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***Olga Petrychenko*[1*], *Maksym Levinskyi*[2]**

[1]Doctor of Philosophy, Theory and Structure of a Ship Department, National University "Odessa Maritime Academy, 8, Didrikhson str., Odessa, 65052, Ukraine. ORCID: https://orcid.org/0000-0002-4893-8204.

[2]PhD in Automation Control, Associate professor at Theory of Automatic Control and Information Technology Department, Head of Foreign Students Department, National University "Odessa Maritime Academy, 8, Didrikhson str., Odessa, 65052, Ukraine ORCID: https://orcid.org/0000-0002-6544-5110.

***Corresponding author:** oapetrycehnko@gmail.com

Trends and preconditions for widespread adoption of liquefied natural gas in maritime transport

The need for sustainable and environmentally friendly maritime transport and the introduction of International Maritime Organization (IMO) regulations on ship emissions have led to the search for a new type of marine fuel. Today, liquefied natural gas (LNG) as a marine fuel is an attractive, potential and technically feasible option for new ships that are being built to comply with air pollution regulations. The aim of the work was to analyze the prospects for the use of LNG as a marine fuel. The set task was achieved by studying the current state of LNG shipping, analyzing the advantages and disadvantages of different types of fuels, and studying the dominant segments of LNG ships. The implementation of LNG on board ships is carried out along with the development of LNG-powered engines, their control and protection systems, fuel tanks, gas supply systems and infrastructure. The object of the study is the prospects for using LNG as an alternative type of fuel in shipping. The most important result is the conclusion that LNG has significant potential as an alternative to traditional types of fuel in shipping, but requires the development of appropriate infrastructure.

Key words: *LNG, marine fuel, emissions, environmental friendliness, sustainable development, engines.*

Introduction. In light of the global drive for economic decarbonization, the water transport sector is preparing for a transition to new technologies and energy sources, which will have a significant impact on costs, asset values and profitability. Shipowners are already feeling increased pressure to reduce greenhouse gas emissions from their activities. Over the next decade, decarbonization in shipping will be driven by three key factors: regulations and policies, access to investors and capital, and expectations from shippers and consumers [1-3].

The International Maritime Organization is developing greenhouse gas emission reduction policies for international shipping. The first regulations, in particular the Existing Vessel Energy Efficiency Index and the Carbon Intensity Indicator, will come into force on January 1, 2023. One of the goals of this activity is to achieve a reduction in the carbon intensity of all ships by 40% by 2030 compared to 2008 levels [4, 5].

The use of alternative fuels and renewable energy has the greatest potential for reducing greenhouse gas emissions. All alternative fuels for water transport face difficulties and barriers to their use, although the complexity of overcoming these barriers will differ for different types of fuels. Typical key barriers include the high cost of required machinery and equipment, on-board fuel storage systems, the need for additional storage space, low technical maturity, high fuel prices, limited fuel availability, lack of global bunkering infrastructure, and safety issues including flammability and explosiveness of fuels. As of June 2021, only 0.5% of ships worldwide used alternative fuels, but 11.8% of orders in 2021 were for ships running on alternative fuels. Of these, 6.1% of orders were for LNG-powered ships, 3.8% for electric battery-powered, 1.5% for LPG, 0.3% for methanol, 0.06% for hydrogen and 0.02% for ammonia [6, 7].

Analysis of recent research and problem statement. In recent years, among the alternative fuels for water transport, liquefied natural gas (LNG) has gained the most distribution. The key environmental benefit of LNG is reduced SOx, particulate matter, NOx and CO2 emissions compared to traditional petroleum products.

Methanol is a good substitute for gasoline, used in blended fuels, and can also provide good performance in diesel engines. To use methanol in diesel engines, a small amount of diesel fuel must be injected along with the methanol or an ignition enhancer must be used. Since methanol contains no sulfur, NOx emissions are formed in small quantities during combustion, and particulate emissions are absent, this fuel is considered promising for water transport. However, the toxicity of methyl alcohol should be emphasized.

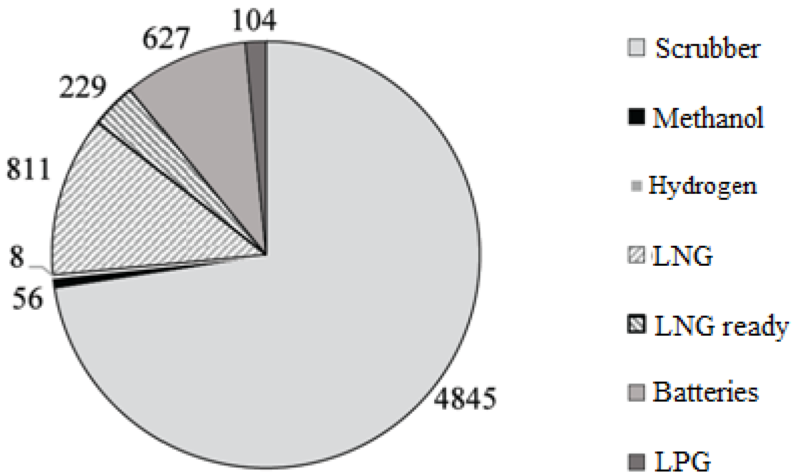

Fig. 1. **Number of ships in operation and on order by alternative fuel types and scrubber usage**

The purpose and tasks of the study. Ammonia is of considerable interest as a potential zero-carbon fuel for transportation. Compared to the marine fuel MGO, the energy content by mass of liquid ammonia is less than half and by volume is about 30%. Ammonia can be used as a marine fuel in both internal combustion engines and fuel cells. Due to its high autoignition temperature, ammonia requires a higher compression ratio (35:1 and higher) than typical diesel engines (16-23:1). Such an engine is difficult to design, and therefore additional fuel with a lower autoignition temperature needs to be used to ensure more stable combustion. Hydrogen is a colorless, odorless, non-toxic gas. For shipboard use it can be stored cryogenically liquefied, compressed, or chemically bonded. Hydrogen can be liquefied at temperatures down to minus 240°C by increasing the pressure to the "critical" point of 13 bar. The energy density per mass of hydrogen, taking into account the lower heating value of 120 MJ/kg, is approximately three times higher than the energy density of fuel oil. At the same time, the volumetric density of liquefied hydrogen (71 kg/m3) is only 7% of the figure for fuel oil. This results in an approximately fivefold increase in volume compared to the same amount of energy stored in fuel oil. When storing hydrogen as compressed gas, its volume is approximately 10-15 times (depending on the pressure) higher than the volume of the same amount of energy in fuel oil. The distribution and bunkering infrastructure for hydrogen in water transport is still absent.

