conventional methods of propulsion to modern and more economical and environment friendly methods. The propulsion system for LNG vessels is closely related with the generation and consumption of the cargo boil-off. Both the fuels used as well as the emissions regulations are factors that influence the direction of LNG vessel propulsion systems. However, the prime driver of which propulsion technology is viable, will be energy density. Any fuel replacement must be easy to store on-board without compromising safety, weight or a ship's carrying volume. With the IMO's marine sulphur cap in place, a more protracted battle begins for shipowners over which cleaner fuels can cut the sector's emissions in half by 2050.

The LNG shipping sector has been tremendously cautious in choosing the propulsion system, and the steam turbine has been practically an exclusive option for LNG carriers over the last several decades. Influencing factors including economic consideration, environmental regulation, as well as safety issues made profound impact on the technology developments implemented on LNG carrier propulsion systems. Since 2004 many LNG carrier projects with propulsion other than steam turbine have been under construction, such as dual-fuel diesel electric (DFDE) propulsion and two-stroke diesel engine propulsion with re-liquefaction plant. Steam turbine domination in the LNG carrier sector has been gradually broken. So far there is no standard propulsion system applicable to all types of LNG vessels (Fernandez et al, 2017)[64].

This chapter discusses the state-of-art of the marine propulsion technologies, and gives an overview of the suppliers of engines of the next generation of propulsion. It will also focus on the emissions and exhaust gas abatement techniques such as scrubbers installed on board of the vessels and exhaust gas recirculation (e.g SCR). Therefore, the purpose of this chapter is to study the various LNG carrier propulsion systems, taking into account the latest technology progress and innovation in this field.

7.1 BOIL-OFF GAS PROBLEM

Heat transfer to the LNG from the environment through insulated spaces and holding tanks results in the boiling of the load, with the consequent formation of steam, referred to as boil-off gas (BOG). Natural gas remains liquefied by staying at a consistent pressure, but when boil-off occurs and it returns to gas, the larger volume of gas will increase the tank pressure. Most of LNG carriers have the boil-off gas problem which takes place during storage, loading or discharging and the ship's voyage. LNG carriers are designed to carry natural gas in liquid form at a temperature below its boiling temperature point. Despite tank insulation designed to limit the admission of external heat, even a small amount of it will cause slight evaporation of the cargo, known as boil-off gas (BOG). The amount of liquid that is evaporating from cargo due to heat leakage and expressed

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[64] Fernandez, I., Gomez, M., Insua, A. (2017), "Review of propulsion system on LNG carriers", In Renewable and Sustainable Energy Reviews.

in % of total liquid volume per unit time. Typical values are 0.15%/day or below, recent projected LNG carriers are offered with a boil off rate close to 0.1%.

There are two distinct types of gas made from LNG depending on how it is extracted:

- *"Natural boil-off gas"*, which is taken off the top of the LNG tanks above the liquid will have a high methane content and some nitrogen and thus have a high knocking resistance. Analysis show values typically around MN (methane number) 100 and LCV (low calorific value) between 33 - 35 MJ/nm3. This is a somewhat special application typical for fuelling of LNG tanker propulsion plants.
- *"Forced" boil off gas"* i.e. LNG extracted from down in the tanks and evaporated separately. This gas will contain a mixture of all hydrocarbons in the liquid and its resistance to knocking may differ from origin to origin and even from load to load, with the MN typically in the range between 70 and 80. The calorific value will be higher than natural boil off gas and quite stable at around 38 - 39 MJ/nm3. This gas type is now becoming very popular as fuel for general shipping.

"Natural boil-off gas" from the top of the tanks is very high in methane and has a good knocking stability. It is therefore particularly well suited as an engine fuel. However, when a propulsion system is laid out for the use of this, it is important to ensure that there is always enough natural boil-off gas with sufficiently high methane content available, so that there should not be any need for mixing "forced boil-off gas" from the bottom of the tanks.

Engine installations specifically designed to be fuelled by LNG should preferably be of the *"forced boil-off"* type with the LNG taken from deep down in the tanks and well mixed before extraction into the evaporator. This will ensure good homogeneity of the LNG taken out and hence constant gas quality. This type of LNG-based fuel gas will be different from the "natural boil-off gas" from a tank top and the rating of the engine will have to be based on a somewhat lower MN in this case, in order to ensure knocking-free operation. Evaporator sizing must be sufficiently large in order to ensure that no gas droplets are entering the engine even under severe transient operation.

Even when safely handled, BOG offers other challenges. The composition of LNG shipped onboard varies depending on its source. However, the main component is always methane, which condenses (liquefies) beneath -161°C. As this temperature is considerably lower than that at which the other (heavier) hydrocarbon components (e.g ethane, propane and butane) of LNG condense, it means that the methane is the first such hydrocarbon component to vaporise (through *"natural"* boil-off) as the LNG absorbs heat. However, within the composition of an LNG cargo (aside from the hydrocarbons all of which are within the alkane group) there is usually a small percentage of inert gas, such as nitrogen. Nitrogen will preferentially boil-off, as compared to the methane component, as its atmospheric boiling point is -196°C. Therefore the energy value of *"natural" boil-off* vapours should increase over time (e.g sea passage), as the nitrogen component is depleted. This changes the composition and quality of LNG over time in a process known as ageing - displaying how even the smallest change in LNG can have major effects.

If *"natural"* boil-off is insufficient to meet the fuel consumption needs of the LNG carrier at the required sea speed, "forced" boil-off can be used as a supplement to remove or minimise reliance on fuel oil. This process is performed by taking LNG (as liquid not vapour) from a cargo tank (by way of the stripping or spray pump system) and passing it through forcing vaporizers until it emerges as vapour at the same temperature (about -40 °C) as the "natural" boil-off taken from the cargo tank headers.

The BOG result from natural evaporation is unavoidable and has to be removed from the tanks in order to maintain the cargo tank pressure. To relieve the pressure in LNG tanks, BOG can be re-liquefied, used as fuel or burned in a combustion unit. Re-liquefaction occurs when evaporated LNG is cooled and reverted back to its liquid state. Excess gas can also be led to the engines which have a capability of burning gas fuel. Another alternative is to burn the unwanted gas in combustion unit, but this results in wastage of materials and valuable energy.

As the insulation cannot prevent heat-in-leak, vaporization of the LNG is an avoidable consequence. As the LNG vaporizes, the pressure within the cargo tanks has to be relieved, to avoid endangering the integrity of the containment system. However, maintaining a constant vapour pressure within the cargo tanks also assists in maintaining the liquid temperature of the LNG - because of the property known as auto-refrigeration, whereby the vaporization draws heat away from the liquid (ReedSmith, 2018)[65].

7.2 TECHNOLOGIES FOR SUPPLYING GAS PROPULSION

7.2.1 ENGINE SUPPLIERS

The four main suppliers of gas engines are Rolls-Royce, Wärtsilä, Mitsubishi and MAN. Rolls-Royce and Wärtsilä are also suppliers of complete engine and propulsion design and supply packages as well as complete ship designs. Wärtsilä and MAN are the main suppliers of dual fuel engines whereas Rolls-Royce and Mitsubishi are the main suppliers of gas engines. The large fast ferries are often powered by diesel engines and/or gas turbines in various propulsion system configurations delivered by specialized companies. The efficiency of the individual systems does differ, but no further consideration is given to the detailed efficiency of the individual systems in this study.

Nowadays commercial ship propulsion system manufacturers such as Finland's Wärtsilä, Germany's MAN Diesel &Turbo or Siemens, Japan's Mitsubishi or British Rolls-Royce produce large bore dual-fuel diesel engines that comply with all modern emission legislation when sailing in environmentally sensitive areas and which meet the strict safety requirements that LNG vessels operate under. All above-mentioned manufacturers can deliver LNG systems for propulsion and power generation for any applicable types of ship or engine. Navy applications need tailor made solutions in order to meet the severe requirements such as high shock resistance, low noise and vibration levels.

