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Critical Overview and Challenge of Representative LNG-Fuelled Ships on Potential GHG Emission Reduction

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Abstract: International cargo transportation is largely dominated by shipping, and it is a crucial aspect. To minimize the negative impact on the environment, ships are expected to abide by strict regulations concerning greenhouse gas emissions. Many shipping companies are turning to Liquefied Natural Gas (LNG) as a primary alternative fuel to reduce these emissions. This is because LNG has been found to have cleaner emissions than traditional fossil fuels. There have been several studies conducted to explore ways to implement LNG as a ship fuel effectively, but there is a lack of research on the specific reduction of greenhouse gas (GHG) emissions from using LNG. This report provides a comprehensive analysis of the current state of LNG-powered ship development, including current applications, initiatives by the International Maritime Organization, existing challenges, and potential measures for reducing GHG emissions. According to measurements compared to conventional ship fuel, NOx, SOx, and PM_{10} emission factors have a high potential for GHG emission reduction. The global fleet of LNG-powered vessels is expected to expand in the future. The LNG-fuelled ship mainly operates in the emission control area. The essential concerns for future research should be involved regarding the environmental issue of significant methane slip, geopolitical impact, and risk of LNG bunkering.

Keywords: Ship alternative fuel; LNG-fuelled ship; GHG emission, methane slip, geopolitical impact

1. Introduction

Greenhouse gas (GHG) emissions significantly contribute to the global climate change issue. Burning fossil fuels and industrialization have been identified as major sources of these emissions[1,2]. Developing and emerging market economies have seen an increase in industrialization, leading to high pollution levels that affect an individual's quality of life[3]. With rising demand, GHG emissions have escalated, and nature is on the verge of collapsing[4-6]. GHGs, including carbon dioxide (CO_2) and methane (CH_4), are rising as a result of human (anthropogenic) activity. CO_2 is the most released GHG among them[7]. To address this problem, practical and effective solutions must be implemented to reduce these emissions and mitigate the effects of climate change.

The maritime sector is one of those that plays a critical role in today's global trade. The demand for sailing services ensures global warming is a continuing problem[8,9]. The shipping industry, which plays a vital role in global trade, is also a significant contributor to GHG emissions. The increasing demand for shipping services results in higher fuel oil consumption, directly contributing to emissions. Therefore, it is crucial to investigate and implement new technologies to reduce emissions and promote environmental sustainability.

GHG emissions from the shipping industry have been a growing concern in recent years. According to the International Maritime Organization (IMO), the shipping industry is responsible for approximately 2-3% of global

GHG emissions. it makes it one of the largest sources of emissions in the transportation sector. The increased fuel oil consumption of ship systems directly causes an increase in fuel oil availability[10,11]. As a result, novel mitigating emissions was necessary through intense investigations for technological applications[12]. Environmental sustainability is being advanced by distributing new scientific findings that will reduce CO_2 and other GHGs[13].

Indonesia currently seeks to cut GHG emissions by 29 to 40% by 2030 by increasing the usage of alternative energy sources[14]. One of the possible options for reducing GHG emissions from maritime transportation is to use LNG as a fuel. The International Maritime Organization (IMO) has recommended it[15]. IMO has set a target of reducing yearly GHG emissions from shipping by at least 50% by 2050 compared to 2008[16]. Although the value of GHG emissions from sea transportation is less than that of land transportation, decreasing emissions from shipping has become a major issue in numerous countries.

In addition to many shipping companies exploring using LNG as an alternative fuel, there are also examples of LNG-powered ships currently operating. One such ship is the MV Glutra, operated by Fjord Line and uses LNG as its primary fuel[17]. Before 2000, LNG carrier ships had been utilizing evaporated or boil-off gas as fuel since 1964. However, in recent years, there has been growing interest in using natural gas as the primary fuel for ships[18]. According to recent estimates, there are currently 175 LNG-fuelled ships in operation worldwide[19]. This number is expected to increase as more shipping companies adopt LNG as an alternative fuel to reduce emissions and improve their environmental footprint.