From vegetable oil raw materials, three main types of biofuels are produced: straight (i.e. untreated) vegetable oil (SVO), biodiesel (FAME) and renewable diesel fuel (HVO), which are used as substitutes for diesel fuel or as component of blended fuels. SVO, FAME and HVO production technologies are proven and commercially available. Theoretically, it is possible to use marine diesel engines on 100%

biodiesel fuel, but this requires certain engine settings and certification, so more often FAME is used in blended fuels.

Based on the results of a comparative analysis and assessment, the following alternative fuels are considered the most promising for Ukraine's water transport: biomethane, which can be used in compressed or liquefied form; biodiesel (FAME) and hydrotreated vegetable oil (HVO); liquefied natural gas, as well as the use of electric power units with battery packs.

This work differs in that an analysis of alternative fuels was carried out, the main LNG ship segments were studied, on the basis of which some important conclusions can be drawn. LNG-fueled ships represent a growing market, driven by strict air pollution regulations; widespread development of LNG engines, fuel tanks and gas supply systems; and future LNG infrastructure projects. Indeed, significant LNG market growth is expected over the next decade, although external factors like LNG price and availability could impact it. Today, the main segments dominating the LNG fleet are car/passenger ferries, PSVs, harbor tugs, LNG carriers and container ships. The paper identifies several general points for LNG-powered ships, these findings can be used as a basis for further development for other ship types.

Table 1. **Characteristics of traditional and alternative fuels for water transport**

Characteristics	Diesel fuel	LNG	Methane	Methanol	LPG⁾	Hydrogen
Molecular formula	CnH1,8n; C_8-C_{20}	CnHm; 90-99% CH_4	CH_4	CH_3OH	C_3H_8 та C_4H_{10}	H2
Carbon content, wt.%	86,88	near 75	74,84	37,49		
Density at 160C, kg/m^3	833… 881	431… 4641)	422,51)	794,6	505	0,08
Boiling point at 101,3 кPa, $^0C^{2)}$	163…399	-160 (-161)	-161,5	64,5	-42	-253
Lower heating value, MJ/kg	42,5	49	50	20	47	120
Lower heating value, GJ/m^3	35	22		16		
Autoignition temperature, ^0C	257	580	537	464	457	585
Flash point, $^0C^{3)}$	52…96	-136		11	-60	
Cetane number	>40	0		5		
Flammability limits, vol.% in air	1,0…5,0	4,2…16,0	1,4…7,6	6,72…36,5	2,1…9,6	4…59
Solubility in water	No		No	Complete		
Sulfur content, %	varies, <0,5 oro <0,1	< 0,06	0	0		

Liquefied petroleum gas (LPG) is a mixture of saturated hydrocarbons: propane C3H8 and butane C4H10, whose molecules consist of hydrogen and carbon atoms [8]. LPG has two sources: approximately 60% is extracted during the production of natural gas and oil from the ground, while the other 40% is formed during the refining of crude oil.

Natural gas contains 90% methane CH4. The remaining 10% consist of 5% propane and 5% other gases, including butane. During the processing of crude oil, liquefied hydrocarbon gas is separated in the upper part of distillation columns during technological operations. LPG makes up 2 to 3% of all resulting products, meaning one ton of processed crude oil yields 20 to 30 kg of LPG.

LPG is gaseous at normal temperature (15°C) and atmospheric pressure (1013 mbar), and liquefies at low pressure: 1.7 bar for butane, 7 bar for propane. Their boiling temperatures are: 0°C for butane, -44°C for propane, – 25°C for liquefied petroleum gas. One liter of liquid butane releases 239 liters of gas (at 15°C - 1 bar); one liter of liquid propane releases 311 liters of gas (at 15°C - 1 bar).

The LPG components have high and constant calorific value. Butane provides a lower gross calorific value (PCI) of 12.66 kWh per kg, propane PCI is 12.78 kWh per kg. Given their high superior calorific power (SCP), butane and propane have 13.7 kWh and 13.8 kWh per kg respectively.

Advantages:

Energy density: LPG contains a high energy density, which means that less gas volume is needed to obtain more energy. This facilitates transportation and storage.

Versatility: LPG can be used for various purposes, including heating, cooking, powering vehicles and generating electricity. Ease of storage and transportation: LPG can be easily compressed to reduce volume, making it convenient to store and transport in liquid form.

Disadvantages:

High freezing temperatures: LPG can freeze at low temperatures, which can cause problems in cold climates. Oil dependence: LPG is produced from oil, so its prices may be subject to fluctuations in global oil markets.

The advantage of LPG is non-toxicity, no corrosiveness, high octane number (102-108). LPG burns much cleaner than gasoline or diesel.

Liquefied natural gas (LNG) is a form of natural gas that has been cooled to very low temperatures - minus 162 degrees Celsius at which it becomes liquid. The liquefaction process takes place in several stages and is quite costly. In vapor phase, natural gas has about three times less calorific value than propane.

LPG is transported under pressure of 10-15 atmospheres. LNG is used in vehicles at a pressure of 200-250 atmospheres. Due to the pressure difference, different cylinders are needed for storage. For LPG, a metal cylinder with a wall thickness of 4-5 mm is sufficient, while for LNG much thicker cylinders with low thermal conductivity are needed.

Advantages:

Environmental friendliness: Liquefied natural gas is considered more environmentally friendly as its combustion produces less carbon dioxide and other pollutants compared to other fuels.

Disadvantages:

Specialist infrastructure needed: Storing and transporting LNG requires specialist infrastructure such as gas liquefaction terminals and tankers.

High infrastructure costs: Constructing and maintaining infrastructure for LNG production, storage and transportation can require significant expenditure.

The above factors make LPG a more promising fuel type for internal combustion engines.

Materials and methods of research. More than 90% of the world's goods by mass and volume are transported by sea [2]. The water transport sector is expected to continue developing in the coming years thanks to investments in the shipbuilding industry and inland waterways in many countries. Diesel engines are the most popular in this sector. According to 2015 WLPGA data, they were installed on 70% of marine vehicles. However, as environmental fuel requirements tighten, maritime transport owners and operators will be forced to seek a more environmentally friendly alternative to fuel oil and other traditional fuels.

To date, LPG is the most common alternative motor fuel in the world [3, 9]. Despite this, propane-butane still cannot gain a foothold in the marine fuel market. Currently, LPG as a bunker fuel is used by recreational and fishing vessels mainly in the US, Chile, Germany, Italy, Spain, UK, Turkey, Northern European countries, as well as in Indonesia. At the same time, there are no large ships worldwide using liquefied gas as motor fuel. The vast majority of tankers are equipped with diesel engines, with natural gas being promoted as an alternative - LNG or CNG.

