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Representative application of LNG-fuelled ships: a critical overview on potential GHG emission reductions and economic benefits

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Review paper

Summary

The shipping industry is the primary and most significant mode of international cargo transportation. The ship must comply with strict rules regarding reducing greenhouse gas (GHG) emissions as a dominant transportation mode. Liquified Natural Gas (LNG) is the primary alternative fuel option for several shipping companies. In essence, many studies recommend LNG as a transitional and alternative fuel because its emission characteristics are cleaner than other fossil fuels. Several previous investigations have been carried out to develop an action plan for integrating the use of LNG as a ship fuel. However, there have been few discussions on the estimation of GHG emission reduction and the economic efficiency of a representative LNG-fuelled ship. The recent progress on LNG-fuelled ships is systematically reviewed to summarize the pathways and highlight the core technological concepts, technical issues, current LNG-fuelled ship applications, and future outlooks regarding integrating LNG energy resources into ship power systems to measure GHG emission reductions and cost savings estimations. The report will discuss the current development in the maritime sector and the effects of the macroeconomic scale. The result reveals that future research on ship-based LNG energy systems will probably concentrate on integrating new energy source generating strategies with existing ship power systems to improve energy efficiency. Several potential research areas for future outlook were also discussed to anticipate future challenges.

Keywords: Marine alternative fuel; LNG-fuelled ship; GHG emission; economic benefit

1. Introduction

Maritime transportation is essential to international trade and the global economy. For centuries, shipping has served as a trade link between countries, transporting goods such as natural resources and industrial products. Over 80% of international trade in goods is carried by sea, which is even higher in most developing countries [1]. Sea transportation is recognized as an effective energy-efficiencies mode of transportation compared to other modes based on the fuel consumption ratio per goods moved [2]. The marine industry seems to have survived the Covid-19 disruption in 2020, with a lesser impact than anticipated, despite the Covid-19 pandemic's devastating effects on global trade, economies, and many industries. Volumes fell less dramatically than expected and had recovered by the end of 2020, laying the groundwork for a major transformation in global supply chains and new maritime trade patterns to emerge in 2021 [3].

The global economy's dependence on the shipping sector must be paid for by CO_2 emissions that are detrimental to the environment. In 2018, shipping activities produced 1056 million tons of CO_2 emissions, or around 2.89% of anthropogenic CO_2 emissions [4]. Although the value of CO_2 emissions from sea transportation is not as much as that generated from land transportation, reducing shipping emissions has become a severe concern for several countries. China has set a target to become carbon neutral by 2060, and the United States (US) aims to reduce GHG emissions by 50% by 2030 compared to 2005. Japan and Canada have the same goal of 40-45% reduction, while the European Union (EU) will reduce emissions by 55% in 2030 compared to 1990 and become neutral by 2050 [5]. Meanwhile, International Maritime Organization (IMO) has set a target to reduce shipping emissions by at least 50% by 2050 compared to 2008 [6]. Achieving the 50% reduction target of shipping emissions by 2050 requires a mix of technical, operational, and innovative solutions that can be applied to ships.

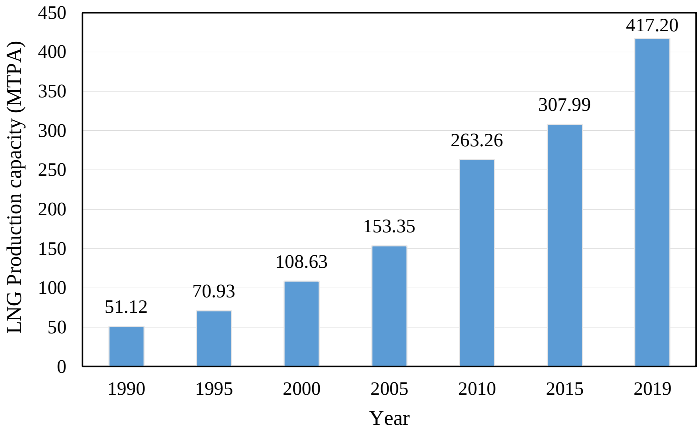
There are numerous ways to decrease emissions in the maritime sector. Decarbonization may be fueled by increased efficiency, such as the energy efficiency design index (EEDI), and the use of alternative fuels. Table 1 presents the solutions recommended by IMO, along with their estimation of potential GHG reduction rates on ships [7]. In general, three aspects of the solution are offered: improving ship's efficiency, optimizing ship's operationand converting to alternative fuels: low-emisson fuels, zero-emisson fuels or carbon neutral fuels.. Based on the data, several alternative fuels, such as hydrogen, biofuel, bio LNG(Liqified Natutal Gas)/LPG(Liqufied Petroleum Gas), and systhetic fuel, can be used as a solution to reducing GHG emissions.

Table 1. Several offered solutions to reduce GHG emissions on the ship [7]

No	Solutions offered	Solution aspect	Potential GHG emission reduction rate
1	Power and propulsion system	Ship's efficiency	5 – 15%
2	Fleet management, logistics, and incentives		5 – 50%
3	Trade route optimization		1 – 10%
4	Concept, speed, and capability		2 – 50%
5	Speed optimization		up to 75%
6	Ship superstructure		2 – 20%
7	Energy Management		1 – 10%
8	Hydrogen and other synthetic fuels	Ship's fuel	80 – 100%
9	Third generation biofuels		90%
10	Bio-LNG/LPG		35%
11	Electric battery		50 – 90%

Several alternative fuels are currently available for the shipping industry. As the primary fuel, LNG is one of the alternative fuels. One of the driving forces behind the push for LNG can be attributed to the IMO's stringent environmental regulations. Since January 2020, sulfur content limit in marine fuel, consumed on ship operating area, excludeing sulfur Emisson Control Area (S-ECA, sulfur content limit is 0.1%), became restricted from 3.5% to 0.5% as global cap. This regulation change has drived Exhaust Gas Cleaning System (EGCS) installation, fuel convertion to low sulfur petroileum fuel, or conversion to LNG. In addition, LNG .production in the world is increasing by an average of 2.1% per year, while consumption as natural gas is growing by 1.7% per year. The increase suggests that until zero-emission fuel technologies are developed and deployed, the use of LNG in the maritime sector as an alternative to marine gas oil (MGO) or heavy fuel oil (HFO) could be of substantial benefit [9].

The use of LNG offers significant economic and environmental opportunities and is expected to become the primary ship fuel by 2030 [10]. LNG is clear, odourless, non-corrosive, non-toxic, however, because LNG must be stored less than -260.0°F, it is difficult to store and transport , to require insulated storage tank. And LNG is less explosive or flammable in the liquid phase, however, natural gas boiled off from LNG cause an explosion [11]. As global oil reserves decline, global LNG production increases. In 2019, LNG production reached 419 million tons of LNG per annum (MTPA), with 37% in Asia-Pacific and 24% in the Middle East [12]. Fig. 1a describes the global LNG production capacity, which has continued to increase since 1990, and Fig. 1b presents data on LNG production capacity based on different regions in 2019.