Whether new built or retrofitted, LNG ships are clearly the way of the future. According to the data published by MAN Diesel &Turbo, more and more new-building has been constructed as LNG-ready, which means that they can relatively easy be retrofitted with dual fuel engines at a later point. The MAN B&W ME-GI engines offer extremely flexible fuel modes that range from 95% natural gas to 100% HFO and anywhere in between. A minimum of 5% HFO for pilot oil is required as these are compression ignition engines and natural gas is not self-combustible.

Wärtsilä is also recognised as a leader in propulsion solutions for gas fuelled vessels, and has led the way in developing a complete value chain of systems, solutions and bunkering arrangements, both on-board and shore-based, to accelerate the use of environmentally sustainable and economically competitive LNG fuel. Since 2000, Wärtsilä's engines have been selected for more than 200 LNG fuelled vessels either in operation or under construction (Rudkowski, 2016). This company has an extensive track record in delivering propulsion solutions for Offshore Patrol Vessels (OPVs) that are used to perform many non-military functions, providing coast guard and rescue operations, as well as policing of exclusive economic zones (EEZ).

For example, the Finnish Border Guard next generation OPV uses LNG and diesel oil as fuels, which ensure that the ship's own emissions stay low. The vessel "Turva" is powered by three eco-friendly Wärtsilä 34DF dual-fuel engines burning either crude oil-based marine fuels or LNG. The engines can alternate among fuels without loss of power or speed. In the depth of the vessel, special attention has been paid to environmentally friendly and energy-efficient solutions. As well as performing border management duties, the multipurpose vessel serves in maritime search and rescue missions and demanding environmental safety operations such as oil spill response.

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[65] Reed Smith (2018), "The Difference with LNG? It is just about boil-off, isn't it?"

7.3 PROPULSION SYSTEMS

Propulsion systems have gone through big transformation starting with steam turbines to tri-fuel diesel electric and to medium-speed diesel engines. Definitely the next generation propulsion system is going to be something completely different, and it will use a completely different type of fuel. However, in order to improve operational efficiency, reduce engine room size and increase cargo capacity, alternative propulsion options have been developed in the sector.

In 2004, the four stroke (4S) dual fuel engine broke the domination of the steam turbine and started to be used on LNG carriers as a part of dual fuel diesel electric propulsion system. After 2010, two-stroke dual fuel technology has made a breakthrough and has been applied to LNG carriers, including both the high pressure and low pressure gas injection concepts. The two-stroke (2S) dual fuel engines can offer substantial efficiency advantages over both the dual - fuel diesel electric (DFDE) and steam turbine based propulsion systems. So they become a popular propulsion system choice for LNG carriers.

Steam turbine (ST) based propulsion has been the main system implemented on LNG vessels since 1960, as this system allows the simultaneous burning in boilers of heavy fuel-oil together with the BOG generated during transportation, which in turn feed the propulsion turbines and electric turbo generators. Since 2003, LNG vessel propulsion systems have been at a turning point, steam turbines are being replaced by internal combustion engines due to improvements in the efficiency of the latter and because, as abovementioned, these allow burning of both heavy fuel oil as well as BOG from the cargo.

This shift is reflected in the ordering of 159 methane tankers from mentioned date to be constructed with engines as the propulsion system. These engines capable of consuming different fuel types, are known by the acronym DF (Dual Fuel). The DF engine adopted the lean-burn concept from the Otto-cycle, and a small amount of diesel as the pilot fuel, approximately 1 to 8%, which is used for ignition in the combustion chamber in its operation with gas as fuel (gas mode).

Dual fuel (DF) engines developed around the year of 2003 are 4-stoke (4S). At present, however, owing to technological advances which enable the use of natural gas in 2-stroke engines (2S), a new change in propulsion systems to be implemented on LNG vessels is occurring. To follow, a description of the main LNG propulsion systems is detailed (except the steam turbine that are being replaced with more modern propulsion options), highlighting their main advantages and disadvantages on board.

7.3.1 DEVELOPMENT OF LNG FUELLED MARINE ENGINE CONCEPTS

The development of the LNG fuelled marine engines started in 1980 in order to develop engines for LNG carriers utilizing boil-off gas. The commercial engine development started in 1984, resulting in 3 engine concepts:

- Spark ignited Lean Burn engine (Otto cycle);
- Diesel ignited Dual fuel engine (Combined Otto/Diesel cycle);
- High pressure direct injection engine (Diesel cycle).

LEAN-BURN GAS ENGINES

Lean-burn gas engines are designed for being supplied only with LNG and work according to the lean-burn Otto principle. These gas engines are supplied with natural gas through a gas valve unit (GVU) that filters and controls natural gas pressure. Gas engine cylinders are fed by individual pipes, which are connected to a main double wall pipe running along the engine. Gas engines are fuelled with a lean premixed air-gas mixture, which is ignited in the pre-combustion chamber by a spark plug. The mixture of air and gas contains more air than is needed leading to a lower combustion temperature, and therefore, NO_x emissions are reduced and efficiency increases due to higher compression ratio and an optimized injection timing (DNV-GL, 2015b; LNG Fuelled Vessels Working Group, n.d-a; Rolls-Royce, 2012; Woodyard, 2014).

The air-gas mixture is injected at low pressure (4-5 bars) and is generated outside the cylinder behind the turbocharger. The gas can be provided directly from the pressurized LNG fuel tanks because of lean-gas engines are low-pressure engines. In addition, gas engines have high-energy efficiency at high load, generate low NOx emissions and reduce GHG approximately 20% (DNV-GL, 2015; LNG Fuelled Vessels Working Group, n.d-a. 2012, Woodyard, 2004)[66].

Furthermore, propulsion systems using lean-burn gas engines present two applications, gas-mechanical application and gas-electrical application. In a gas-mechanical layout, the lean-burn gas engine provides propulsion power to the propellers through reduction gears and shaft lines, whereas, in a gas-electrical layout the generation sets, which are driven by a lean-burn gas engine, supply electric motors with electric power to propel the propellers (Baumgart &Bolsrad, 2010; Rolls-Royce, n.d-e, n.d-f)[67].

Rolls-Royce is the main producer of lean-burn gas engines and has developed a wide variety of LNG powered propulsion systems with a power range from 1,400 to 9,400 kW. Rolls-Royce lean-burn gas engines operate at medium speed and are characterised by their high efficiency, low operating costs and improved environmental performance resulting in very low emission levels. In addition, Rolls-Royce gas engines present a high gas quality tolerance and reduce noise, lube oil composition and maintenance costs. The company has developed two series of lean-burn gas engines, Bergen B and C.

Bergen B series are engines designed for large ferries and Roll on-Roll off (RO-RO) vessels, and provide a power output from 3,500 to 7,700 kW. Alternatively, Bergen C series are addressed to tugs and small ferries and cargo vessels, and provide a power output from 1,460 to 2,430 kW. Both engines series are available in gas-mechanical and gas-electric layouts (Rolls-Royce, n.d-a, n.d-b, n.d-c, n.d-d, and n.d-g)[68].

DUAL FUEL ENGINES

These engines are designed for being supplied with LNG and liquid fuels, e.g. MDO (marine diesel oil or HFO (heavy fuel oil). Dual fuel (DF) engines work according to the lean-burn Otto principle in gas mode and according to the normal diesel cycle in diesel mode. DF engines working in gas mode are supplied with natural gas through a GVU that filters and controls natural gas pressure. Engine cylinders are fed by individual pipes, which are connected to a main double wall pipe running along the engine. When working in gas mode, DF engines are fuelled with a lean premixed air -gas mixture, which reduces peak combustion temperature and NO_x emissions owing to the air-gas mixture contains more air than is needed. The air-gas mixture is fed into the cylinder during the intake stroke and is ignited by a small amount of diesel injected into the combustion chamber at the end of the compression stroke, since the self-ignition temperature of air-gas mixture is too high to be achieved with the compression of cylinder. In 4-stroke engines (4S), the air-gas mixture is injected at low pressure (4-5 bars) and is generated outside the cylinder behind the turbocharger. As four-stroke engines are low-pressure engines, natural gas can be provided directly from the pressurized LNG fuel tanks (DNV-GL, 2015b; LNG Fuelled Vessels Working Group, n.d-a, Stenersen, 2011; Wärtsilä, 2015; Woodyard, 2004)[69].