At the same time, this situation seems a bit illogical. If LPG has become the most popular alternative fuel in the automotive sector, then why can't it occupy the same niche in the water transport sector?

Especially since the International Maritime Organization (IMO) is tightening requirements for ship fuel quality from 2020. The maximum allowable sulfur content will be reduced from the current 3.5% to 0.5%. In addition, stricter environmental standards are already in effect off the coast of North America and in northern Europe – in the North Sea and the Baltic Sea – allowing no more than 0.1% sulfur in fuel oil. It is possible that in a few years, environmental standards for marine fuels will be further tightened, as it happened with gasoline and diesel fuel worldwide.

There is a growing realization in the maritime transport sector that the era of cheap and dirty fuel oil must end and be replaced by a more environmentally friendly fuel. The only question is how quickly this will happen. Against this background, ships using LNG as fuel began to emerge globally. Currently, natural gas is considered the main fuel oil alternative. There are already over a hundred ships running on this type of fuel worldwide, with about a hundred more under construction.

However, the World LPG Association (WLPGA) believes that propane-butane is more attractive for maritime transport than LNG. As the organization's report emphasizes, the transition of ships to LPG requires lower investment costs and, accordingly, has shorter payback periods. Moreover, propane-butane prices are less volatile. Propane-butane, which has proven itself well among motorists, certainly has a number of advantages over its competitors.

Firstly, LPG is an affordable fuel. Its global consumption is still below production volumes. According to WLPGA estimates, the surplus ranges from 15 million to 27 million tons per year. Falling liquefied gas prices in North America caused by the shale revolution are also an important factor that could influence the spread of LPG as a marine fuel.

Indeed, there are no problems with supplies of liquefied gas globally. According to WLPGA, world production of this fuel type in 2015 amounted to 284 million tons, which is equivalent in energy content to approximately 310 million tons of oil. At the same time, global LPG production is growing by about 2% annually. For comparison: fuel consumption in the maritime sector in 2010-2012 was estimated by the International Maritime Organization at 307 million tons. Liquefied gas production is growing fastest in North America and the Middle East. It is important to note that the US, as a result of increased hydrocarbon production from shale, became a net exporter of LPG back in 2012. As noted in the annual report of the large LPG carrier BW Group, LPG production in the US in 2016 amounted to 76.5 million tons (+1.8% over the previous year), while consumption was 54.3 million tons (-1 .5% compared to the previous year). Thus, the propane-butane surplus in the country is about 22 million tons per year.

Secondly, the LPG market has existed for a long time and there is no lack of infrastructure for transporting and storing this type of fuel worldwide, which cannot be said about LNG. In fact, around the world there are storage facilities, export terminals and refineries equipped with loading/unloading equipment for LPG tankers.

Liquefied gas exports from the US continue to grow as the country produces more product than it consumes. Over the next 10 years, according to forecasts by leading world analysts, the United States will become the world leader in oil production. This means that supplies of LPG to the world market will also grow. As a result of production growth, prices for the product in North America have fallen significantly, and this trend may continue, which is beneficial for consumers. The increase in hydrocarbon production in the US in the medium term will restrain world LPG prices, since American liquefied gas is already supplied to major consumers in Asia. After the Panama Canal was reconstructed in 2016, doubling its capacity, it has become even easier and more convenient to supply resources from the Gulf of Mexico to Asia.

According to BW Group, there are currently 244 large-capacity vessels for transporting LPG in refrigerated form (usually at -50°C) with a capacity of about 80 thousand m3 of gas (about 42 thousand tons) in the world. Tankers carrying semi-refrigerated LPG (at -10°C) usually have a capacity of 6 to 12 thousand m3, while propane-butane transported under pressure (about 17 atm) is usually transported in small batches - from 1 to 3 thousand m3. The way of storage is one of the advantages of LPG compared to LNG: it can be stored on board as a non-cryogenic liquid. Moreover, transportation and storage of propane and butane is cheaper since they do not require such low temperatures as LNG, which must be kept at -162° in cryogenic tanks.

Some marine operators and shipbuilders are already considering the possibility of creating and using LPG-powered tankers as the primary fuel. Moreover, there are no technical obstacles to using LPG for ships of various sizes - from ocean liners to small boats.

Most likely, large vessels using LPG as the primary fuel will soon appear on the water, as the relevant technologies are evolving. For example, last year in Tokyo, the design of the new LPG carrier LPGreen was presented, developed by a consortium of companies including Hyundai Heavy Industries (HHI), Wärtsilä Oil & Gas and DNV GL. Its creators sought to design an energy efficient, environmentally friendly vessel for transporting liquefied gas. And reportedly, they succeeded. Fuel cost savings for the LPGreen tanker, which will run on propane-butane, could reach up to 30%.

In addition, in May last year, GE Marine Solutions announced the development of the world's first ferry that will use LPG as its primary fuel. The vessel is intended for the Korean market. A consortium of companies has been working on its creation, in particular Youngung Global, DINTEC, Korea Industry Association, GE Marine Solutions and Far East Ship Design & Engineering Co. It was reported that the LPG ferry is being created both for economic benefits and for improving the environment through low fuel prices and low sulfur oxide emissions.

Recently, vehicle models with electric motors powered by a battery have also begun to emerge, however they use LPG as a source for generating electricity. Riding the wave of fighting air pollution that is gradually engulfing Europe, manufacturers have seen prospects in such hybrids, since "clean" electric vehicles still either have insufficient range per charge, or cost too much. For example, electric trucks have been created in the Netherlands that use LPG to generate electricity and increase range. This involves using an ordinary and perhaps somewhat simplified internal combustion engine that burns gas and charges batteries with electricity.

The same technology can also be used on ships. Its main advantages are low noise levels, as well as fuel cost savings. Quiet electric motors could first be used by military ships, survey ships, cruise ships, etc. As noted in the WLPGA report, ships that mainly move at low speed, with a hybrid engine system, could use 30-35% less fuel than those equipped with traditional internal combustion engines.

In addition, LPG can become the optimal fuel for use in nature reserves as an alternative to traditional types that emit much more exhaust gases. Besides, gasoline and diesel fuel pollute water bodies through fuel spills during refueling, which is excluded when using gas.

Maritime transport is an international industry, as over 80 percent of world trade according to IMO data is carried by ships [10, 11]. Although shipping is the most efficient and reliable means of international transport, it emits several gases and particles into the atmosphere, the most important of which are CO2, NOX and SOX. According to the third greenhouse gas study (IMO, 2014), in 2012 international shipping emitted 796 million tons of CO2, 18.6 million tons of NOX, and 10.6 million tons of SOX. This accounts for approximately 2.2%, 13% and 12% of global emissions of these gases, respectively.