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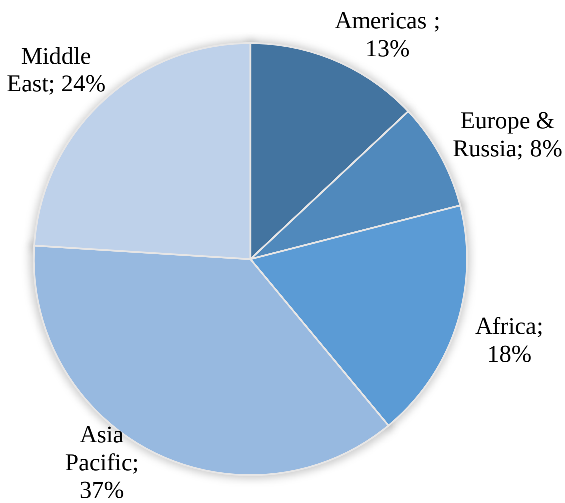

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Fig. 1. a) Dynamics of world LNG production capacities, b) Shares of regions in the global production capacity of LNG in 2019 (redrawn from Merkulov et al. [12].

Recently, studies on LNG-fueled ship have published , whose type is only LNG carrier (LNG as cargo and fuel) but also cargo ship without loading LNG and passanger ship (LNG as only fuel) , and a few applications have been put into practice. The first 100% LNG-fuelled vessel, MV. Glutra was launched in 2000. This car ferry was first operated in Norway under the auspices of the company "Fjord Line" with Det Norske Veritas (DNV) as a ship classification society [13]. Following that, DNV published the first regulations for gas-powered vessels in 2001 [14]. In 2022 there were 175 LNG-fuelled vessels in operation [15]. IMO specifically issued the adoption of the international code of safety for ships using gases or other low – flashpoint fuels (IGS code), which regulates the use of gas fuels for ships [16,17].

An extensive collection of literature examines the possibility of cleaner alternative fuels for the maritime transport industry, cutting-edge technologies, actions, and the potential for decreasing GHG emissions from shipping. This study adds to previous work by providing a comprehensive database of potential GHG emissions on the recent application of LNG-fuelled ships. The current work will qualitatively and quantitatively analyze and assess the developmental trends and the latest progress in using LNG as a ship's fuel. The systematic review will be highlighted in several discussions. The investigation will focus on the design consideration of LNG-fuelled ships, the recent development of LNG-fuelled vessels from the perspective of potential GHG reduction, and the economic benefit of implementing LNG as a ship's fuel based on the philosophy of maritime industries. The future challenge and potential development of LNG-fuelled vessels will be discussed further.

2. LNG-fuelled Ship Design Concepts

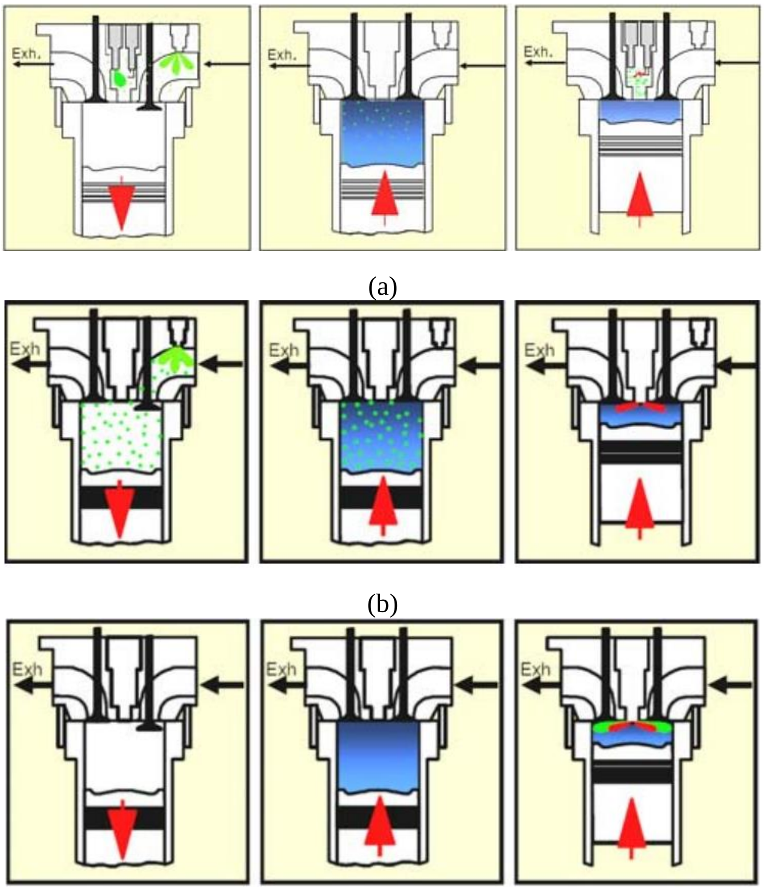
This section will briefly discuss the design consideration of LNG-fuelled ships. Several discussions will be presented in several subsections, such as a review of different LNG engine configurations, machinery space arrangement, bunker tank arrangement, and LNG tank types.

2.1.1 LNG-fuelled ship engine configuration

In general, LNG-fuelled ship engines are divided into two categories, modified diesel engines with the installation of a conversion kit and engines explicitly designed for LNG fuel. Conversion kits convert a diesel engine to run on LNG, which generally requires a special fuel management system. All fuel lines, valves, and vaporizers must be cryogenic [18]. Meanwhile, marine gas engines are divided into three different types such as [19]:

- Lean burn spark ignited (LBSI), also known as Otto cycle engine, is the most common choice when the diesel engine is modified to operate on gas fuel due to some special requirements for marine applications, as seen in Fig. 2a [19,20].
- Dual fuel (DF) engine or diesel-ignited gas engine operating as an Otto cycle on gas and a diesel cycle on diesel or HFO, this type of engine was the first to establish itself in the marine industry and is currently the dominant engine type in today's market, as depicted in Fig. 2(b) [19]. DF engine can be divided into three types: low-pressure dual-fuel 4-stroke (LPDF 4-stroke), High-pressure dual fuel 2-stroke (HPDF 2-stroke), and low-pressure dual-fuel 2-stroke (LPDF 2-stroke). LBSI and LPDF 4-stroke engines are commonly used in smaller ships, whereas HPDF and LPDF 2-stroke engines are commonly used in larger vessels such as LNG carriers.
- Multi-fuel gas diesel (GD) engine cycle, also called direct gas injection engine, operates in a standard diesel cycle where gas is injected directly into the cylinder at the end of compression. The ignition is triggered by a small amount of diesel fuel capable of operating on LNG or MDO, and its use in the shipping industry is auspicious. However, so far, the

application is still limited [19]. Schematic illustration of multi-fuel gas diesel is illustrated in Fig. 2c.



(c)

Fig. 2. Type of marine gas engine: (a) lean burn spark ignited (LBSI), (b) dual fuel (DF) engine, (c) multi-fuel gas diesel (GD) [19].