To ensure minimum NO_x emissions the amount of diesel injected at the end of the compression stroke is very small, usually less than 1% of the total fuel consumption. DF engines use a micro-pilot injection and an engine speed and load control and monitoring system so as to optimize combustion (DNV-GL, 2015b; LNG Fuelled Vessels Working Group, n.d-a; Wärtsilä, 2015ö Woodyard, 2004).

When DF engines work in diesel-mode, diesel in injected into the combustion chamber at high pressure. Gas admission is deactivated, even

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[66] DNV GL (2015), "LNG as Ship Fuel. Latest developments and projects in the LNG industry".

[67] Rolls-Royce (2017), "MARINE products and Systems", Rolls-Royce: Newcastle, UK; pp. 25-33.

[68] Ibid, 2017.

[69] Wärtsilä (2015), „Wärtsilä Solutions for Marine and Oil&Gas Markets", Wärtsilä: Helsinki, Finland, pp. 91-100.

though, the micro-pilot is activated so that it ensures reliable pilot ignition when the engine changes from diesel mode to gas mode (DNV-GL, 2015b; LNG Fuelled Vessels Working Group, n.d-a; Wärtsilä, 2015ö Woodyard, 2004).

Switchover from diesel mode to gas mode is a gradual process, diesel supply is slowly reduced meanwhile the amount of natural gas provided is increased. However, transferring from diesel mode to gas mode has a minimal effect on the engine load and speed. Although, switching from LNG to MDO or vice versa does not require engine modifications, switching from LNG to HFO requires minor engine modifications (DNV-GL, 2015b; LNG Fuelled Vessels Working Group, n.d-a; Wärtsilä, 2015; Woodyard, 2004)[70].

MAN is one of the main manufacturers of DF engines, although, it has developed two-stroke DF engines, which lightly differ from four-stroke DF engines. MAN DF engines operate at high pressure, and consequently, they compress the air, start the combustion stroke injecting fuel oil and inject the natural gas in the air-fuel oil mixture. For this reason, natural gas pressure must be high (300 bars) and two-stroke DF MAN engines use pumps to increase LNG pressure.

HIGH PRESSURE DIRECT INJECTION ENGINE

Pilot-ignited high- pressure direct-injection (HPDI) natural gas engines have drawn much attention since being proposed, as these engines can maintain high performance and led to clean combustion compared with conventional diesel engines. This prospective concept is not only used in vehicle engines but it is also used in large-scale marine engines. Different types of gas engines have been summarized in the literature. These engines, categorised mainly by two different ignition principles, operate primarily either by diffusion or by pre-mixed combustion. When burned with diffusion combustion, a pilot of diesel fuel is usually injected into the hot air slightly prior to the ignition of natural gas and serves as an ignition source. Natural gas is directly injected into the cylinder near the top dead centre (TDC)[70], and this ignition requires a high gas injection pressure, that is 250-300 bar. In such cases, the gaseous fuel is ignited upon its interaction with the pilot fuel flame. As a result, the energy released by the pilot diesel fuel serves only as an ignition source.

Gas burning engines operate according to two different principles, the "pre-mixed" Otto and direct-injected Diesel cycles. Otto gas engines can be divided into 2 groups:

- **Spark-ignited** gas engines ("gas only") with either carburettor or port injection of gas. These are "single-fuel" engines and therefore must meet some redundancy requirements for marine applications.

- **Diesel-ignited** gas engines with conventional low pressure gas feed (as described above) but with ignition by the injection of a certain quantity of Diesel fuel, also known as "Otto DF" or "low pressure DF principle. These will always need a certain quantity of diesel fuel for running even in Gas mode, but on the other hand they may also run on 100% liquid fuel (diesel or HFO), i.e. dual fuel capability.

Otto gas engines with their homogeneous combustion generally have low NO_x emissions and high efficiency and will typically comply with the IMO Tier III limits without exhaust after-treatment. However, they require a certain stability of the fuel gas against self-ignition and they must be carefully developed in order to keep un-burnt gas ("methane slip") to a minimum. Spark-ignited and diesel-ignited gas engines show some differences in this respect, especially at part load.

7.3.2 MEDIUM SPEED 4-STROKE LEAN BURN SPARK IGNITION (LBSI) ENGINES

These engines run only on natural gas and operate based on the Otto cycle. A spark plug is used to ignite the air-fuel mixture in the combination chamber or in a pre-chamber. These engines have an efficiency of about 42% (Stenersen et al., 2017)[72] and power output ranging from 316kW

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[70] Ibid, 2015.

[71] The point in which the piston in the number 1 cylinder position of the engine is at its highest point on the compression stroke

[72] Stenersen, D., Thonstad, O (2017), "GHG and NO_x emissions from gas fuelled engines", SINTEF Ocean AS (OC2017 F-108 – Unrestricted).

to 9.7 MW. Rolls-Royce Marine/Bergen, Mitsubishi and Hyundai are manufacturers of these engines. These applications have included ferries, small cargo vessels, offshore support vessels and a number of other smaller vessel applications. Although this engine adoption has been hampered by the inability to run on traditional liquid fuels as a back-up. Rolls-Royce has also recently released a high-speed spark-ignited gas engine for marine propulsion based on its popular MTU 4000 series platform (Rolls-Royce, 2017). Under the MTU brand. Rolls-Royce Power Systems markets high-speed engines and propulsion systems for ships, for heavy land, rail, and defence vehicles, and for the oil and gas industry.

The stoichiometric spark-ignited engine technology with exhaust gas recirculation that is popular in heavy duty truck engines is not used in marine applications. However, LBSI manufacturers do use richer fuel mixtures (closer to stoichiometric mixtures) in parts of the engine operating range to improve load acceptance.

7.3.3 MEDIUM SPEED 4-STROKE LOW PRESSURE DUAL-FUEL (MS-LPDF)

These engines also operate based on the Otto cycle and require a lower compression ration than diesel engines of the same size to prevent pre-ignition or knocking. This results in a lower power output per cylinder. The efficiency of these engines is about 44% (Stenersen et al, 2017). When in gas mode, gas is injected into the air intake of each cylinder and is ignited by a pilot injection of liquid fuel. Alternatively, this type of engines can operate in liquid fuel mode, providing flexibility to use different fuels depending on fuel availability or price. LPDF engines were initially developed for LNG bulk carriers where boil-off gas could be used to power the auxiliary or main ship engines. They have been successfully deployed in ferries, platform support vessels, service vessels, and several other vessel types. These engines are available in power output ranging from 720 kW to 17.55 MW manufactured by Wärtsilä, MAN and MAK.

7.3.4 LOW SPEED 2-STROKE LOW-PRESSURE DUAL-FUEL (LS- LPDF)

When the development of the two-stroke low-pressure DF lean-burn technology started, the extensive experience from Wärtsilä's four-stroke developments could be utilized as a base in several technology areas. These include engine automation and control, pilot injection, gas supply system and engine testing to mention a few.

The low-pressure dual –fuel technology developed by WinGD (Winterthur Gas and Diesel Ltd) for its X-DF engine series builds on Wärtsilä's long experience with what has become a well-proven industry standard on medium-speed dual-fuel engines. In contrast to high-pressure gas injection engines, which operate on the Diesel cycle, WinGD's low pressure X-DF engines work on the lean-burn Otto cycle when operated in gas mode – i.e. ignition of a compressed lean air/gas mixture by injection of a very small amount of liquid pilot fuel.