The IMO's strict environmental requirements are one of the factors influencing the desire for LNG. A global sulphur cap of 0.5% will apply to ships trading outside Emission Control Area (ECA) beginning in January 2020. 3.5% is the current upper bound. The emissions are significantly reduced from heavy fuel oil (HFO) to LNG. So-called local emissions particles are virtually eradicated, nitrous oxide is reduced dramatically, and sulphur oxides are eliminated. That is one of the major advantages of allowing shipping to become more environmentally friendly[20,21].

Special regulations are needed to handle LNG as a fuel, and this is because LNG has different characteristics from conventional fuels. LNG is clear, odorless, non-corrosive, non-toxic when this gas is cooled to about -260°F, is easier to store and transport by sea, does not require pressurized storage, is non-explosive or flammable in the liquid phase, and is non-volatile so creates pressurized steam which may cause an explosion [22]. To control the use of gas fuels for ships, the IMO explicitly issued the IGS code (Adoption of the international code of safety for ships utilizing gases or other low-flashpoint fuels)[23].

Two main reasons exist for the growing interest in using LNG as a ship fuel. Firstly, LNG is considered a more environmentally friendly fuel source when compared to traditional fossil fuels. It is considered a short-term solution for reducing emissions from ships. Secondly, the use of dual-fuel engines that can run on both LNG and non-LNG fuels is expected to be an effective way to minimize emissions in the long-term[24]. In the near future, LNG is expected to become the primary fuel for shipping due to its many economic and environmental benefits[25]. It is projected that by 2030, LNG will be widely adopted by shipping companies to reduce emissions and improve their environmental performance. When LNG is cooled to about -260°F, it becomes clear, odorless, non-corrosive, and non-toxic. It is also simpler to store and transport by sea, does not require pressurized storage, is neither explosive nor flammable when in the liquid phase, and is non-volatile, so it does not produce pressurized steam that may result in an explosion[22].

Several investigations on the use of LNG-fuelled ships have been carried out. It aligns with IMO's steps to reduce global emissions, including using environmentally friendly alternative energy. This study will use a systematic literature analysis to present the most recent advancements in using LNG fuel. Conducting a systematic review, which enables one to acquire, evaluate, and interpret a complete and comprehensive body of existing/available data rigorously and objectively, is a crucial first step in evaluating the conclusions that science supports[26].

There have been numerous systematic literature reviews on the utilization of LNG. Arefin et al.[27] conducted a study on the opportunities, challenges, and reactions of utilizing LNG on dual-fuel engines. Wang and Notteboom[28] focus on legal, economic, technological, and public social analysis and the challenges of using LNG as LNG fuel in ECA. This comprehensive state-of-the-art review aims to extensively analyze the current and projected state of liquefied natural gas (LNG) as an alternative fuel for ships. While previous studies have explored the potential advantages of using LNG in line with the International Maritime Organization's (IMO) resolution to reduce greenhouse gas (GHG) emissions from ships, this report goes beyond by offering a systematic review of various discussions and research on the subject.

The primary focus of this investigation is to examine the IMO's strategy for GHG emission reduction and assess the actual measurement of emissions reductions achieved by LNG-powered ships. Furthermore, the report provides an overview of the operational LNG-powered ships, showcasing real-world examples of successful implementation.

To present a balanced perspective, the report also addresses the key challenges and potential obstacles associated with developing and adopting LNG-fueled ships in the shipping industry. It delves into critical issues such as the environmental impact of methane slip, the geopolitical implications, and the risks associated with

LNG bunkering.

By conducting this systematic research review, the authors aim to stimulate significant technological advancements in applying LNG as a marine fuel in the business sector and as a catalyst for further research. The report seeks to prompt the scientific community to address the critical issues surrounding using LNG as a marine fuel, ensuring its sustainable and environmentally friendly utilization as the primary fuel for ships. Through its comprehensive analysis and balanced approach, this state-of-the-art review provides valuable insights into the current state of LNG as a marine fuel. It also highlights the areas that require further attention and development.

2. Literature Review Methodology

The systematic review methodology provides a rigorous and comprehensive approach to critically examine and address the pertinent issues surrounding the use of liquefied natural gas (LNG) as an alternative fuel for ships and its potential for reducing greenhouse gas (GHG) emissions. This approach aims to contribute valuable insights to the scientific community regarding the development and implementation of LNG as a means to mitigate GHG emissions.