Today LNG as a marine fuel is an available and potential solution for compliance with future air pollution requirements. In addition, the use of LNG to power ship engines is an attractive commercial solution for both new LNG-powered ships and existing ships. There are three main factors that make LNG a real alternative. Firstly, LNG as a marine fuel completely eliminates SOX emissions, reduces NOX emissions by up to 90%, and also minimizes CO2 emissions by about 20%. Secondly, there are a significant number of ships in the shipping industry that use LNG as fuel, as LNG carriers have been using it for several years. LNG carriers use the natural boil-off of LNG stored in their cargo tanks to power their engines. Finally, LNG as a marine fuel is commercially attractive due to its worldwide availability, as LNG stocks will be able to meet marine industry LNG demand in the coming years, as well as its low price compared to the main marine fuel used on board ships. Although it is the low price of natural gas and LNG compared to high sulfur marine fuels, including HFO or IFO, and low sulfur distillates (MDO and MGO) in some markets that makes LNG attractive as a marine fuel. Today in the United States (USA) and Europe (EU) the price of natural gas is much lower than high sulfur fuel oil and low sulfur distillates, while in Asia the price of LNG is higher than high sulfur fuel oil but lower than low distillates sulfur. However, it should be taken into account that natural gas requires infrastructure, as it needs to be liquefied, stored and supplied to ships. For this reason, the low price of natural gas may not translate into a low price for LNG.

However, LNG as a marine fuel faces several challenges: the development of LNG-fueled engines, LNG handling and storage equipment on board, and LNG bunkering infrastructure. Liquefied natural gas engines have already been used on LNG ships but not on other ship types such as ferries, containerships and naval vessels. As a result, engine manufacturers have started developing dual-fuel (DF) engines capable of burning both diesel fuel and LNG. Secondly, LNG needs to be stored at a very low temperature during voyages, for this reason, fuel tanks, pipes and conveying systems must be fitted with insulating alloys capable of keeping LNG at the proper temperature (-162°C). Finally, port facilities for the production, storage and fueling of bunkering stations or vessels are required to reliably and efficiently supply LNG-fueled ships.

LNG-fueled ships are mainly equipped with two types of engines: lean-burn gas engines and dual-fuel engines [12]. Lean-burn gas engines comply with IMO Tier III regulations while dual-fuel engines comply with IMO Tier II regulations when operating in liquid fuel mode and IMO Tier III regulations when operating in gas mode. Currently, the main manufacturers of LNG engines are Wärtsilä, Rolls Royce and MAN, which offer a wide selection of engine designs across all power ranges.

Lean-Burn Gas Engines

Lean-burn gas engines are designed to run on LNG only and operate on the Otto lean burn principle [13]. Lean-burn gas engines are fueled with natural gas through a Gas Valve Unit (GVU) which filters and controls the pressure of the natural gas. The cylinders of a gas engine are fed by separate pipes connected to a main double pipe running along the engine. Gas engines run on a pre-mixed lean air-gas mixture which is ignited in the pre-chamber by a spark plug. The air-gas mixture contains more air than required, resulting in a lower combustion temperature, hence NOx emissions are reduced and efficiency is increased due to higher compression ratios and optimized injection timing.

The air-gas mixture is injected at low pressure (4-5 bar) and is generated outside the cylinder behind the turbocharger. Gas can be supplied directly from LNG fuel tanks under pressure as lean-burn gas engines are low-pressure engines.

In addition, propulsion systems using lean-burn gas engines have two applications: mechanical and electric. In a mechanical scheme, the lean-burn gas engine provides propulsive power to the propellers through gearboxes and shaft lines, while in an electric scheme, generator sets driven by the lean-burn gas engine supply electric motors with electric power to propel the propellers.

Rolls Royce є основним виробником Rolls Royce is the main manufacturer of lean-burn gas engines and has developed a wide range of LNG-fueled propulsion systems with a power range from 1400 to 9400 kW. Rolls Royce lean-burn gas engines operate at medium speeds and are characterized by high efficiency, low operating costs and improved environmental performance resulting in very low emission levels. In addition, Rolls Royce gas engines have high tolerance for gas quality and reduce noise, lube oil consumption and maintenance costs. Rolls Royce has developed two series of lean-burn gas engines, Bergen B and C. The Bergen B series are engines designed for large ferries and Roll On-Roll Off (Ro-Ro) vessels and provide output power from 3500 to 7700 kW. In addition, the Bergen C series is intended for tugs, small ferries and cargo ships and provides output power from 1460 to 2430 kW. Both engine series are available in mechanical and electric versions.

Dual Fuel (DF) Engines

DF engines are designed to operate on both LNG and liquid fuel such as MDO or HFO [14]. DF engines operate on the lean burn Otto principle in gas mode and according to the normal diesel cycle in diesel mode. DF engines operating in gas mode are fueled with natural gas through a GVU which filters and regulates the pressure of the natural gas. The cylinders of the engine are fed by separate pipes connected to a main double pipe running along the engine. When operating in gas mode, DF engines are charged with a pre-mixed lean air-gas mixture which reduces peak combustion temperatures and NOx emissions as the air-gas mixture contains more air than required. 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, as the self-ignition temperature of the air-gas mixture is too high to be achieved by cylinder compression. In four-stroke engines, the air-gas mixture is injected at low pressure (4-5 bar) and is generated outside the cylinder behind the turbocharger. As four-stroke engines are low-pressure engines, natural gas can be supplied directly from LNG fuel tanks under pressure. To ensure minimum NOx emissions, the amount of diesel fuel injected at the end of the compression stroke is very small, usually less than 1% of the total fuel consumption. DF engines utilize micro-pilot injection and an engine speed and load monitoring and control system to optimize combustion.

When DF engines operate in diesel mode, diesel fuel is injected into the combustion chamber at high pressure directly before top dead center. Meanwhile, gas supply is switched off although the micro pilot is activated to ensure reliable pilot ignition when the engine shifts from diesel to gas mode.

DF engines easily switch between modes during operation. Switching from gas to diesel mode takes less than one second and does not affect engine load and speed. In case of LNG supply loss or engine component failure, the transition from gas to diesel mode occurs instantly and automatically. The transition from diesel to gas mode is a gradual process, the supply of diesel fuel is slowly reduced while the amount of natural gas is increased. However, shifting from diesel to gas mode minimally impacts engine load and speed. Although switching between LNG and MDO or vice versa does not require engine modification, switching between LNG and HFO requires minor engine modifications.