WinGDs X-DF engines are characterized by stable combustion, inherently low NO_x emissions and high overall system efficiencies as well as safe gas operation. Moreover, with the low-pressure gas admission, the gas fuelling system does not require any high-pressure compressors, considerably reducing equipment costs, on-board energy consumption and maintenance during operation. Additionally, a large supplier base is available, as the components are similar to systems installed on numerous 4-stroke DF engines, proven in thousands of hours in field operation.

The larger low-speed 2-stroke dual-fuel engines operate on a similar principal to their 4-stroke counterparts, however when in-gas mode, gas under low pressure is injected into the cylinder before the compression stroke. The efficiency of these engines is about 51% (WinGD, 2018)[73]. WinGD licenses designs for manufacture of 2-stroke LS-LPDF engines in the power range of 4.5 MW to 65 MW (ibid, 2018).

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[73] Winterthur Gas & Diesel (2018), "X92DF Marine Installations Manual", Winterthur.

7.3.5 LOW SPEED 2-STOKE HIGH PRESSURE DUAL-FUEL (LS-HPDF) ENGINES

The dual fuel power technology is most easily used in dual-fuel, medium speed and high-speed engines of both main propulsion and generating sets, in which the evaporated gas is supplied to the engine at low pressure (about 0.5-0.8 MPa) to the air inlet valves of the individual cylinders and mixed with the air in the combustion chamber.

However, the highest thermal efficiency is obtained with low-speed 2-stroke piston engines. That is why, for many years, design and experimental work has been carried out, which led to the creation and introduction of slow-speed 2-stroke dual-fuel engines into the propulsion system.

The gas-powered low-speed engine installation is more complex than the medium-speed engine. In the case of ME-GI series engines offered by MAN, it results, among others, from the necessity of compressing the gas to high pressures (15-30 MPa), for which extremely energy-consuming multistage compression systems are needed.

The gas injection to the combustion chamber is feasible thanks to the fact that the cylinder head is supplied with the gas injectors together with the ELGI valve (electronic gas injection). In order to ensure smooth engine operation on gas, it is essential to provide so-called liquid pilot fuel (i.e. small amount thereof just before the main injection), amounting to 5-8% of its volume. Research conducted by the manufacturer has proven that without such a pilot injection, the engine operates unstably; knocking combustion occurs or there might be even misfiring. The cause of this, among others, is the higher temperature of the vaporized gas' spontaneous combustion.

ME-GI engines, apart from having all the systems widely used in all ME series engines, must be also additionally equipped with a number of other installations, like among others:

- Ventilation system of the spaces between the interior and exterior compartments of the double-walled installation fuelling the engine with the vaporized LNG gas;
- Sealing oil system, the aim of which is to separate the gas injection from the pilot fuel dose;
- PLC control unit – comprising of a set of sensors and analyzers. Its main function is to turn on and off the gas supply installation. In case of a breakdown, the PLC control unit will automatically switch from gas to the heavy fuel supply without any losses of power in the main engine;
- IGS (i.e. Inert Gas System) – part of the PLC control unit; its purpose is to keep the main engine supply installation free from gas.

A complex technical system, by its nature, is prone to movement disturbances and other malfunctions. That is a reason why the Dual-Fuel 2-stroke Diesel engines for long time had been remaining only in a design-experimental phase. However, after many years of adaptation work, MAN's ME-GI series engines have found applications in the main propulsion of ships, mainly LNG carriers.

These dual fuelled engines provide a similar performance to diesel engines with power loss, though NO_x emissions are higher than Otto cycle engines due to higher combustion chamber temperatures. The direct gas injection system assures much lower methane emission from the tailpipe exhaust. The efficiency of these engines is the same as the low-speed diesel engines they are derived from, about 50% marine LS-HPDF engines are currently manufactured under license from MAN only for large low-speed 2-stroke engines to provide power up to 42.7 MW.

7.3.6 GAS TURBINES

The gas turbine (GT) was a technological innovation introduced on LNG vessels because of their ability to consume diesel and BOG without any limitations, their high reliability derived from the aeronautical industry and a very high power/weight ratio, meaning a reduced size of the system (Fernandez et al, 2017))[74].

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[74] Fernandez, I., Gomez, M., Insua, A. (2017), "Review of propulsion system on LNG carriers", In Renewable and Sustainable Energy Reviews.

The first vessels to install a GT as a main propulsion system were those belonging to the navy and also passenger ships. These combined the GT with ST or diesel generators to produce electric power. On the contrary, LNG vessels with GT propulsion are not combined with any other generation system, because all of the BOG is used to as fuel, thus coping the energy demand of the vessel.

GTs are combined with electric propulsion, called the DFGE system (dual-fuel gas turbine electric propulsion). The high specific consumption along with the need to use costly clean fuels so as to comply with ISO-F DMA regulations make the turbines a less attractive option to be used on ships. However, the GT enables the recovery of waste heat for the implementation of a combined cycle, thereby increasing plant efficiency to 40%. There is also the possibility of using BOG as fuel, which would be option to consider installing as a propulsion system on LNG vessels.

There are different combined cycle-based system configurations, which can be subdivided into 2 groups: (1) power driven combined cycle; and (2) combined gas turbine electric & steam system (COGES).

The power driven combined cycle is an unusual layout on LNG vessels because all the advantages of the flexibility provided by the DFGE system are dismissed with the installation of an auxiliary power generator. The system comprises a GT of around 36 MW which is responsible for supplying the required torque through a reducer, to rotate the ship's propeller. The exhaust gases generated in the GT are sent to the recovery boiler where they provide the heat input required to generate steam that is sent to a turbine of around 10 MW, coupled to a generator that supplies power to the vessel during navigation. The plant also includes three auxiliary generators with a combined capacity of between 6 and 12 MW used for power generation at port, when both turbines are stopped.

Combined gas turbine electric & steam system (COGES) are electric propelled combined cycles. These systems are composed of elements similar to those that form a power driven combined cycle system, but with a difference in the layout of its components and with the main propulsion being electric.

Two arrangements can be distinguished within COGES, each associated with their manufacturers, these being Rolls-Royce and General Electric. The arrangement of COGES designed by Rolls-Royce has two GTs with different powers, one of 35 MW and another of 5 MW, designed in such a way that the exhaust gases of the GT with greatest power are exploited in a heat recovery steam generator. The steam generated is used to power a 10 MW steam turbine, which together with the more powerful GT, provides the electric power and propulsion demand during ship sailing.

The COGES plant designed by the manufacturer General Electric has two gas turbines, each of 20 MW. The reliability of this type of system increases because, in the event that there is a fault in a GT, the system could guarantee 50% of the electric power supply to continue with the voyage. The disadvantage, however is its high consumption while at port as it does not have low power auxiliary generator as is the case of the Rolls-Royce design (Fernandez et al, 2017).

7.3.7 ENGINE TECHNOLOGY COMPARISON OF DIFFERENT OPTIONS TO MEET ENVIRONMENTAL REGULATIONS AND CHALLENGES

One of the main issues with LBSI and LPDF engines is methane slip, particularly at partial loads. Methane slip occurs when methane from the fuel enters the engine exhaust unburned. The primary cause is incomplete combustion either due to incorrect air-fuel mixtures or gas getting trapped in crevices in the combustion chamber. In 2-stroke engines, such as the LS-LPDF, gas is injected into the cylinder while the exhaust valve is still open, and careful timing and direction are equipped to ensure unburned fuel does not exit through the exhaust valve during this scavenging process. Methane is a potent GHG and has a global warming potential (GWP) of 30 to 85 times greater than CO2 (Myhre et al., 2013)[75]. In publications before 2015, methane slip from ship engines was estimated to be between 1.9% and 2.6%. However, recent measurements by SINTEF Ocean in 2017 showed methane slip of 2.3% and 4.1% from LBSI and MS-LPDF engines, respectively. This is despite improvements made by engine manufacturers in combustion chamber design and tighter air-fuel ratio control to minimise methane slip.