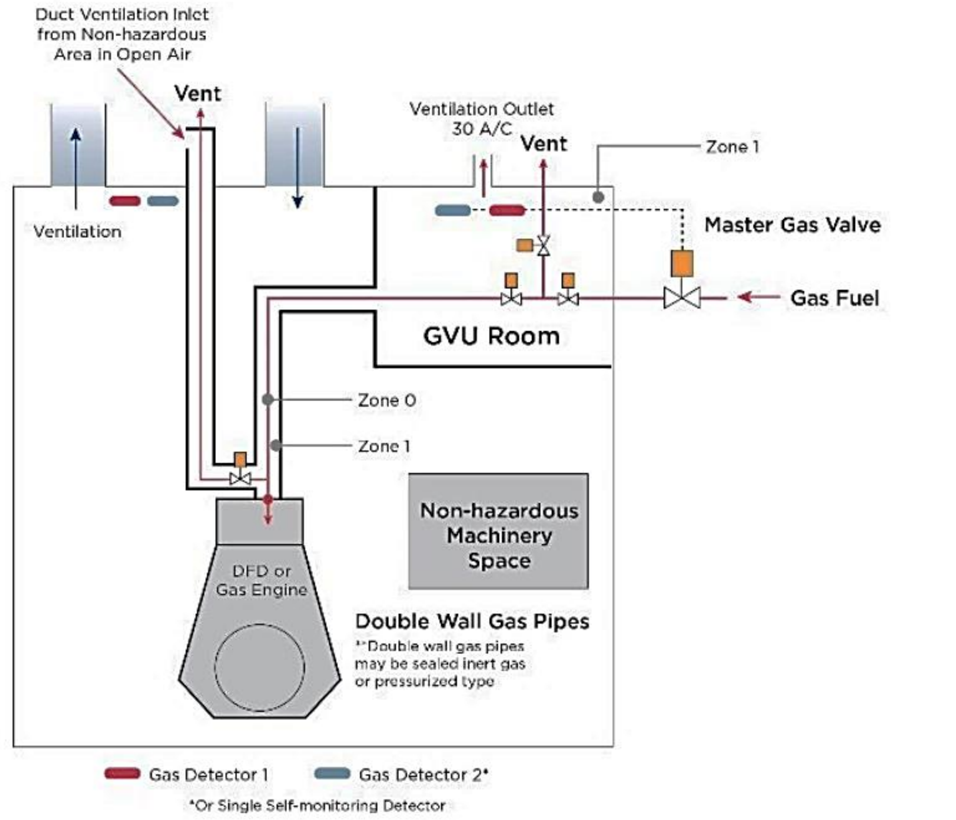
2.1.2 Machinery space arrangement

LNG-fuelled ships require a special space for the placement of their supporting components. LNG-fuelled ships usually have several components: gas/dual gas engine/dual fuel boiler, LNG fuel storage tank, LNG vaporizer, LNG gas heater, , tank safety, line safety valves, water-glycol heating system, nitrogen generator, nitrogen holding tank, gas detection system, ventilation system, gas valves unit, electrical equipment in the hazardous area, and ventilation system [21].

To handle LNG with flammable and explosive properties IMO stipulates the existence of an emergency shutdown (ESD) [16]. The emergency shutdown-protected engine space concept introduces additional measures to provide a level of security equivalent to that of a non-hazardous conventional engine room [17]. Another concept besides ESD is the non-hazardous machinery concept. The idea behind the engine compartment is to use numerous barriers for all gas-containing parts to prevent the leakage of gaseous fuel into the chamber in the event of a single barrier failure [17].

The fundamental difference between the two ideas of the machinery space is shown in Fig. 3. a) of Fig. 3 depicts the "International Code of Safety for ships using Gas or Other Low-Flashpoint Fuels " (IGF code) non-hazardous machinery concept, and b) of Fig. 3 presents the

IGF ESD machinery space concept with the non-hazardous machinery also has a view of the gas valve unit (GVU) room. It may be a separate location outside the machinery space, or it may be a GVU unit. This self-contained unit serves as an extension of the double barrier pipe system and may be installed inside the non-hazardous equipment space [17].



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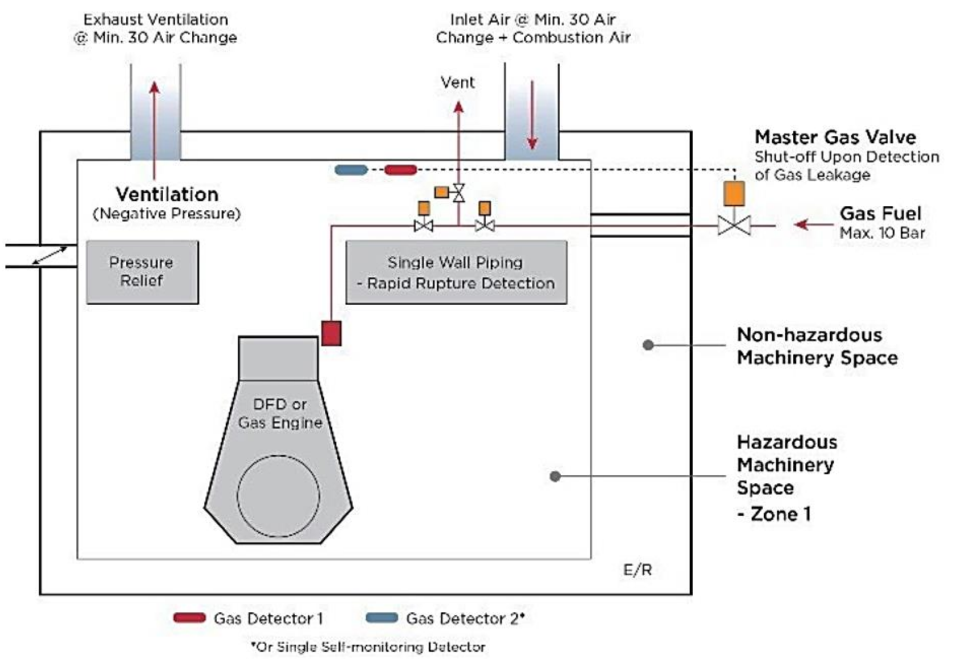

(b)

Fig. 3. a) IGF non-hazardous machinery concept, b) IGF ESD machinery space concept [17].

2.1.3 LNG bunker tank location arrangement

Besides machinery space arrangement, determining the location of the LNG bunker tank is also a major consideration in the arrangement of LNG-fuelled vessels. LNG must be stored in 260.0^{o}F, and has lower density than the conventional fuels, therefore, LNG fuel tank must be insulated and larger space to install the tank is required. The protective LNG tank location criteria can be based on a deterministic approach considering tank volume or probabilistic methods [17]. In general, the position of the LNG tank is divided into two categories, inside the hull, and outside the hull. The configuration and regulation of the LNG bunker tank in the hull are regulated in the IGF [16]. Fig. 4 shows several examples of LNG bunker tank configurations on several ships, such as anchor handlers, passenger ferries, container carriers, cruise ships, oil tankers, and ro-ro vessels. In the case of converting conventional-fuelled vessels into LNG-fuelled vessels, the placement of LNG bunker tanks is generally outside the deck. Usually, two or three saddle supports are required to install the LNG tank longitudinally to prevent bending moments and deflections due to hull shagging and hogging moments [22]. The calculation of the strength on the saddle takes into account the force loads around the LNG bunker tank, namely cargo load, structural weight, pressure of sea water, tank momentum, and load during the test [23].