The systematic review process begins by formulating a well-defined and answerable research question, which serves as the guiding principle for identifying relevant studies. Subsequently, a four-stage process is undertaken. In the initial stage, a comprehensive search is conducted across various electronic databases, including international journals, conference proceedings, websites, and technical reports, in order to locate the most pertinent and comprehensive sources of information. During this stage, reviewers also determine the specific journals and technical reports to consult and establish the timeframe of the research, ensuring a comprehensive coverage of relevant literature.

The second stage involves assessing the selected studies based on their alignment with the review question. Eligibility criteria are established to filter out irrelevant literature, and an initial screening of potential studies is performed. This necessitates the identification of appropriate keywords and their preferred location within the literature, such as in the title, abstract, keywords section, or a combination thereof. Consequently, literature items that directly address the review question are collected and further examined.

The third stage of the systematic review entails a detailed analysis of the selected literature items. Specific and useful data are extracted, and the obtained results from the included studies are compared and synthesized. This involves identifying the most significant findings, trends, and patterns across the literature. To facilitate a comprehensive understanding and presentation of the findings, the extracted data are often organized into tables and charts.

Finally, the last stage of the systematic review process involves discussing the key results that have emerged from the preceding stages. The findings are critically evaluated, their implications are considered, and potential areas for further research are identified. This final step provides a comprehensive overview of the current state of knowledge and highlights the important insights gained from the review.

The systematic review method is a robust and reliable approach to comprehensively evaluate and discuss the role of LNG-fueled ships in reducing GHG emissions. By adhering to a well-defined research question, conducting a thorough literature search, analyzing and synthesizing the selected studies, and discussing the key findings, the systematic review methodology contributes valuable knowledge to the scientific community and informs decision-making processes regarding the adoption and implementation of LNG as an alternative marine fuel.

3. GHG emission of LNG-fuelled ship

This section will discuss the International Maritime Organization's (IMO) plan to reduce GHG emissions from shipping and the potential for reducing GHG emissions from LNG-fuelled ships. We will examine the different strategies and technologies being developed and implemented to reduce emissions from shipping and how LNG-fuelled ships fit into this overall plan. Additionally, we will explore the various studies conducted to assess the potential for reducing GHG emissions from LNG-fuelled ships, including the different emission factors associated with different types of fuels and the potential for future emission reductions through advanced technologies. Overall, this section will provide a comprehensive overview of the current state of GHG emission reduction in the maritime sector and the potential for LNG-fuelled ships to play a key role in reducing emissions and promoting environmental sustainability in the shipping industry.

3.1 IMO plan to reduce GHG emission

There are two pathways to achieving emission reduction: technological innovation and regulatory and policy. The use of eco-friendly fuel and the effectiveness of ship design are examples of technological innovation pathways. Meanwhile, for regulatory aspects, IMO, through MARPOL Annex VI, introduced three mandatory mechanisms, Energy Efficiency Design Index (EEDI), Ship Energy Efficiency Management Plan (SEEMP), and Energy Efficiency Operational Indicator (EEOI), as depicted in Fig. 1[29]. EEDI (MEPC.308(73)) is applied to new ships to measure the energy efficiency of vessels, calculated using a complex formula as the ratio of the ship's potential carbon dioxide emissions to the available carrying capacity to usable weight[30]. In addition, Marine Environment Protection Committee (MEPC) 78/6 updates The International Towing Tank Conference (ITTC)

recommended procedures and guidelines concerning determining and verifying the EEDI requirements[31].

Meanwhile, SEEMP is applied to older ships to optimize operational and technical management processes for fuel efficiency[31]. The goal is to improve ship energy efficiency by developing specific measures by the shipowner on the specific ship, resulting in lower CO_2 emissions. The SEEMP was adopted as a necessary tool under MARPOL Annex VI reg. 22 as revised In MEPC 2012 and went into effect on January 1, 2013. MEPC.346(78) resolution on 2022 is a guideline for developing SEEMP, as detailed in Annex 8[32]. Moreover, EEOI is an essential tool for calculating operational energy efficiency. IMO MEPC.1/circ 684 Voluntary Use Guidelines EEOI establishes standards for the voluntary usage of EEOI. However, we could only determine the amount of fuel utilized by the ship. The fuel mass to CO_2 mass conversion factor calculates the quantity of CO_2 emitted by the fuel[32].