Analyzing the methane slip and NO_x emissions in marine vessels a competing trend between these species can be seen, especially at low engine loads. LBSI and LPDF engines can control NO_x emissions (for instance to meet more stringent Tier III NO_x emissions) by using lean fuel-air mixture to reduce the combustion temperature (Stenersen et al., 2017)[76]. However, this technique increases the CO emissions. On the contrary, a rich fuel-air mixture can minimise methane slip, improve load acceptance and reduce CO emissions at a cost of increasing NO_x emissions. It seems that despite the best efforts of engine manufacturers, these undesired emission from LBSI and LPDF engines will continue to reduce the GHG benefits of natural gas fuelled ships using these engine types.

LS-HPDF engines in contrast, have been found to have lost no methane slip (about 0.01%). However, the complex fuel gas supply system required to supply the fuel increases costs by about 40% compared to LBSI and LPDF engines and their NO_x emissions are between diesel and LPDF engines (Stenersen et al, 2017). To comply with the NO_x levels in MARPOL Annex VI - Tier III, these engines should use exhaust gas recirculation (EGR) and/or selective catalytic reduction (SCR) to reduce NO_x emissions (ibid, 2017).

The ability for LBSI and LPDF engines to meet NO_x Tier III emission standards without the need for additional after-treatment or exhaust gas recirculation make them an attractive choice for vessels operating consistently in the ECAs where the Tier III standards apply, despite the fact that the methane slip from these engine types are higher that that from LS-HPDF engines.

Gas turbines (GT) have been proposed as an alternative to piston engines due to their more compact and lighter characteristics. However, GT are less efficient. To increase their efficiency, a combined cycle turbine can be used. GTs are predominantly used in warships, where high power output and rapid response outweigh the operation cost and fuel consumption. GTs have also been successfully deployed in cruise ships. Combined cycle gas turbines with heat recovery have been proposed for LNG fuelled ships.

While all four LNG ship engine types meet NO_x Tier II requirements, not all four engine types can meet NOx Tier III requirements - a ship equipped with a dual fuel high pressure engine would need one of the above mentioned additional exhaust gas treatment to meet NOx Tier III requirements. The two dual fuel engine types that can meet Tier III requirements, i.e. the dual fuel low pressure engines, would have to be operated in the gas mode to fulfil Tier III requirements.

In principle, with all four LNG ship engine types, ships can comply with all sulphur requirements. (For the dual fuel engines this of course depends on the actual fuel mix used). For sulphur requirements, an alternative for an LNG-fuelled ship could for example be a HFO-fuelled ship retrofitted with a scrubber.

When a scrubber is the option a number of different costs need to be considered. For this specific emission abatement method initial investment costs will depend primarily on the type of scrubber selected, ranging from open-loop to closed-loop and hybrid systems. Recurring costs, also dependent on the type of systems chosen, will invariably consist of water (sludge) disposal, water treatment and equipment power consumption, and maintenance. The overview of the exhaust gas abatement in detail is given in section 7.5.

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[75] Myhre, G., Shindell, D., Breon, F., Collins, W., Fuglestvedt, J., Huang, J. "Anthropogenic and Natural Radiative Forcing", In Climate Change, 423 (2013), pp. 659-740.

[76] Stenersen, D., Thonstad, O (2017), "GHG and NO_x emissions from gas fuelled engines", SINTEF Ocean AS (OC2017 F-108 – Unrestricted).

7.4 THE PROPULSION SYSTEMS OF THE FUTURE

The focus of research and development activities are currently focusing on four areas: one of them is the improvement of diesel technology in terms of emissions and fuel consumption. This means that exhaust gas treatment will gain a significance. Another key focus is on the extension of gas technology beyond current stationery areas of applications to include mobile applications. A third area is the hybridization of the power train in order to reduce fuel consumption and to enable an electrical propulsion system to provide low power operations or to generate electrical energy for other applications. Improving services and economy by analysing operational data is a fourth key focus of research and development activities that will result in the improvement in terms of greater availability, lower maintenance costs and lower operational costs.

Ships will still be powered by internal combustion engines at the beginning of the 21st century. Other types are not yet capable of delivering the power that vessels need. Electric drive systems running on fuel-cells or accumulators would theoretically also be possible, but both have limited power density and range, particularly on account of their energy storage systems. But there will undoubtedly be an increasing level of electrification around all aspects of the internal combustion engine.

The marine propulsion system of the future, depending on the type of vessel, mission profile and the cost and availability of fuel, will incorporate a diesel or gas engine as the prime energy converter. The power train will be electrified to a greater extent, as this will enable to reduce fuel consumption in most of the real-life operational profiles and to provide electrical power for other on-board applications. There will of course also be ships operating solely on electric power for applications with short mission periods. Big data will not be confined to future marine propulsion systems, but we will also see improved maintenance, early detection of malfunctions and the appropriate response, and autonomous operation.

For continuous-duty power generation, gas engines have virtually displaced diesel engines. Even locomotives, large pump engines and mining vehicles could be operated much more economically with gas. One challenge is the fuel supply, i.e., storage in tanks and delivery to the engine. Apart from lower fuel costs, lower CO_2 emissions and more economical emissions control for future emission stages are increasingly important aspects.

Offshore Patrol Vessels (OPVs) for coastal defence are becoming an important feature in the naval fleet of most nations. Since the operational profiles of these various applications can be quite different, OPV propulsion systems need to be able of adjusting to varying load requirements. While OPVs are typically between 500t and 3300t displacement with a speed of up to 25 knots, the design features can vary considerably from one vessel to another, in line with the intended operational function.

7.5 EXHAUST GAS ABATEMENT TECHNIQUES

International, regional, national and local instruments regulate emissions of SO_x, NO_x and particulate matter from ships. In response to greater concern about air quality the extent and complexity of regulation have increased while emissions limits have become tougher. Annex VI of the IMO MARPOL Convention applies to all ships trading internationally and has been used as the basis for many other regional, national and local regulations.

As emission limits become more stringent, compliance becomes more challenging and costly. There are a number of compliance options, each of which has different technical and operational challenges. To meet reduced SO_x emission limits, ship can operate on low-sulphur residual and distillate fuels, and in the longer term alternatives such as LNG, biofuels, DME (dimethyl ether) and methanol can provide solutions. The alternative to these options are exhaust gas treatment systems (EGTS) known as SO_x scrubbers, which clean the exhaust gas to reduce sulphur emissions to a level that is equivalent to the required fuel sulphur content. This offers the flexibility to either operate on low-sulphur fuels or to use higher sulphur fuels.

From switching to low-sulphur fuels to installing an exhaust gas cleaning system (EGCS) on board, the shipping sector is looking at all technologies and procedures to achieve full compliance with IMO's sulphur cap implementation in 2020. Applying this technology to ships allows us to obtain sulphur-free gas that meets the objective of the IMO's sea transport decarbonisation goals. From 2020 onwards, the options will involve using less polluting fuels or decontaminating the traditional ones. Many ship owners have already started to use these contaminant gas washing systems. According to figures from consultancy firm Drewry's report, 266 container ships are equipped with scrubbers, a total capacity of 2.2 million TEU. This also involves a penetration largely involving large vessels, so that while only representing 5% of all vessels, it is about double in terms of capacity.

7.5.1 TYPES OF SCRUBBERS AND THEIR CONFIGURATION

An exhaust gas cleaning system (scrubber) is a device installed onboard marine vessels that, quite literally "scrubs" harmful sulphur oxides from exhaust gases. These devices enable vessels to consume cheaper, high sulphur fuel oil (HSFO) while still complying with mandated emissions levels. Vessels with scrubbing technology installed will be able to consume high-sulphur fuel at a significant discount to low-sulphur fuel. This is particularly true as low-sulphur options are expected to come at a premium due to increased demand.