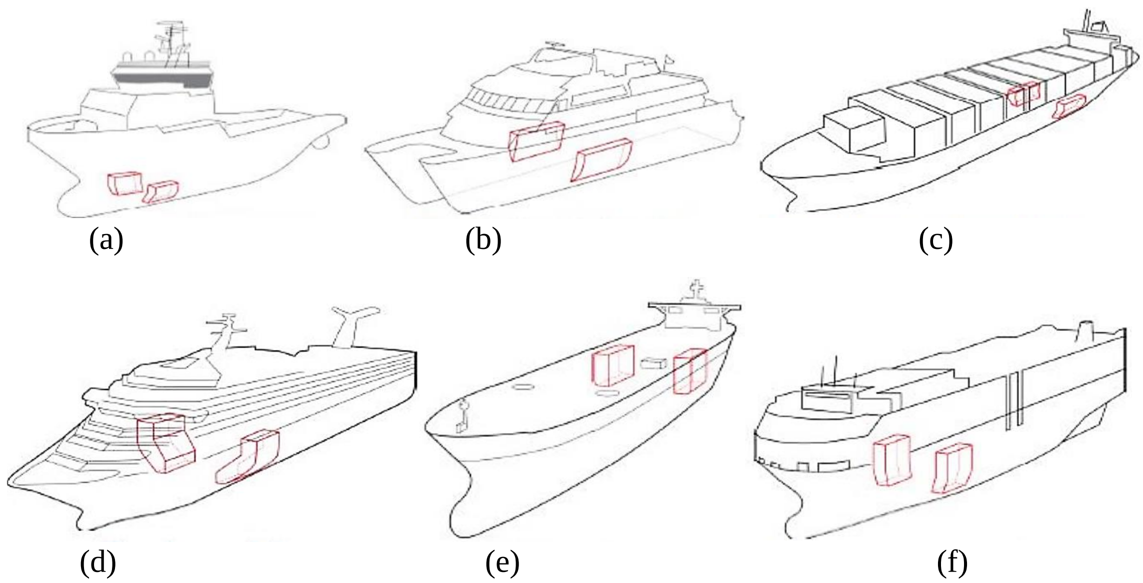

Fig. 4. Design tank location of LNG bunker inside the hull a) anchor handlers, b) passenger ferries, c) container carriers, d) cruise ships, e) oil tankers, f) ro-ro vessels [22].

2.1.4 LNG tank types

The bunker tank must be designed to avoid leakage as an LNG storage place. There are four types of gas tanks, including membranes tanks, Type A, Type B, and Type C. Type B tanks are further divided into moss tanks (spherical) and SPB tanks (prismatic) [24]. Table 2 summarizes feature comparison of the four types of LNG tank [17,25,26]. According to Table 2, a Type C tank is one that has been demonstrated to be utilized for LNG fuel bunker tanks and can be fitted both outside and inside the ship's hull. This fact is due to a more straightforward design and higher flexibility.

Table 2. Comparison of different LNG tank types

Parameters	**Type A**	**Type B**	**Type C**	**Membrane**
Barrier	Full secondary barrier	Partial secondary barrier	No barrier	Full secondary barrier
Self-supporting	Independent self-supporting	Independent self-supporting	Independent self-supporting	Non-self-supporting
Pressurize condition	Fully refrigerated at atmospheric pressure	Fully refrigerated at atmospheric pressure	Pressurized at ambient temperature or lower temperature	Fully refrigerated at atmospheric pressure
Capability to retain boil-off Inside the Tank	Can not withstand the pressure developed by the boil-off for a long time	Design pressure is not higher than 0 7 bar and cannot withstand the pressure developed by the boil-off for a long time	High-pressure accumulation capability; e g LNG tanks 10 bar and LPG 18 bar	Design pressure is not higher than 0 7 bar and cannot withstand the pressure developed by the boil-off for a long time
Design vapour pressure	< 0.07 MPa	< 0.07 MPa	High pressure	≤ 0.025 MPa
Records of gas-fuelled ship	Nil	Nil (under consideration)	good	nil
Features	Good volume efficiency (prismatic tank)	Volume efficiency spherical: low, prismatic: good	• Simple design & construction • The flexibility of working pressure • Low volume efficiency	• Good volume efficiency • Sloshing concern

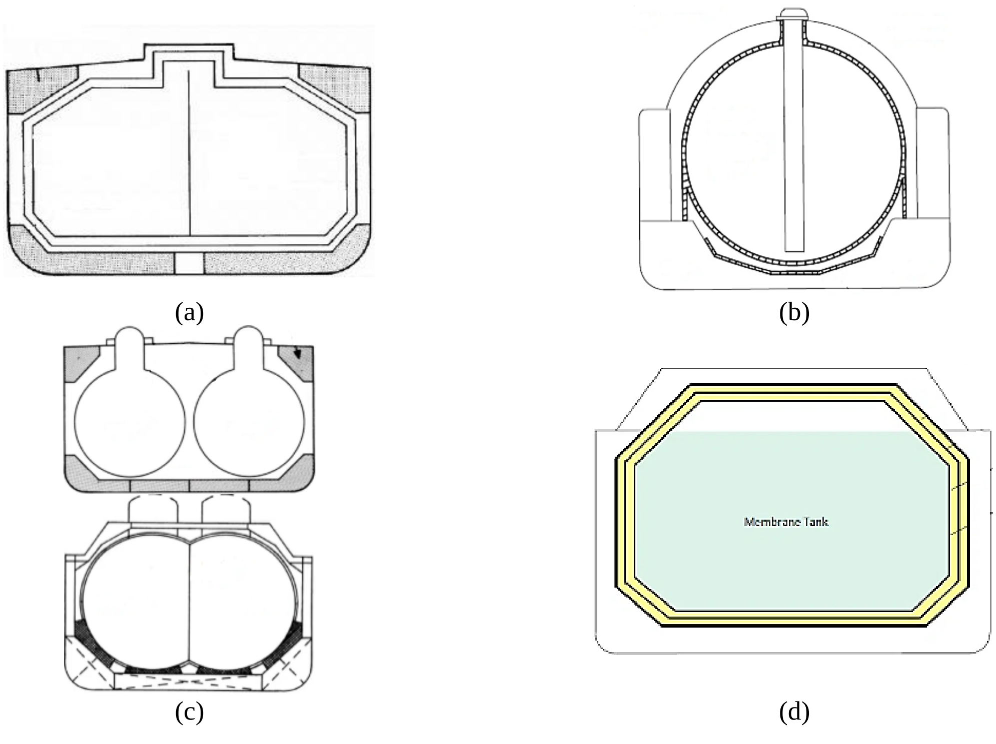

Fig. 5. Type of LNG storage tank a) Type A and type B (prismatic), b) Type B (spherical), c) Type C, Type membrane tanks [27].

3. LNG-Fuelled Ship on GHG Reductions and Economic Benefits

This section will review the potential of GHG reduction and the economic feasibility of the current implementation of LNG-fuelled ships. The discussion is separated into two different sections. Section 3.1 will highlight the GHG reduction estimation of current LNG-fuelled ship projects, and Section 3.2 will discuss the economic evaluation of the current implementation of LNG-fuelled ships.

3.1 Recent progress of LNG-fuelled ships on potential GHG reduction

Maritime transport accounts for approximately 2.5% of global greenhouse gas emissions, or around 1000 million tons of CO_2 annually. The situation of shipping emissions, which are heavily dependent on future economic growth, is exacerbated by the fact that global GHG emissions are expected to rise by 50 to 250% by 2050. During IMO's 72nd Marine Environment Protection Committee (MEPC) held from April 9 to 13, 2018, a new long-term strategy for reducing GHG emissions from ships was defined. According to IMO's official statement: "*The vision confirms IMO's commitment to reducing GHG emissions from international shipping and, as a matter of urgency, aims to phase them out as soon as possible in this century. More specifically, under the identified levels of ambition, the initial strategy envisages for the first time a reduction in total GHG emissions from international shipping, which should peak as soon as possible and reduce the total annual GHG emissions by at least 50% by 2050 compared to 2008, while, at the same time, pursuing efforts towards phasing them out entirely*." Since IMO issued a target to reduce GHG emissions from shipping by 50% by 2050, there has been a lot of research and development of fully LNG-powered and the conversion of LNG-fuelled vessels. LNG carrier ships have used evaporated gas (boil-off gas/BOG) as fuel since 1964. It was thought to use natural gas as the primary fuel for ships [28]. In general, there are two arguments for the development of LNG as a ship's fuel: the first argument relates to the short-term benefits of LNG as a single energy source, and the second argument relates to increasing the ability of dual-fuel engines (LNG and non-LNG) to reduce emissions as low as possible [29].