MAN is a major DF engine manufacturer although it has developed two-stroke DF engines that slightly differ from four-stroke DF engines. MAN DF engines operate at high pressure, hence they compress air, initiate combustion stroke by injecting fuel oil and inject natural gas into the air-fuel mixture. For this reason, natural gas pressure needs to be high (300 bar) and MAN two-stroke DF engines utilize pumps to boost LNG pressure. MAN DF engines can operate in three different fuel modes: fuel oil only mode, minimum fuel mode and set gas mode. Fuel oil only mode DF engines run on fuel oil only. When operating in minimum fuel mode, DF engines require pilot fuel and natural gas injection into the combustion chamber. The minimum amount of pilot fuel ranges from 5-8% of the total fuel consumption when the engine operates with load from 30% to 100%, and it can use either HFO or MDO as pilot fuel. At engine loads below 30%, stable combustion of natural gas and pilot fuel is not guaranteed. As a result, the engine switches from minimum fuel mode to fuel oil only mode. Finally, set gas mode DF engines allow operators to inject a set amount of natural gas.

In addition, DF engines are mainly represented by two propulsion system schemes: mechanical DF engines and electric DF engines. On the one hand, DF-mechanical engines provide propulsive power to propellers through a gearbox and shaft. On the other hand, electric DF engines supply electric motors with electric power to propel the propellers.

Wärtsilä is a major DF engine manufacturer and has developed a wide range of LNG-fueled propulsion systems with a power range from 0.9 to 18.3 MW. Wärtsilä DF engines operate at speeds ranging from 500 to 1200 rpm and feature fuel flexibility, low exhaust emissions and application flexibility as DF engines can operate either at constant speed as generator sets or at variable speed as mechanical drives. In addition, Wärtsilä DF engines utilize proven and reliable DF technology, an integrated mode switching automation system and provide fuel savings at any engine load. Wärtsilä has developed four DF engine series: Wärtsilä 20DF, Wärtsilä 34DF, Wärtsilä 46DF and Wärtsilä 50DF. The Wärtsilä 20DF is intended for tugs and small cargo vessels and ferries operating as a tug but it is also suitable for a wide range of vessels when operating as a generating set. It provides an output power from 0.9 to 1.6 MW. Secondly, the Wärtsilä 34DF is suitable for a wide range of vessels both as a main engine or generating set. It provides an output power from 2.8 to 8.0 MW. Thirdly, the Wärtsilä 46DF is designed to operate as either a DF-mechanical or DF-electric engine and provides an output power from 6.2 to 18.3 MW. Finally, the Wärtsilä 50DF is intended for large LNG carriers and ferries when operating as the prime mover. It provides an output power from 5.7 to 17.5 MW.

LNG Fuel Tanks and Gas Supply Systems

Due to increasingly stringent air pollution regulations, shipowners started ordering newbuilds and retrofitting their current fleet with LNG-fueled engines as LNG as a marine fuel is considered an available and feasible solution complying with international ship emission restrictions [15]. LNG-fueled engines require a gas fuel supply system and LNG fuel tanks storing the LNG needed to feed them throughout the entire voyage. However, LNG fuel tanks pose some challenges. First of all, LNG fuel tanks require more space compared to HFO storage tanks, in particular they are approximately 2.5 times bigger than HFO tanks. In addition, LNG fuel tanks need to maintain the very low temperature of LNG (-162°C) and minimize boil-off to avoid pressure build-up and as a consequence, they are fitted with insulation measures that also increase tank size.

LNG engine manufacturers have also started developing LNG storage and conveyance systems onboard ships that can supply their engines. Several LNG fuel tank and gas fuel supply system options are available depending on ship size and engine type. According to ship size, large vessels can be fitted with three different tank types although different tank options onboard large vessels require further optimization. On the other hand, small vessels are fitted with Type C vacuum insulated tanks. In addition, gas fuel supply systems differ depending on the working pressure of engines, low pressure engines and high pressure engines. LNG fuel tanks are designed according to the International Code for the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk (IGC code). Moreover, IMO guidelines define the tank types allowed for storing LNG, namely type A, B and C tanks.

On the other hand, small LNG-fueled vessels are fitted with shop fabricated Type C vacuum insulated cryogenic tanks.

The main purpose of gas fuel supply systems is the safe handling of LNG and natural gas onboard ships. This is why the entire LNG supply chain, from shore bunkering stations to engine gas valves, needs to be properly integrated. The design of gas fuel supply systems varies depending on the working pressure of engines. LNG-fueled engine manufacturers have developed two gas fuel supply schemes: one for low pressure engines and another one for high pressure engines. Nevertheless, both gas supply schemes are quite similar in their mode of operation.

On the one hand, gas fuel supply systems for low pressure engines consist of a Pressure Build Up unit (PBU), a product vaporizer, GVU and a control system. Low pressure engines need to be fueled with natural gas at a pressure of 4-5 bar, hence LNG has to be stored at the proper pressure and vaporized. First of all, LNG from shore terminal or LNG bunker vessel is fed through a ship bunker station containing one bunker line, one return line and one nitrogen purging line, all fitted with adequate pressure relief valves. LNG circulates through vacuum insulated lines from the bunker station to the LNG cryogenic fuel tank where it is stored at around 5 bar pressure. Then LNG flows to the PBU whose purpose is to boost storage tank pressure after bunkering and maintain required storage tank pressure. Low pressure engines can achieve maximum power when tank pressure is kept at the required level (5 bar). Furthermore, gas inlet pressure requirements to the engine are met by keeping proper LNG fuel tank pressure since gas fuel supply system is not equipped with cryogenic pumps or compressors. Additionally, LNG flows out of the bottom of the tank into the PBU owing to pressure difference between top and bottom of the tank, then returns to the tank through its top. The natural circulation of LNG between storage tank and PBU ceases once required pressure in tank is achieved. Afterwards LNG is fed to the product vaporizer where it gets converted to natural gas and heated up to at least 0°C depending on engine requirements. Both PBU and product vaporizer utilize engine cooling water system hot water as heat source to boost tank pressure and vaporize LNG accordingly. Finally, natural gas enters the GVU which regulates natural gas pressure according to engine load and ensures safe disconnection of gas fuel supply system. The GVU is located between LNG handling system and LNG-fueled engine and placed inside hull to allow installation in same engine room reducing complexity and installation costs.

On the other hand, gas fuel supply systems for high pressure engines consist of a high pressure LNG pump, pump control system, heat exchanger and buffer tank system. High pressure engines need to be fueled with natural gas at 250-300 bar pressure, hence LNG has to be pressurized and vaporized. The high pressure pump is fed LNG stored in LNG cryogenic fuel tank by means of a pump located in the tank, and is utilized to boost LNG pressure to 200-300 bar and circulate pressurized LNG through a heat exchanger (LNG vaporizer). The heat exchanger utilizes engine cooling water system hot water as heat source to vaporize LNG. Then pressurized natural gas is conveyed to the buffer tank system (natural gas accumulator) where it is stored to feed the engine at a constant natural gas flow rate and pressure.