The idea of using water droplets to scrub exhaust gases clean was first explored in the 1950s, rapidly becoming an approved and accepted common technology in shore-based industries across the world. Exhaust gas scrubbers, in combination with the use of HFO have been accepted as an alternative means to lower sulphur emissions. Four different types of scrubbers are available today:

Currently there are 4 types of SO scrubbers:

1. Seawater scrubbers (open loop) utilize untreated seawater, using the natural alkalinity of the seawater to neutralize the sulphur from exhaust gases.

2. Freshwater scrubbers (closed loop) are not dependent on the type of water the vessel is operating in because the exhaust gases are neutralized with caustic soda, which is added to freshwater in a closed system.

3. Hybrid scrubbers give the possibility to either use closed loop or open loop technology.

4. Dry scrubbers do not use any liquids in process but exhaust gases are cleaned with hydrated lime-treated granulates.

So-called wet SO_x scrubbing (using sea or freshwater) is a simple, effective technology that has been used in industrial applications for many years. Wet SO_x scrubbers broadly comprise the following components:

- A scrubber unit - a vessel or series of closely coupled components, which bring water into intimate contact with the exhaust gas from one or more combustion units. The unit is typically mounted high up in the ship in or around the funnel;
- A treatment plant for conditioning of wash water before discharge overboard;
- A residue handling facility for sludge separated from the wash-water;
- A scrubber control and emissions monitoring system.

These components will be interconnected by pipework with various pumps, coolers and tanks, depending on the scrubber system configuration. One piping system and wash water treatment plant may service more than one scrubber. There will also be a monitoring and control system, with instrumentation either dedicated to a single scrubber or shared across an integrated system.

Within wet SO_x scrubbers category there is a need to timely mix wash water with the exhaust without creating a back pressure that exceeds the combustion unit manufacturer's limits and, if applicable, the engine's NO_x certification limits. There are, however incentives to make the scrubber unit as small as possible, as this will reduce space required for installation and will also reduce manufacturing costs. The design would therefore make optimum use of the minimum practical wash water flow to dissolve sulphur oxides, to bring emissions down to the required level while retaining sufficient buffering capacity. A wet SO_x scrubber system may also include a reheater to increase the exhaust gas temperature above the dew point, and a demister to remove fine water droplets.

Any of these systems use seawater as the washwater due to the salinity negating the need to add further chemicals. This happened over 12 years ago on a UK ferry that demonstrated the ability to clean a ship's emissions of sulphur oxides and particulate matter, as well as to make a dent in a ship's nitrous oxide emissions. The first commercial scrubbers on vessels began to appear in the following years, notably on a few hundred vessels, that were likely to be sailing permanently or occasionally in the emission control areas. Vessel operators realized the benefits of installing scrubbers to ensure they could use existing fuel oils rather than to switch to more expensive ultra-low sulphur fuels, namely refined distillate products with a sulphur content of less than 0.1%. With over 60 years continuous development and growth in shore-based electricity generation and other industrial plants, wet scrubbers and other similar technologies have been a crucial help in the continued development of society. With such success ashore, it was a natural consideration to adjust this effective environmental technology for marine use.

Wet scrubbers are able to operate in **"open loop"**, in "closed-loop" or even in a combination of these two modes, on what is commonly called "hybrid-mode". The first commercial option for sulphur emission reduction was open-loop scrubber. It uses the natural alkalinity of sea water to react with the SO_x compounds in the exhaust gases. As it needs water with natural alkalinity and this type of scrubbers are therefore designed mainly for use in ocean water. In wet open loop SO_x scrubbing (including hybrid systems operating in open loop mode) seawater is pumped from the sea through the scrubber, cleaned and then discharged back to the sea. Wash water is not recirculated. The wash water flow rate in open loop systems is approximately $45m^3/MWh$. A SO_x removal rate close to 98% with full alkalinity seawater should be expected, meaning emissions from a 3.50% sulphur fuel will be the equivalent of those from a 0.10% sulphur fuel after scrubbing. In the design process seawater temperature also has to be considered as SO_2 solubility reduces at higher seawater temperatures.

Some systems have wash water treatment units, but the large water quantities of wash water cause difficulties. All marine **closed loop** SO_x scrubbers (including hybrid SO_x scrubbers when operating in closed loop mode) use fresh water treated with sodium hydroxide (NaOH) as the scrubbing media. The system is similar to open-loop, but instead of using sea water, fresh water is circulated in the system, which makes it independent of seawater alkalinity. Therefore, closed-loop systems are recommended solution for areas with lower sea water alkalinity (Wärtsilä, 2018). This results in the removal of SO_x from the exhaust gas stream as sodium sulphide. Rather than the once-through flow of an open loop scrubber the wash water from a closed loop scrubber passes into a process tank where it is cleaned before being recirculated. Closed loop systems can also be operated when the ship is operating in enclosed waters where the alkalinity would be too low for open loop operation.

Closed loop systems discharge small quantities of treated wash water to reduce the concentration of sodium sulphate. If uncontrolled, the formation of sodium sulphate crystals will lead to progressive degradation of the wash water system. Information from scrubber manufacturers suggests that the wash water discharge rate is approximately $0.1m^3/MWh$. The rate of fresh water replenishment to the system is not only dependent on the discharge to sea but also losses to the exhaust through evaporation and via the wash water treatment plant. The rate of evaporation is influenced by exhaust and scrubbing water temperatures, which in turn are governed by factors such as engine load and the temperature of the seawater supply to the system coolers. Some of the water vapour incorporated within the exhaust may be captured after the scrubber and reused to reduce fresh water consumption. By being able to operate in zero discharge mode, closed loop systems also provide a measure of mitigation against wash water discharge regulations that may come into force in the future.

While closed-loop scrubbers retain the sulphur emissions for safer disposal at port, open-loop scrubbers release pollutants back in the sea after turning the sulphur dioxide into sulphuric acid. By being able to operate in zero discharge mode, closed loop systems also provide a measure of mitigation against wash water discharge regulations that may come into force in the future.

There are also hybrid scrubbers, which switch between open and closed loop depending on situations such as local rules which may or may not prohibit the discharge of water. So far, open-loop systems have witnessed more uptake in the industry compared to closed units. According to DNV GL, there are currently 3,756 vessels with scrubbers installed - a huge increase from the 767 in 2018 - and only 65 have closed loop. This figure is estimated to cross 4, 000 in 2020 by the time the IMO legislation is enforced (Sarayogi 2020)[77].

In the maritime sector there is ongoing scrubber debate which highlights the need to take into account some environmental concerns while choosing the type of scrubber to be installed on board of the vessel. According to the ship technology experts, ship-owners prefer open-looped system over closed loop because “they are easy to install, require less maintenance and do not require storage for waste materials - as water is directly pumped back into the sea after on-board treatment”. Therefore, the industry is facing a fierce debate over whether open-loop scrubbers represent an environmentally sound option.

An expose by the British newspaper “Independent” in September 2019 brought the issue of open-loop scrubbers to the forefront, revealing shipping companies have already invested more than 12 billion dollars on open-loop scrubbers for the sake of ships meeting IMO’s standards. The investigation claimed that ship-owners were doing so despite knowing that scrubbers “have a devastating effect on wildlife in British waters and around the world”.

According to the estimates of the International Council on Clean Transportation (ICCT) cruise ships using heavy sulphur fuel and open loop scrubbers will discharge 180 million tons of contaminated scrubber wash water overboard in 2020. As a result, some jurisdictions and ports are already restricting their use in the waters, necessitating either the use of closed-loop scrubbers or lower sulphur marine fuels. China, for instance, has already banned the use of open-loop scrubbers within its emission control areas covering inland waters and most of its coastline. Other countries with bans or restrictions are United Arab Emirates, Malaysia, India, Belgium, Germany, Lithuania, Latvia, Ireland, Norway and parts of the U.S. Singapore even went further by classifying residues from scrubber operation as “toxic industrial waste (TIW) under Singapore’s Environmental Public Health Regulations.