With a nearly 98%, 86%, 11%, and 96% reduction in SOx, NOx, CO_2, and PM pollution, respectively, LNG is the best alternative for reducing GHG emissions and should be used by newly constructed ships [30]. Several emission factors are used as standards in measuring GHG and pollutant emissions. Emission factors for GHG and pollutants standardized by IMO are carbon dioxide (CO_2), nitrogen oxides (NOx), sulphur oxides (SOx), particulate matter (PM), carbon monoxide (CO), methane (CH_4), nitrous oxide (N_2O), non-methane volatile organic compounds (NMVOC) [31].

Commercial ship-related gas emissions have been extensively examined, and the findings have been reported in several research articles. In the systematic review, the author compares previous research studies regarding the potential for reducing GHG emissions from using LNG fuel on several types of ships compared to conventional ship fuels. The emission factors observed in this study are limited to NOx, SOx, and PM_{10} emissions. NOx is a term to describe the seven nitrogen oxide compounds that are most relevant to air pollution that harm the ozone layer, namely nitric oxide (NO), nitrous oxide (N_2O), dinitrogen dioxide (N_2O_2), dinitrogen trioxide (N_2O_3), nitrogen dioxide (NO_2). dinitrogen tetroxide (N_2O_4), and dinitrogen pentoxide (N_2O_5) [32,33]. sulphur oxides (SOx) are compounds of sulphur and oxygen molecules mainly found in the lower atmosphere. These compounds are produced from burning fuel containing sulphur and are very harmful to humans' lungs and respiratory systems [34]. Meanwhile, particulate matter (PM), more fully airborne particulate matter, is solid material such as dust, dirt, soot, smoke, and liquid that is emitted into the air [34]. There are two standards in PM measurement, namely PM_{10} and $PM_{2.5}$. PM_{10} is particulate matter smaller than 10 µm diameter , while $PM_{2.5}$ is smaller than 2.5 µm diameter .

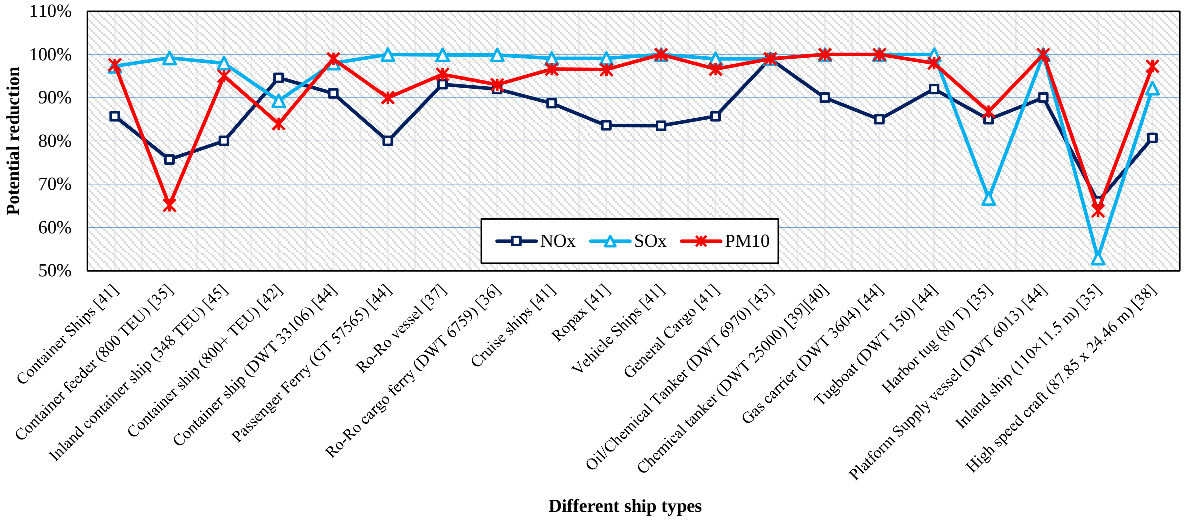

Fig. 6. GHG emission reduction potential compared to conventional fuels (NOx, SOx, PM_{10}) from the latest project.

A systematic review shows that the average GHG emission reduction potential of NOx, SOx, and PM_{10} emission factors is 86.1%, 94.5%, and 92.7%, respectively, compared to conventional ship fuel. Data on emission factors for emissions from burning maritime transportation fuels (HFO, MDO, and LNG) have been reviewed by IMO in Table 3 [31,46].

Table 3. Comparison of **e**mission factors for fuel combustion according to IMO

Emissions substance	**HFO emission factor (g/g fuel)**	**MDO emission factor (g/g fuel)**	**LNG emission factor (g/g fuel)**
Nitrogen oxides (NO_x)	0.093	0.087	0.008
Sulphur oxides (SO_x)	0.049	0.003	Trace
Particulate matter (PM)	0.007	0.001	Trace

Growing numbers of ships are being modified to use LNG as a fuel, a notable global development in the marine industry. Compared to the conventional fuels, LNG is a cleaner energy source, which can help reduce the emissions of pollutants. Along with strict emission regulations, LNG-fuelled vessels (new ship building and conversion projects) have experienced an increasing trend. In 2022, there are 175 LNG-fuelled vessels in operation, 145 LNG-ready notated vessels, and 195 vessels in order [15], with the most trends being offshore, tugs, and ferries [47]. Table 4 briefly overviews several LNG-fuelled, conversion, and dual-fuel vessels. Table 4 describes several LNG-fuelled vessels currently available, both ships built using dual-fuel engine technology and conversion vessels. Several classification societies have ogled the rules regarding converting ships into LNG-driven ones, one of which is Bureau Veritas (BV) through regulation NI654 about Guidelines on conversion to LNG as fuel [48]. Based on the data in Table 4, it can also be concluded that the engine mainly used is a dual fuel type engine, which means the ship can move with LNG fuel but requires diesel fuel as a pilot fuel to ignite combustion/diesel ignited. As for LNG storage, Type C tanks are the majority choice. Type C tank has more placement flexibility than other types of tanks.