In essence, the gas fuel supply system stores LNG, converts LNG to natural gas and supplies engines with natural gas under ideal and stable conditions, and it is characterized by enhanced safety and reliability. The main advantages of a compact gas fuel supply system are efficient space utilization, fewer interfaces, reduced capital and operating costs and maximum increase in LNG storage space. Additionally, gas fuel supply system designs offer different configurations allowing installation of several tanks and GVUs depending on ship requirements.

LNG Infrastructure

LNG marine trade constitutes an important segment in global shipping as LNG has been transported as cargo for many years and currently large LNG volumes are transported by LNG carriers [16]. LNG exports from liquefaction and production plants to import terminals supplying local pipeline gas distribution LNG system by LNG carriers is a well-established sector with pricing mechanisms, fixed contract models and proven technology and operations. Additionally, it is regarded as one of the safest segments in the shipping industry. On the other hand, small scale re-export of LNG intended for supplying LNG-fueled vessels from large export or import terminals is not currently a well-oiled sector, although it appears to be an emerging sector owing to recent air pollution regulations reinforcing ship emission limits [17].

Nowadays LNG infrastructure faces two main challenges hindering it from becoming a consolidated market. Firstly, LNG infrastructures require massive investments owing to their high complexity level and necessity to comply with safety standards. The return on investment (ROI) for such infrastructures ranges from years to decades while charter agreements between ship owners and charterers span over a time period of months or in some cases years. As a result, this amortization uncertainty impacts infrastructure development. Secondly, prices for HFO used for conventional bunkering are most updated online while only LNG prices at export and import terminals rather than LNG as marine fuel prices are available online. Due to these reasons a well-established small scale LNG sector will develop once these challenges are overcome.

LNG bunkering facilities refer to all installations required for supplying ships with fuel, in this case LNG, at port and include all elements across LNG value chain. Additionally, key drivers for developing LNG bunkering infrastructure are the following:

- Availability of LNG
- Reliable and safe logistic concepts
- Established legislation and regulatory framework
- Favorable investment climate and tax regime
- Required competencies, know-how and skills
- Public acceptance.

Additionally, LNG bunkering facilities need to ensure safety at all times through: planning, design and operation; safety management; and risk assessments.

Speaking of global LNG infrastructure, five areas can be highlighted: Canada, US, EU, Middle East and Far East. Canada and US are major LNG exporters although they also have a growing demand for LNG as marine fuel. The Middle East is an LNG producer and supplier of LNG as marine fuel. The Far East is a major LNG consumer and could also become an LNG as marine fuel supplier. Finally, the EU is divided into three geographical zones: Northern Europe, Central Europe and Southern Europe. Northern Europe corresponds to European ECA where SOX emissions are limited to 0.1% and hence it is the main driver for LNG as marine fuel usage. In Central Europe, the main driver for LNG as marine fuel usage is reducing NOX emissions from inland navigation vessels. In Southern Europe, LNG bunker capacities could potentially supply vessels sailing the Mediterranean since LNG is available at many import terminals [18, 19].

Examples of using liquefied gas engines demonstrate various applications and advantages within different contexts.

Car/Passenger Ferries

Ferries are designed for transporting passengers and their vehicles, typically on fixed routes across coastal waters such as the Baltic Sea, North Sea, North America and Caribbean Sea United States. Supplying this type of vessels with LNG as marine fuel appears as a feasible option for operational, regulatory and economic reasons (IMO, 2016a). LNG-fueled ferries represent the largest LNG-fueled fleet segment as by March 2016 there were 26 LNG-fueled ferries and 12 LPG-fueled ferries in operation. One of the most popular LNG-fueled ferries is Viking Grace as it is the largest LNG-fueled passenger vessel (Wärtsilä). The Viking Grace is a combined ro-ro and passenger ferry powered by LNG. The ferry was built at STX Turku shipyard (Finland) and was delivered in January 2013. It is operated by Viking Line on a trans-Baltic route between Turku in southwest Finland and Stockholm in Sweden.

Viking Grace is manned by a 200 crew members and has a passenger capacity of 2800 with a total number of 880 cabins. It has a car deck capacity of 1275 lanemeter plus 500 lanemeter on deck 4 and 500 lanemeter on deck 5 for cars. Additionally, the hull was strengthened and hydro-dynamically optimized based on 1A Super ice class to be able to operate in ice waters during Baltic winter.

The vessel is supplied with LNG on a daily basis owing to limited LNG supply at Stockholm port. LNG bunkering operations take place while the vessel is loading or unloading passengers and cargo, and are conducted at sea via an LNG bunker barge, not hindering operational activity. An LNG bunkering takes 45 minutes while loading and unloading takes one hour. Thus, LNG bunkering does not delay vessel schedules. The RoPax ferry operates 21.5 hours a day over 300 days a year (6450 hours a year) [20].

LNG is stored in two vacuum insulated stainless steel fuel tanks of 200 m3 capacity each. The LNGPac system developed by Wärtsilä consists of both the LNG fuel tanks and gas supply system. The LNG storage tanks are located at the stern part of the vessel in an open space above the stern ramp. No cargo space was lost owing to space occupied by tanks.

Platform Supply Vessels (PSV)

PSVs are designed for supplying offshore oil rigs with provisions, household goods and spare parts [21]. Depending on their area of operation, this type of vessels may navigate within an ECA. A significant number of PSVs currently operate in the North Sea and since it is an ECA, they are supplied with LNG as marine fuel (IMO, 2016a). LNG-fueled PSVs represent an important LNG-fueled fleet segment as by March 2016 there were 18 LNG-fueled PSVs and 8 LPG-fueled PSVs. One of the most relevant LNG-fueled PSV currently in operation is Viking Energy as it was the first LNG-fueled PSV.

The Viking Energy is an LNG-fueled platform supply vessel whose hull and superstructure were built at Maritim Shipyard (Poland) then fitted out at Kleven Verft AS Ulsteinvik (Norway). The vessel was delivered in April 2003 and chartered by Statoil for carrying deck cargo to oil and gas platforms in the North Sea. The PSV is homeported in Haugesund (Norway).

Viking Energy's propulsion system is designed based on DF-electric concept. The PSV is fitted with four 6-cylinder Wärtsilä 6L32DF engines with an output power of 2010 kW each (total output power 8040 kW). The four Wärtsilä engines drive four main generator sets feeding two contra-rotating aft thrusters of 3000 kW each (total propulsive power 6000 kW) and other services with electric power.

Additionally, Viking Energy is fitted with two 1000 kW bow thrusters, one 880 kW retractable azimuth thruster and one 116 kW emergency generator. The marine engines develop a service speed of 16 knots at full load condition and this type of power drives minimize noise and vibrations.