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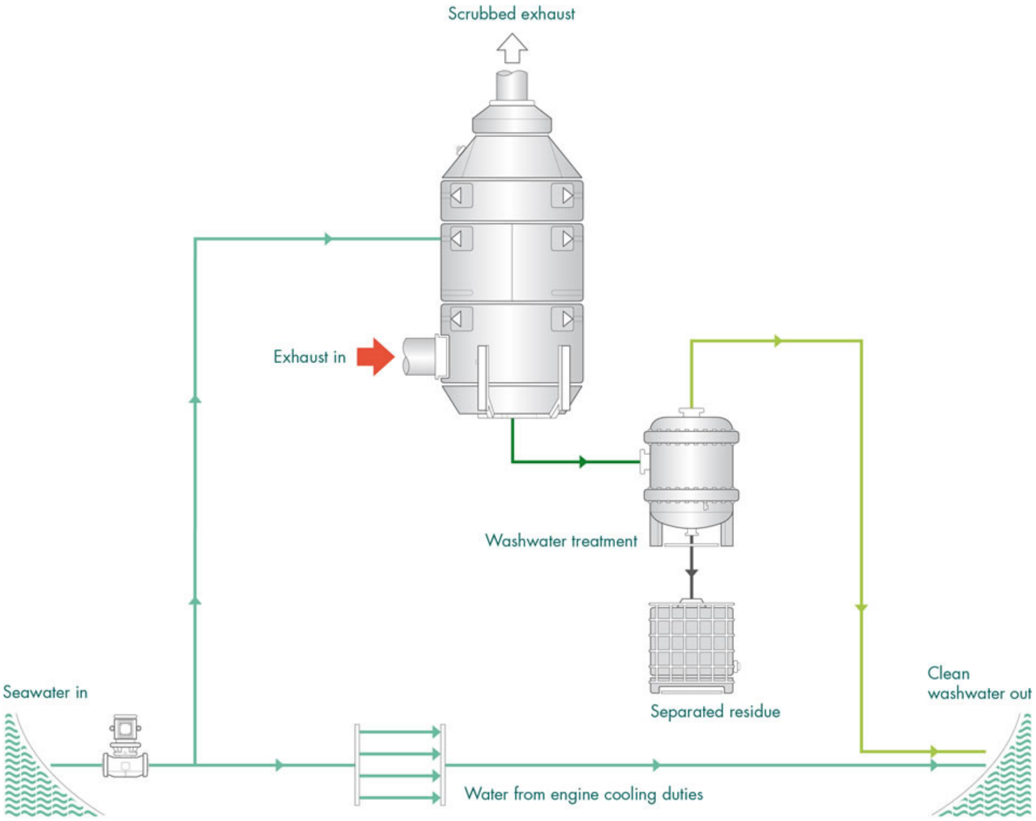
[77] Sarayogi, V. (2020), “Debunking: the problem of ship using open-loop scrubbers”, in Ship Technology newsletter, 20 January 2020.

Figure 14. Open-loop exhaust gas cleaning system.



Source: EGSA (2020)

According to the data from 2018, the 1,031 vessels in operation (globally) that are using some form of adaptation include 769 with scrubbers (75%), 143 fuelled by LNG (14 per cent), and 119 battery powered (including hybrids) (11 per cent). The uptake of scrubbers is mostly by large cargo vessels. Of the 2,702 vessels in operation or on order with scrubbers, 2,257 (84 per cent) are bulk carriers, car carriers, container ships, crude oil tankers, gas tankers, general cargo ships, oil product/chemical tankers, and ro-ro cargo ships, while a further 258 (10 per cent) are cruise ships. Approximately 84 vessels (in operation or on order), belonging to the categories of ferries, fishing vessels, offshore supply ships, and "other service vessels" have opted for scrubbers. No scrubber has been so far installed on Navy vessels which can be principally driven by the requirement of having an adequate security clearance and this process can be time-consuming. The Navies are still considering their options how to contribute to the green agenda and are rather looking towards some new technologies.

By contrast, the uptake of battery propulsion is largely focused on vessels that operate over relatively short distances, in relatively limited geographical areas - precisely those vessel types that have not opted for scrubbers. Of the 300 battery-powered vessels in operation and on order, passenger ferries, roll-on, roll-off passenger ferries (ro/pax), and other passenger vessels account for 136 (45 per cent), while fishing vessels, tugs, offshore supply ships, other offshore vessels, and vessels engaged in "other activities" (such as dredgers) account for a further 124 (41 per cent). By contrast, bulk carriers, container ships, crude oil tankers, general cargo ships, oil product/chemical tankers, and ro-ro cargo ships account for just 22 (7 per cent), with cruise ships also accounting for 17 (6 per cent).

A key element in the profitability of the scrubbers is the availability of high sulphur fuel oil (HFO). Thanks to the implementation of scrubbers, vessels may continue to use this type of fuel. However, it is difficult to gauge future demand and its subsequent price. HFO estimates were lower for 2020 in relation to other fuels which comply with the 0.50% sulphur emission limit, but a boom in the implantation of scrubbers could mean that demand remains high and there is no reduction.

7.5.3 EXHAUST GAS RECIRCULATION AND SELECTIVE CATALYTIC REDUCTION

In recent years, engine manufacturers have been required to reduce the levels of nitrogen and sulphur oxides in engine exhaust gas to meet increased environmental legislation. This requirement can be accomplished by changes in engine design that include the use of exhaust gas recirculating systems (EGR). It is a mature technology within the automotive market, but new to ships.

A proportion of the exhaust from before the turbocharger is re-introduced to the cylinders with the charge air which lowers the oxygen content of the mixture and increases its heat capacity. This in turn, results in a reduction of peak combustion temperatures and hence the formation of thermal NO_x is suppressed. As such, EGR is a method of primary NO_x control rather than a true exhaust gas treatment system. For example, the test engines by MAN Diesel&Turbo have shown that with 40% recirculation, EGR has the potential to reduce NO_x down to Tier III levels on a two-stroke low-speed marine engine and that increased fuel consumption, carbon monoxide emissions and PM emissions resulting from reduced combustion efficiency are manageable with engine adjustments. It i also reported that specific fuel consumption is much improved when using EGR to reduce NO_x down to Tier II limits, when compared with using engines adjustments to achieve the same level of emissions, particularly at part load. No high-speed or medium-speed engine manufacturer currently offers EGR NO_x abatement technology.

Selective catalytic reduction (SCR) is an advanced active emissions control technology system that injects a liquid-reductant agent through a special catalyst into the exhaust stream of a diesel engine. The reductant source is usually automotive-grade urea, otherwise known as Diesel Exhaust Fluid (DEF). The DEF sets off a chemical reaction that converts nitrogen oxides into nitrogen, water and tiny amounts of carbon dioxide (CO_2), natural components of the air we breathe, which is then expelled through the vehicle tailpipe.

SCR technology is designed to permit nitrogen oxide (NO_x) reduction reactions to take place in an oxidizing atmosphere. It is called "selective" because it reduces levels of nitrogen oxide by using ammonia as a reductant within a catalyst system. The chemical reaction is known as "reduction" where the DEF is the reducing agent that reacts with NO_x to convert the pollutants into nitrogen, water and tiny amounts of CO_2. The DEF can be rapidly broken down to produce the oxidizing ammonia in the exhaust system. SCR technology alone can achieve NO_x reductions up to 90 percent.