Table 4. Identification of several LNG-fuelled vessels with LNG specifications

LNG-Fuelled Ship Name	Companies Involved	Main Engine	LNG Storage	Ref.
Isla Bella - Container ship (IMO 9680841)	• Sea Star Line (owner) • General dynamic NASSCO (shipyard) • MAN Energy Solution (engine manufacturer)	MAN B&W L70ME-C8.2-TII • Dual fuel with a total power output of 25191 kW at 104 rpm	2 x stainless steel cryogenic tanks (total capacity 900 m^3) at the aft of the ship (external)	[44]
Viking Grace - Passenger Ferry (IMO 9606900)	• Viking line (owner) • STX Turku Yard (shipyard) • Wärtsilä (engine manufacturer)	Wärtsilä 8L50DF • Dual fuel - electric • Total power output 30400 kW	2 x vacuum tanks (capacity 200 m^3 each) at the aft of the ship (external), integrated with the LNGPac system	
Viking Energy – PSV (IMO 9258442)	• Eidesvik (owner) • Maritim shipyard • Wärtsilä (engine manufacturer)	Wärtsilä 6L32DF • Dual fuel – electric with a total power output of 8040 kW	Double barrier stainless steel horizontal cylindrical tank with domed ends (total capacity of 220 m^3) at the middle of the ship (internal)	
Borgøy – Tugboat (IMO 9662112)	• Buksér og Berging AS (owner) • Sanmar Denizcilik A.S. (shipyard) • Rolls–Royce – Bergen (engine manufacturer)	Bergen C26:33L6PG • Lean-burn gas with a total power output of 3410 kW at 1000 rpm	Double walled tank (total capacity of 80 m^3) at the middle of the ship (internal)	
Coral Energy – LNG carrier (IMO 9617698)	• Antony veder (owner) • Meyer werft. (shipyard) • Wärtsilä (engine manufacturer)	Wärtsilä 8L50DF • Dual fuel – mechanic with a total power output of 7800 kW at 514 rpm	LNG is supplied from boil-off gas from cargo	
Coral Star – Gas carrier (IMO 9685499)	• Antony veder (owner) • AVIC Dingheng Shipbuilding Co., Ltd. (shipyard) • Wärtsilä (engine manufacturer)	Wärtsilä 6L34DF • Dual fuel – mechanic with a total power output of 2700 kW at 750 rpm	2 x C type horizontal tanks (total capacity of 4700 m^3) at the deck (external)	
Creole Spirit – LNG tanker (IMO 9681687)	• Teekay LNG partners (owner) • DSME (shipyard) • MAN Energy Solution (engine manufacturer)	MAN B&W G70ME-C9.2-GI-TII • Dual fuel • M-type, Electronic Controlled, Gas Injection	LNG is supplied from boil-off gas from cargo	[49, [50]
Sajir – Container ship (IMO 9708784)	• Hapag-Lloyd, Germany dan Hudong-Zhonghua Shipbuilding Group (shipyard) • MAN Energy Solution (engine manufacturer)	MAN B&W ME-GI • Dual fuel	This ship is classified as “LNG ready,” a ship whose arrangement is prepared for installing an LNG-powered system. LNG tank placed in a space equal in size to 290 TEU (internal)	[51, 52]
Bit Viking - Chemical tanker (IMO 9309239)	• Tarbit shipping (owner) • Germanischer Lloyd / GL (class society) • Wärtsilä (engine manufacturer)	Wärtsilä 50DF • Multi-fuel burn	2 x C type LNG storage tanks (total capacity 1000 m^3), mounted on deck (external)	[39, 40]
MTS Argonon – inland	• Argonon shipping (owner) • Shipyard TRICO	Caterpillar 3512C	1 x C type LNG storage tanks (total capacity 40 m^3),	[53]

chemical tanker (IMO 9552903)	• Caterpillar Inc. (engine manufacturer)	• Dual fuel with power range 1280-2551 BHP	mounted on the deck (external)	
Eiger nordwand - inland container ship (MMSI 244660203)	• Danser (owner) • Innovation and Networks Executive Agency (INEA) • Wärtsilä (engine manufacturer)	Wärtsilä 6L20DF • Dual fuel with total power output 900 kW	1 x type C LNG storage tanks (total capacity 60 m^3), internal	[45, 54]
Coral sticho – inland LPG tanker (IMO 9685504)	• Anthony veder (owner) • Avic dingheng shipbuilding (shipyard) • Wärtsilä (engine manufacturer)	Wärtsilä W6L34DF • Dual fuel with a total power output of 2700 kW	2 x type C LNG storage tanks (total capacity 200 m^3), mounted on the deck (external)	[54]
Abel Matutes of – passenger ship (IMO 9441130)	• Baleria (owner) • Caterpillar Inc. (engine manufacturer)	MAK 9M43C • Dual fuel with a total power output of 9000 kW	2 x type C LNG storage tanks (total capacity 356 m^3), mounted on the top deck (external)	
RPG Stuttgart – inland tanker barge (ENI: 2337160)	• Plouvier transport (owner) • VEKA shipbuilding (shipyard) • Wärtsilä (engine manufacturer)	Wärtsilä 6L20 DF • Dual fuel with a total power output of 900 kW	1 x type C LNG storage tanks (total capacity 60 m^3), internal	
Samuel de Champlainlain – hopper dredger (IMO 9234408)	• Dragages port (owner) • Damen (shipyard) • MAN Energy Solution (engine manufacturer)	MAN 6L35/44DF • Dual fuel with a total power output of 9540 kW	2 x type C LNG storage tanks (total capacity 459 m^3), mounted on deck (external)	[55]

3.2 Economic feasibility of implementation of LNG as ship fuel based on the perspective of maritime industries

Economic factors have always been the primary consideration for shipping companies to switch to more eco-friendly fuels because it takes much investment to convert ships. In general, using new energy will be costly initially, and the cost will decrease along with the widespread use of new energy. cost of natural gas (LNG) could be about half as much as crude oil, according to fuel prices from March 2013. The energy from crude oil is also provided by natural gas. As a result, using natural gas as a fuel source for the transportation industry, including maritime applications, may be less expensive than doing so with conventional crude oil fuel [56].

Most LNG-fuelled ships are dual-fuel engines, which in operation require pilot fuel as an ignition for combustion. Until now, the marine gas engine / dual engine market has been dominated by large manufacturers such as "MAN Energy Solution", "Wärtsilä", "Caterpillar Inc.", "Hyundai Heavy Industries," "Kawasaki Heavy Industries", "Rolls–Royce" and others [57]. Significant manufacturers of engine technology usually focus on one concept for research and development. The coming years are expected to be a transitional period that will see increased utilization of dual fuel, which is advantageous due to its versatility [58]. Fig. 7 contains several marine engines from manufacturers capable of operating on LNG fuel and their power output rate [59-64].

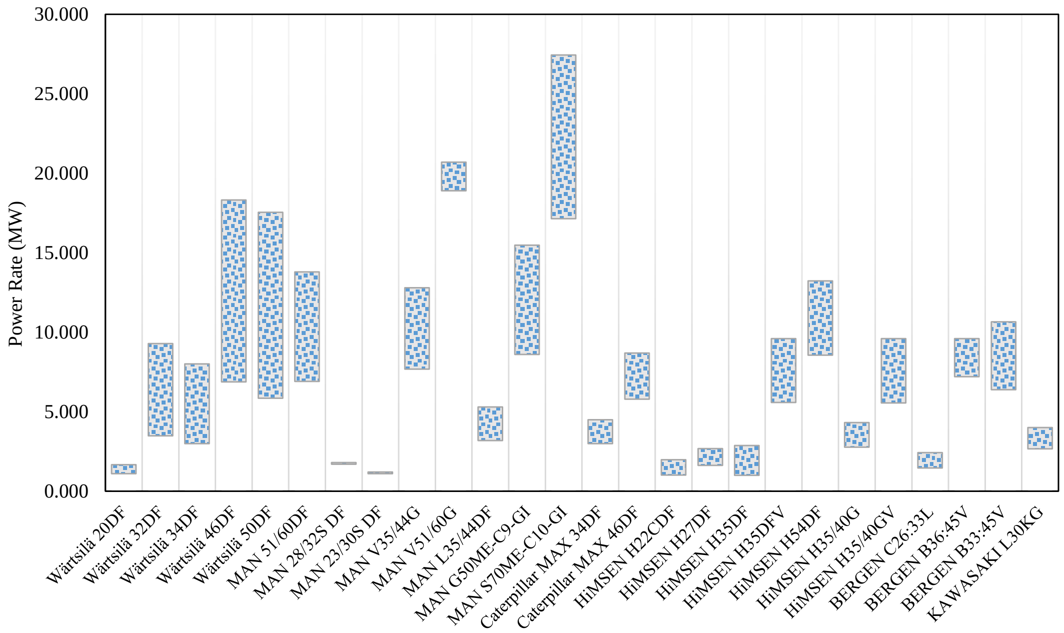

Fig. 7. Comparison of LNG-fuelled engines and power output in MW.