LNG is stored in a horizontal cylindrical tank with domed ends made of stainless steel consisting of an inner and outer chamber insulating the LNG at -162°C. The storage tank is located amidships and has an effective fuel capacity of 220 m3. Additionally, the tank is placed in a compartment protected with fire insulation and gas lines and valves enclosed in ventilated enclosures (Wärtsilä, n.d.-c).

LNG Carriers.

LNG carriers are designed for transporting liquefied gases such as natural gas, petroleum gas and ethylene among others [22]. LNG carriers utilize the natural boil-off of LNG stored in their cargo tanks to power their steam turbines. However, new LNG carriers are fitted with DF engines allowing them to operate on both LNG and other marine fuel. LNG-fueled LNG carriers represent a significant LNG-fueled fleet segment as by March 2016 there were 7 LNG-fueled LNG carriers and 12 LPG-fueled LNG carriers in operation. The two most relevant LNG-fueled LNG carriers currently in operation are Coral Energy, which was the first LNG-fueled LNG carrier fitted with DF engines; and Coral Star, which was the first liquefied ethylene gas (LEG) carrier powered by LNG and fitted with DF engines.

The Coral Star is a LEG carrier fitted with DF-mechanical propulsion. The LNG carrier was built by AVIC Dingheng Shipbuilding Co., Ltd. (China) and was delivered in July 2014. The vessel carries LEG from SABIC Wilton plant at Teesside (UK) to manufacturing plants in Northwest Europe and Scandinavia.

Coral Star’s propulsion system is designed based on DF-mechanical concept. The LNG carrier is fitted with one 6-cylinder Wärtsilä 6L34DF engine with an output power of 2700 kW at 750 rpm. The main propulsion engine drives a CPP through a gearbox. Additionally, Coral Energy is fitted with a 450 kW bow thruster and two 6-cylinder Wärtsilä 6L20DF generating set engines with an output power of 1056 kW each driving generators. The vessel engine develops an average speed of 13.5 knots. LNG is stored in two deck-mounted fuel tanks with an LNG capacity of 100 m3 each.

Containership.

Containerships are designed for transporting cargo packed into containers and are usually operated in liner trade [6, 23]. This type of vessels has a wide choice of sizes ranging from small feeders to ultra large container carriers and LNG-fueled containership designs have started to grow in LNG-fueled vessel market. Nevertheless, LNG fuel tank size seems to be a major issue for large container carriers due to loss of cargo space resulting from their larger size.

LNG-fueled containerships constitute a potential segment in LNG-fueled fleet as by March 2016 there were 2 LNG-fueled containerships and 13 LPG-fueled containerships in operation. One of the most relevant LNG-fueled containerships is Isla Bella as it was the first LNG-fueled containership.

The Isla Bella is a DF-propelled LNG-fueled containership. The containership was built at General Dynamics NASSCO (USA) along with sister-ship Perla del Caribe and was delivered in October 2015. It is operated by Sea Star Line covering a route from Jacksonville (Florida) to San Juan (Puerto Rico). Both vessels were built to cover this Puerto Rican trade lane and replace company vessels serving this route. Isla Bella has a cargo capacity of 3100 twenty-foot equivalent units (TEUs) and its optimized design allows increased cargo capacity compared to predecessor vessels. Additionally, the containership is able to transport a large volume of refrigerated containers.

Isla Bella’s propulsion system is designed based on DF-mechanical concept. The containership is fitted with one 8-cylinder MAN 8L70ME-C8.2-GI engine with an output power of 25,191 kW at 104 rpm driving a propeller through a gearbox. Additionally, Isla Bella is fitted with three 1,740 kW HFJ7 638-10P auxiliary engines each. The vessel engine develops an average speed of 22.0 knots.

LNG is stored in two stainless steel cryogenic tanks with a total capacity of 900 m3 located at the stern part of the vessel. Bunkering is conducted while the vessel carries out cargo operations and takes place from shore through several LNG bunker barges.

After analyzing the main LNG-fueled vessel segments, some important conclusions can be drawn. LNG-fueled ships represent a growing market, driven by strict air pollution regulations; widespread development of LNG-fueled engines, fuel tanks and gas supply systems; and future LNG infrastructure projects. Indeed, significant LNG market growth is expected over the next decade, although external factors like LNG price and availability could impact it. Today, the main segments dominating the LNG-fueled fleet are car/passenger ferries, PSVs, harbor tugs, LNG carriers and containerships. Comparing the dominant LNG-fueled vessel segments highlights the following:

- Regardless of vessel type, LNG-fueled vessels operate in liner trade covering pre-agreed routes and spend most of their time inside ECAs or shuttle between ports located in ECAs.
- Most LNG-fueled vessels (car/passenger ferries, PSVs, LNG carriers and containerships) are fitted with DF engines allowing them to continue operation in case of LNG unavailability.
- Harbor tugs constitute a unique analyzed segment fitted with lean-burn gas engines as they only operate in ports where LNG is available.

- LNG-fueled vessels that shuttle short routes, have variable engine load and frequently port in and out are designed according to DF-electric concept such as car/passenger ferries and PSVs.
- LNG-fueled vessels operating longer routes and constant engine load are designed according to DF-mechanical concept such as LNG carriers and containerships.
- All analyzed LNG-fueled vessel segments are equipped with Type C vacuum insulated tanks, with the exception of LNG carriers as they utilize LNG stored in their cargo tanks.
- Bunkering operations are usually conducted by trucks indicating that currently small LNG volumes are transported to feed LNG-fueled engines.
- LNG bunkering operations take place concurrently with loading/unloading in order not to delay vessel schedule and minimize port stay.

All vessel types are capable of using LNG but certain vessel segments have higher potential depending on several features [23]. After analyzing them, several conclusions regarding LNG-fueled vessel potential can be drawn. Firstly, LNG as a marine fuel is available for both new LNG-fueled vessels and existing vessels although most LNG-fueled vessels are newbuilds since retrofitting existing vessels requires massive investments and implies major modifications in engine room. Secondly, domestic vessels and vessels serving SSS routes spend most of their time inside ECAs so ferries, tugs, PSVs and containerships are more likely to fuel their engines with LNG. Thirdly, vessels operating in areas where LNG infrastructure availability and LNG pricing lower than conventional marine fuel are guaranteed constitute potential LNG consumers to feed their engines. Then vessels sailing a fixed route with LNG bunkering facilities at homeport, ports of call or destination port are totally eligible for LNG supply. Additionally, vessel segments like cruise liners, passenger vessels and PSVs which are constrained to preserve green values or exploit sustainability bonuses require an environmentally friendly solution to minimize emissions such as LNG as marine fuel. Finally, when assessing financial viability of LNG-fueled vessels, equipment costs, operation time inside ECA and LNG pricing are taken into consideration.