SCR technology is one of the most cost-effective and fuel-efficient technologies available to help reduce diesel engine emissions. This technology has been used for decades to reduce stationary source emissions. In addition, marine vessels worldwide have been equipped with SCR technology, including cargo vessels, ferries and tugboats. Refinements and improvements to SCR systems will be a critical technology to deliver closer-to-zero emissions. Dosing events, compact designs and placement of SCR systems integrated into commercial vehicles will play an important role in reducing emissions.

Exhaust Gas Cleaning Systems (EGCS) represent, in particular for ships in service, a technically and economically viable solution that can be considered as a strategy to comply with sulphur emissions limitations, using otherwise non-compliant fuel. Different EGCS technologies exist and can be considered.

8. CONCLUSIONS

The transport sector is the fastest growing consumer of energy and producer of greenhouse gases in the European Union. Higher marine fuel oil prices have made way to development of newer technologies based on cost and environment efficient fuels such as natural gas that is a potential winner in terms of being environment friendly, safe, reliable and cost effective. When compared to oil, natural gas has become an important commodity, with a key global energy impact.

With new emission regulation these days the potential application for LNG are expanding. LNG provides a greener alternative to other fossil fuels, which can significantly contribute to improve European air quality and to reduce the existing oil dependency. Studies have shown that usage of natural gas or LNG as fuel has decreased poisonous sulphur emissions or SO_x significantly with a substantial reduction in carbon dioxide (CO_2) and nitrogen oxide (NO_x) gases.

Most forecasts suggest that global demand should be in the range of 25 to 30 mtpa of LNG by 2030. This would require that, very approximately, between 2,000 and 6,000 new or converted vessels would be fuelled by LNG by then. Reaching a fleet of this size would appear challenging at the present level of new builds. It is considered, therefore that a demand level of around 15 mtpa by 2030 is a more realistic prospect. This outlook could change rapidly, however, if a number of large shipping companies were to commit to LNG. All of these forecasts exclude LNG carriers. If all of these were to switch exclusively to LNG, this alone could represent around 17 mtpa of demand by 2030.

LNG as ship fuel will suit to certain segments better than the others. Major container liner companies such as CMA-CGM are working towards developing future ships which are LNG fuelled along with other technologies to reduce harmful ship emissions. The other more promising segments for LNG are RO-RO ferries, cruise ships and bulk carriers. Similarly M/V Bit Viking is considered to be the largest of the vessels afloat and in service with approximately 25,000 dwt powered by LNG. This technology can only be developed when a solution to LNG refuelling has been concretely developed. Wärtsilä, a major ship engine maker has developed and completed conversion from oil-run engines to LNG powered. Such dual fuel engines have now been implemented in several cargo ships. After almost a decade in development of LNG technology, presently, approximately 30 floating vessels are LNG fuelled and servicing the European waters. Tug boats and high speed ferries are next in line for the conversion to LNG.

Some companies are building hybrid ships that are able to run on both oil and gas as fuel. The technology will see ships to be powered by natural gas for up to half way through the voyage and still be capable to switch over to bunker fuel for the remainder of the journey. The idea will be to use natural gas as the primary source of power and bunker fuel as a secondary/emergency one.

Many alternative fuels result in the need to change onboard storage and port infrastructure. The gaseous alternative fuels such as natural gas and hydrogen require compression or liquefaction, resulting in new infrastructure and storage equipment. However, even with compression or liquefaction, the energy densities of these fuels are lower than liquid fossil fuels, requiring more storage space and reducing the available cargo space for vessels. Batteries suffer from a similar issue: the size and weight required for battery powered ships means that their range is limited, and they are not a compatible option with the larger ship types.

There are some barriers that are currently holding back demand for LNG as a bunker fuel, for example uncertainty about the availability of LNG in ports. Some of the uncertainties are likely to be reduced considerably in the coming years. By 2025, LNG will be available in all EU TEN-T core ports, as the Alternative Fuels Infrastructure Directive (AFID) will be implemented. Possibly, a fuel price or price benchmark will become available once LNG is available in more ports. With the number of LNG ships increasing, there will be more experience with LNG, reducing the associated uncertainties.

A potential disadvantage to using LNG is space. Since gas weighs more, volume-wise it requires more space as compared to bunker oil. The farther the journey, the equally larger amount of storage space is required. So far, tanks are designed to be built in the cargo spaces of the ships for using gas as fuel. This is a major setback for the ships' operators. Engineers and architects are working towards developing systems that would make room for storing LNG. This could be anywhere on the vessel, above-deck, in the superstructures, beneath the cargo containers, astern of the vessel, etc. This would also bring along the need for extra insulation, piping and steelwork as far as construction of the vessels is concerned. Moreover, Hyundai has now developed dedicated LNG storage tank.

As a fuel, LNG presents hazards when handling and storing that are not present with traditional oil bunkers. If LNG is spilled onto a hull the cold can shatter steel, for instance. The liquid is constantly boiling, and so the methane must be used relatively constantly to avoid methane being vented through pressure release mechanisms. Whilst there are not the same pollution risks associated with an LNG spill the handlers of this fuel require specialized training and storage tanks, pipes and hoses are specialized and expensive.

Due to the safety reasons (potential threat of spills or leakages) LNG is not widely used in the Navies, even in regions with highly developed infrastructure, such as in the Scandinavian countries. On the other hand, there are many cases where LNG fuelled vessels are used in performing certain non-military operations (patrol boats and OPVs). These vessels generally have regular and predictable journey patterns and they follow routes that allow easy access to LNG facilities. This also means that LNG fuelled vessels can be used if certain conditions are met. For example, the Finnish Frontier Guard LNG powered vessels have dual fuel engines that can switch from one fuel to the other. For refuelling they have access to commercial LNG small-scale facilities.

The fuel options also influence machinery choices. An advantage of some of the biofuels and electro-fuels is that they need no (or very little) modification to current marine diesel engine designs to function. Other alternative fuels require, or significantly benefit from, new machinery options. Fuel cells and batteries, when used as the main energy source for propulsion, require an electric motor instead of an internal combustion engine, and are therefore more suited to new-build ships. Fuel cells can be used with fuels such as hydrogen, LNG, ammonia and methanol. These convert the fuel into electricity to be used with electric propulsion, similar to batteries. Fuel cells have the benefit of a higher efficiency compared to combusting the same fuels in the internal combustion engines. However, fuel cell powered vessels have so far only been tested at the ca 1 MW size, limiting the power of propulsion. This propulsion power can be used in smaller vessels but is currently one or two orders of magnitude away from being the primary power for propulsion of larger ship types (DNV GL, 2017). Electric propulsion motors with suitable power outputs are technologically and commercially mature and have been used for some time in the defence, cruise and offshore supply vessel fleets. There are several competing fuel cell technologies. The most mature (proton exchange membrane) is available commercially at smaller scale, though efficiency improvements and cost reduction are expected through further technological development.

LNG/CNG and hydrogen (gaseous fuels) can be used in gas turbines, spark ignition internal combustion engines or multi-fuel internal combustion engines. These machinery types would require retrofitting to existing vessels, as most vessels currently use marine diesel engines. It is possible to convert some marine diesel engines to use these fuels in a dual-fuel set up, but the conversion is costly. When also considering the required changes in storage, gaseous fuels are more suitable propulsion for new builds. Many ships currently using LNG have multi-fuel engines.

There is no doubt that the growing level of interest displaced in LNG as a marine fuel is justified. The level of usage is certain to grow, driven by environmental restrictions and economic attractiveness. There is, however less certainty over the pace and scale of demand growth. This is partly due to the relatively poor data quality on marine fuel usage but primarily a reflection on the still early nature of market development and uncertainties over alternative fuel options.

LNG is an answer to some of the problems facing marine transport. It is too early to say if it is the answer. To date only a small number of shipping operators have made a clear commitment to new build LNG-fuelled ships. If other large companies start to follow their lead this will be a key indication that LNG will be a significant fuel in marine transport for the next twenty years.

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