The marine engine shown in Fig. 5 has its characteristics based on company research and development policy. There are marine engines with specific adjustments to run with LNG specifications, engines designed with the dual fuel principle (which requires pilot fuel to ignite the combustion process), and engines with multi-fuel capabilities.

Reviewing Table 4, it can be seen that not all shipyards have the same capacity to construct LNG-fueled vessels. This is due to the particular handling requirements and significant risk associated with LNG handling. The Emirates classification society (Tasneef) needs the shipyard to be able to operate and handle an LNG plant and to have a cryogenic workshop [21]. Economic factors are a serious concern for shipping companies in converting to LNG fuel. The company always pays attention to economic benefits and complies with strict regulations regarding emission restrictions from IMO. Several previous studies have examined the economic factors ofLNG-fueled vessels , and the author has collected several scientific studies related to this study. Table 5 shows that LNG-fueled vessels can benefit shipping companies economically. With the growing fleet of LNG-fuelled vessels, the development supporting infrastructure for the LNG supply chain is becoming increasingly developed, such as the LNG pipeline and LNG bunkering stations [65].

Table 5. Economic benefits from several scientific research and LNG-fuelled ship projects

Ship name/type	Research/project review	Economic benefit	Ref.
Trans-ocean/ container ship (9300 TEU)	Study of assumptions regarding conceptual and economic analysis of trans-ocean container ships fuelled by LNG	LNG-fuelled trans-oceanic container ships have more economic attractiveness than conventional fuelled container ships with SCR for 20 years of a lifetime	[66]
3 Ocean-going container ships, with 2 bunker port cases	Analysis of the economic feasibility of using LNG as a fuel on 3 ocean-going container ships: post-Panamax (8560 TEU); new Panamax (13500 TEU); ULC (200600 TEU) with Singapore and Rotterdam as bunker port	The fuel cost savings for LNG-fuelled vessels at refuelling Rotterdam are between US$55016938 and US$71005356 Large-size container ships (>15000 TEU) are considered more cost-efficient than smaller-size LNG-fuelled container ship	[67]
MS otrate / Inland vessel operating in Germany	Study of technical analysis and economic benefits regarding the concept of converting inland water vessels to LNG-fuelled vessels and development to further ship concepts (tanker, dry cargo, cruise, and day trip vessel)	The initial vestment cost would be €859280, and the fuel savings would be €1442851 over 5 years The initial investment cost to construct an LNG ship is higher than the cost to build a diesel-fuelled ship (around 30%).	[68]
MV. Al hurreya / Ro-Ro cargo ship (operating in the red sea)	A case study about economic and environmental analysis of 4 methods of reducing exhaust emissions on a Ro-Ro cargo ship (MV. Al Hurreya), the SCR method, SWS method, conversion to MGO, and conversion to LNG	Conversion to LNG – dual fuel is the most economical method, with an average installation cost of 29.9 $/kW and emission reduction cost-effectiveness factors of 1486 $/ton	[69]
Container feeder (800 TEU)	Study of 3 ships in the Netherlands on the use of LNG as fuel with 3 LNG supplies: • LNG from Peakshaver Rotterdam: as a pipeline from the North Sea • LNG from Peakshaver Rotterdam: as a pipeline from Russia • Supply LNG from LNG carrier from Qatar Assumptions of economic calculation carried out in 2016	An LNG price discount of 2.5 €/MMBTU below diesel fuel price and for payback within 10 years	[35]
Harbor tug (80 T)		An LNG price discount of 10.3€/MMBTU below diesel fuel price and for payback within 10 years	
Inland ship (110×11.5 m)		An LNG price discount of 2.1€/MMBTU below diesel fuel price and for payback within 10 years	
MV. Sajir (Mega container ship, 15000 TEU)	Conversion project carried out by Hapag-Lloyd, Germany, and Hudong-Zhonghua Shipbuilding Group. The ship is classified as "LNG ready", a ship whose arrangement is prepared for installing an LNG LNG-powered.	The total cost of the conversion project is expected to be US$ 30 million	[51, [52]
MTS Argonon / inland chemical tanker	Evaluate the results of the pilot test of the MTS Arganon ship (inland chemical tanker) owned by argonon shipping with a Caterpillar 3512C (dual fuel) engine	Reduced Diesel (EN590) consumption is calculated by replacing the normal amount of EN 590, which is 120 m3 per year for two engines: • Reduction of fuel consumption by 20000 €/year • Reduction of operational cost by 40400 €/year	[53]
Container vessel (14000 TEU)	Study of the company's investment opportunities on the use of LNG as fuel, with a case study of a new vessel (container vessel) with the Asia-US West Coast (USWC) liner routing	LNG as a marine fuel delivers the best return on investment on an NPV basis over a conservative 10-year horizon with fast payback periods ranging from one to two years	[70]

4. Future Challenges and Critical Issues of LNG-Fuelled Ships

Based on a synthesis of articles in each cluster, the potential research areas for future investigations were discussed. In this section, LNG as a low emission fuel is predicted to have very high opportunities and challenges in future applications. From a technical standpoint, the discussion is intended to evaluate the challenges in developing LNG-fuelled vessels, including the environmental issue of high methane slip in Section 4.1. Section 4.2 will briefly discuss the spatial arrangement of the bunker tank, risk mitigation in the bunkering process, sloshing, and dual fuel issues and will be overviewed in Sections 4.3-4.5.

4.1 Environmental issue of high methane slip

LNG-fueled transportation systems use BOG reliquefaction process to maintain storage tank temperature and limit methane leakage [71]. Natural gas is lighter than air, and if it leaks, it disperses into the atmosphere. The LNG evaporation process allows it to float away, unlike other liquid fuels that remain near the engine and bilge [72]. Methane (CH_4) slip is an unburned fuel that is not fully combusted in ship's engine and released into the atmosphere. Methane slip is most likely caused by two factors, the presence of dead volume in the form of gaps between the components of the cylinder unit, and incomplete combustion in the form of quenching in the coldest part of the combustion chamber when the engine run [73]. The growth of the LNG-fuelled fleet with both converted vessels and newbuilt vesselds has resulted in faster growth of methane emissions than the use of LNG itself compared to other GHG emissions [4]. Engines that have methane slip are generally IMO tier III engines and have the characteristics of low-pressure injection before compression, namely lean burn spark ignited (LBSI) of 23.2 g/kg fuel, low-pressure medium speed dual fuel (LPDF) of 40.9 g/kg fuel [74].

4.2 Space arrangement in LNG bunker tank

MarineLNG storage tank is generally larger than the convensional fuel bunker tanks , due to density gap between LNG (430 kg/m^3) and MDO (900 kg/m^3), and installing the insulating tank. It was mentioned earlier that the criteria for the location of the protective LNG tank could be based on a deterministic approach considering the tank volume or probabilistic methods [17]. Even in some cases of ships converting to LNG fuel, cargo space must be sacrificed. For example, in the MV. Sajir conversion project, to place the LNG bunker tank sacrificing 290 TEU of container space [51].