Opportunities Ahead:

Engines will continue getting cleaner and more efficient following the progress of automotive and land-based industrial models.

The use of steam turbines, formerly preferred, is no longer popular for new builds owing to system complexity and low efficiency. Even the LNG sector is looking for new engine schemes to eliminate the need for outdated power stations. This leaves the competitive landscape wide open for diesel and gas turbines. No one can accurately determine which method is superior, however gas turbines have more advantages, yet the diesel engine is more reliable, with good maintainability characteristics.

Marine turbines use marine diesel fuel as fuel, and to take a step closer to the future, new fuel resources need to be opted for ensuring a clean and efficient shipping industry. Liquefied gas, CNG and hydrogen resources are candidates for this operation [24]. The shift towards using liquefied gas as a marine fuel will start to gain momentum with the introduction of new environmental regulations and expansion of bunkering capabilities.

Gaseous fuel will become the dominant fuel source for all trading vessels within 40 years The reason for such growth is the stringent emission standards requiring reductions of sulphur oxides (SOX) and nitrogen oxides (NOX). LPG/LNG, in addition, is becoming cheaper.

Conclusions and prospects for further work in this area. The final conclusions made in the paper regarding the use of LNG/LPG as marine fuel are explained as follows:

Maritime transport faces an alarming situation regarding air pollution owing to high ship emission levels provoking global atmospheric warming, environmental degradation, dense air pollution in cities located near major harbors and serious health issues, among others.

Due to the projected increase in global maritime trade driven by world population growth, ship emissions are expected to rise even further highlighting the need to develop a comprehensive regulatory framework significantly curbing ship emissions.

IMO along with other European bodies adopted regulations aimed at cutting ship emissions. These requirements reduced CO2 emissions by around 20-30%, NOX emissions by 80% and SOX and PM emissions by 95-98%.

LNG as marine fuel complies with current air pollution regulations, has been used onboard vessels for decades and is lower priced compared to other marine fuels. However, insufficient availability of LNG bunkering facilities distributed around high shipping activity areas and LNG price uncertainty in the future are major drawbacks for the use of LNG as marine fuel.

Nowadays the use of LNG as marine fuel is a technically feasible solution since manufacturers have designed and developed a wide range of liquefied natural gas fueled engines (lean-burn gas engines and DF engines), Type C vacuum insulated tanks and gas supply systems.

Lack of LNG bunkering installations due to massive investments and LNG not being established in the market yet hinders the use of LNG as shipping fuel in the maritime sector. Nevertheless, adoption of new air pollution regulations has stimulated LNG infrastructure project proposals and planning.

Regulations for gas-fueled ships have been developed to provide clear guidance regarding design and equipment of gas-fueled ships able to mitigate risks to ship, crew and environment.

Car/passenger ferries constitute the dominant LNG-fueled vessel segment followed by PSVs, LNG carriers and harbor tugs. Additionally, containerships represent a potential LNG-fueled vessel segment.

Regardless of LNG-fueled vessel segment, LNG-fueled vessels operate on fixed routes and spend most of their time inside ECAs or navigate between ports located within ECAs.

Most LNG-fueled vessels are fitted with DF engines. Indeed, propulsion systems of vessels with variable engine load engaged in short routes (car/passenger ferries and PSVs) are designed based on DF-electric concept while propulsion systems of vessels with steady engine load deployed on longer routes (LNG carriers and containerships) are designed based on DF-mechanical concept.

LNG-fueled vessel potential relies mainly on features like: newbuilds, operation time inside ECA, operational areas with LNG availability, LNG pricing, liner vessels and green profile. As a result, according to key LNG-fueled vessel segments, car/passenger ferries navigating the North and Baltic Seas have high potential for LNG utilization as marine fuel since their features match those mentioned above.

Current air pollution regulations greatly minimize NOX, SOX and PM emissions from vessels even though CO2 emissions are not sufficiently reduced and still constitute an environmental issue needing to be addressed. Policy makers need to tackle this problem rigorously and introduce stringent mitigation measures.

IMO along with MEPC will introduce measures aimed at enhancing ship energy efficiency and reducing greenhouse gas emissions although these are not stringent mitigation measures. The overall objective of these requirements is gathering and sharing reliable information on how to address ship energy efficiency and GHG emissions issue.

State-of-the-art emission reduction technologies for improving ship energy efficiency and decreasing greenhouse gas emissions do not totally diminish CO2 emissions, they just provide minor enhancements for different ship areas and components resulting in slight advantages regarding ship environmental performance. Only when a combination of technical improvements is implemented across various ship parts can some CO2 emissions reduction be attained.

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Ольга Петриченко[1] , Максим Левінський[2],

[1]Кандидат технічних наук, доцент кафедри теорії і устрою судна, Національний університет «Одеська морська академія», 8, вул..Дідрихсона., Одеса, 65052, Україна. ORCID: https://orcid.org/0000-0002-4893-8204.

[2]Кандидат технічних наук, доцент кафедри теорії автоматичного управління та обчислювальної техніки, начальник відділу іноземних студентів Національного університету "Одеська морська академія", вул. Дідріксона, 8, м. Одеса, 65052, Україна. ORCID: https://orcid.org/0000-0002-6544-5110.

Тенденції та передумови для широкого поширення використання рідкого природного газу у морському транспорті

Потреба в стійкому та екологічно чистому морському транспорті та введення регулятив Міжнародної морської організації (ММО) з викидів суден привели до пошуку нового типу морського палива. Сьогодні рідкий природний газ (РПГ) як морське паливо є привабливою, потенційно важливою та технічно можливою опцією для нових суден, які будуються для відповідності нормам забруднення повітря. Метою роботи було проаналізувати перспективи використання РПГ як морського палива. Задачу вдалося виконати за допомогою вивчення поточного стану перевезення РПГ, аналізу переваг та недоліків різних видів палива та вивчення домінуючих сегментів суден на РПГ. Впровадження РПГ на борту суден відбувається разом із розвитком РПГ-двигунів, їх систем управління та захисту, паливних баків, систем постачання газу та інфраструктури. Прогнозується, що протягом наступного десятиліття кількість суден, які працюють на РПГ, буде швидко зростати. Об'єктом дослідження є перспективи використання РПГ як альтернативного типу палива у судноплавстві. Найважливішим результатом є висновок, що РПГ має значний потенціал як альтернатива традиційним видам палива у судноплавстві, але для цього потрібен розвиток відповідної інфраструктури.

***Ключові слова**: LNG, морське паливо, викиди, екологічна безпека, альтернативне паливо, двигуни.*