4.3 Risk mitigation in the LNG bunkering process

The LNG bunkering process is hazardous. Several risk aspects of the LNG bunkering process include the cryogenic LNG condition being at a temperature of -162^{o}C, which has dangerous consequences for crews and conventional steel structures or pipes that come into contact. LNG vapors can form explosive clouds in confined spaces and are considered hazardous, requiring special handling of these vapors during bunkering [75].

To deal with fire risk during the LNG bunkering process, adequate fire prevention equipment, certified crew, and prevention strategies for all possible outcomes are required. The possibility of this accident is analyzed based on the probability of occurrence and the factors that initiate the incident. One of these analyzes is by compiling event tree identification. Fig. 6 presents an example of event tree identification in the LNG bunkering process based on the causes of accidents [76]. Based on Fig. 8, the causes of accidents are identified from 2 main technical factors, the presence of leaks and ruptures on the LNG bunker tank.

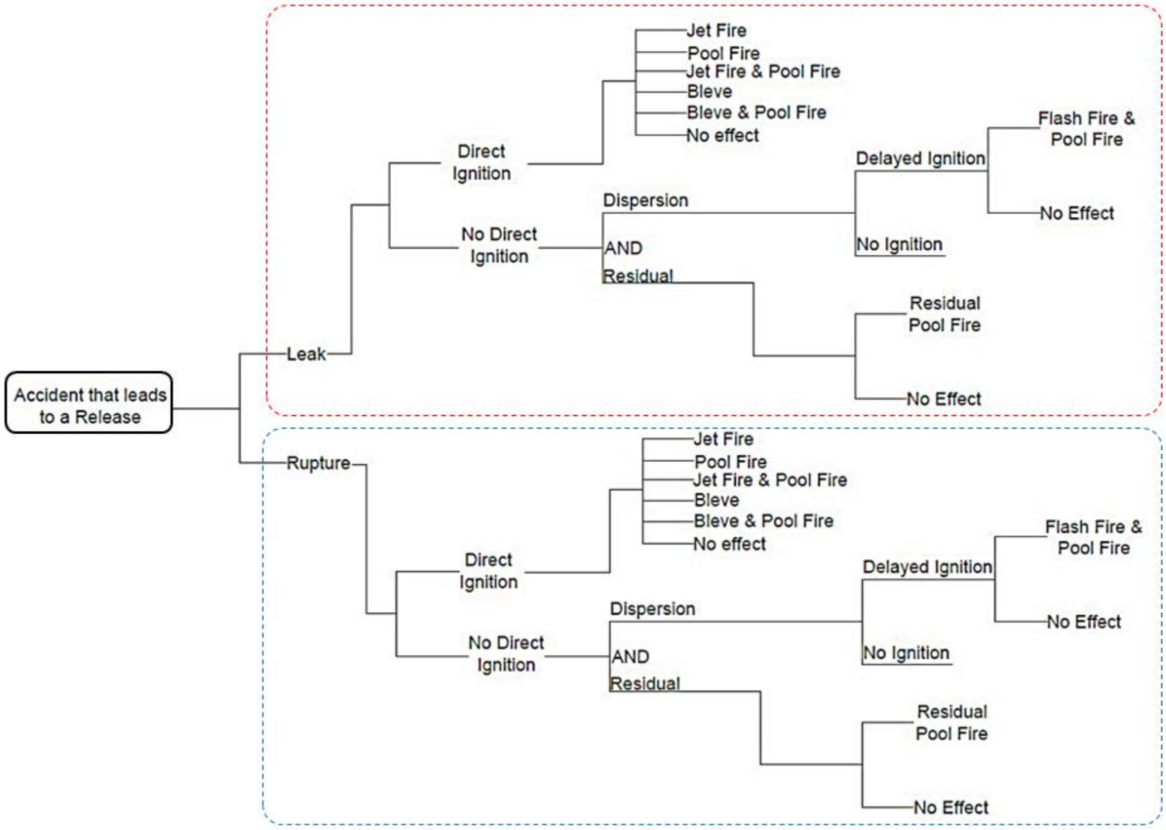

Fig. 8. LNG bunkering event tree identification [76].

4.4 Safety issues on sloshing effect in LNG bunker tank

The problem of sloshing is critical in loading liquids on ships. Sloshing is a naturally occurring phenomenon in LNG carriers, described as fluid movement caused by excitation force in the tank and efficiently minimized by a baffle [77]. Its effect is referred to as the free surface effect (FSE). In fact, LNG ships used to be able to sail with either a full or empty tank, but today it is necessary to allow for traveling with any partial filling. This need poses significant design challenges for the accompanying ship construction as well as the containment system (CS) [78].

The addition of an LNG tank in the ship conversion project to LNG fuel can affect the stability condition, and this can be seen from the righting lever (GZ) curve at each loading condition [79]. The sloshing effect can also affect the condition of the LNG. Sloshing can increase the internal pressure on LNG [80]. According to the IGF code, several regulations need to be considered for placing external LNG tanks [16].

- LNG tanks must be located not less than B/5 of the ship's breadth.
- Cofferdams must separate LNG tanks with a minimum thickness of 900 mm insulated with A-60 grade steel plates.
- Tanks have to be preserved by drip trays. It has to be stainless steel or other materials standing on a low temperature or cryogenic materials. It has to be covered by separated construction to the deck to escape its structure from the damage.

4.5 Technical issues on dual fuel engine application

It has been mentioned earlier that dual fuel engines are widely chosen as the main engine for LNG-fuelled ships. It cannot be separated from several technical challenges. Some problems are related to engine knock reduction, micro pilot fuel injection, control strategy, and safety requirements [18,81]. Knocking is a common problem with dual-fuel engines. One way to increase knocking resistance is to maintain high methane levels in LNG [18], which will most likely impact methane slip. Dual fuel engines require pilot fuel to ignite combustion. In general, the amount of pilot fuel, in this case, diesel fuel, is less than 5% [81]. Strict control and safety requirements of LNG-fuelled engines are also higher than conventional marine engines.

5. Conclusion

Based on the investigation regarding the technical perspectives and challenges of LNG-fuelled ships on GHG emission reductions and economic evaluation, several concluding remarks can be drawn. LNG as a transitional fuel is one of the options recommended by IMO to reduce GHG emissions produced by shipping activities by 50% by 2050. Based on the review, several important remarks are summarized.

Several critical parameters must be considered to build LNG-fuelled ships, such as engine selection based on its configurations, safe machinery space arrangements for the crew, LNG bunker tank location arrangement according to standards, and the selection of LNG tank types. From the latest investigations from various sources regarding the potential for reducing GHG emissions from using LNG as ship fuel has been summarized. LNG was found to reduce the emission factors of NOx, SOx, and PM_{10} by 86.1%, 94.5%, and 92.7% compared to conventional ship fuel. Based on the current data on LNG-fuelled vessels (new buildings or conversion projects), the use of dual fuel engines is the most common choice for ship owners. Moreover, the Type C tank is the most common type of tank used by LNG-fuelled ships, whether it is placed on the ship's hull (internal), which can generally be found in new buildings, or placed on the ship's deck (external), which is generally the most frequent and the easiest way to operate.

It has proven that using LNG as ship fuel can benefit maritime companies economically. These benefits include economic benefits from conversion projects compared to new buildings, fuel cost savings over a certain lifetime, and investment in LNG-fuelled shipbuilding and their payback period. For future consideration, the construction of LNG-fuelled vessels is a critical challenge, involving environmental issues of methane slip, space arrangement of LNG bunker tanks, risk mitigation in the LNG bunkering process, safety issues on the sloshing phenomenon in LNG bunker tanks, and some technical issue with a dual fuel engine.

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