The 2018 IMO Resolution outlines IMO measures to lower GHG emissions from ships. Generally, the targets are to cut annual GHG emissions by at least 50% by 2050 compared to 2008 and to cut CO_2 intensity from international shipping (per transport work) by 70% by 2050 compared to 2008[16]. To achieve the goal, IMO has issued several necessary regulations, such as the EEDI and SEEMP, which have been fully implemented since 2013, and the IMO Data Collection System (DCS), which was started in 2019. The IMO also issues an IMO GHG study every few years, which contains the manifestations of GHG reduction and monitoring from the maritime sector. LNG as an alternative fuel has always been a topic of discussion. Table 1 describes some essential points of using LNG as fuel in the IMO GHG study from 2000 to the present.

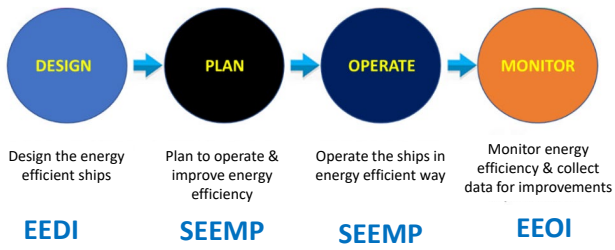


Fig. 1: Ship energy efficiency.

Table 1. Comparison of IMO GHG study about LNG as ship fuel.

Study	Year	Remarks
First IMO GHG study[33]	2000	• Natural gas is better for combustion engines, supported by the large global reserves of natural gas. • Tanks for LNG as ship fuel have a space of 2.5-3 times larger than HFO tanks. • A 30MW powered ship working at 85% capacity for 150 hours will normally need 70-80 units of 20 feet ISO tank containers filled with LNG to provide gas for a week at sea. • In the first IMO GHG study, using LNG as fuel for ships was seen as unrealistic, primarily because of refueling/logistics and the ship's piping system, which is more extensive and complex.
Study	**Year**	**Remarks**

Second IMO GHG Study[34]	2009	• LNG is a low-carbon fuel that has the potential to reduce CO_2 emissions by 5% to 15% CO_2/ton-mile.
		• LNG will become economically attractive, especially for vessels in regional trade within the ECA, and meet Tier III emission levels without the addition of selective catalytic reduction (SCR).
		• LNG has a net global warming benefit of around 15% after deducting CH_4 emissions, which is a disadvantage of using LNG.
		• The scenario for LNG as a future fuel in 2050 is as follows:
		  ○ Scenario A1B, A1FI, and A2 with 25% coastwise +10% of oceangoing crude oil tankers (all size categories)
		  ○ Scenario A1T with 50% coastwise + 20% of oceangoing crude oil tankers (all size categories)
		  ○ Scenario B1 and B2 with 50% of coastwise + 20% of oceangoing crude oil tankers (all size categories)

Third IMO GHG Study[35]	2014	• CH_4 emissions are projected to increase rapidly as the LNG share in the fuel mix increases. • Using the bottom-up method, it is known that CO_2 emissions from using LNG as fuel in international shipping have increased from 2007 to 2012, respectively 13.9 M tons, 15.4 M tons, 14.2 M tons, 18.6 M tons, 22.8 M tons, and 22.6 M tons. • Most LNG-powered engines operating during the 2007–2012 time frame

		are assumed to be otto-cycle with an emission factor of 8.5 g/kWh. • There are 16 business-as-usual (BAU) scenarios for the application of LNG in the ECA along with their emission levels; these scenarios are based on four representative concentration pathways (RCP) and shared socioeconomic pathways (SSP). Globally, there will be a 95% increase in emissions from using LNG as fuel in 2050 compared to 2012.
Fourth IMO GHG Study[36]	2020	• Heavy Fuel Oil (HFO) still dominates as shipping fuel (79% in 2018), while LNG usage increased by 0.9%. • In one period, there was an 87% increase in CH_4 emissions. This was due to an increase in LNG consumption as a shipping fuel. • Despite a general decline in the use of HFO and an increase in the usage of LNG and marine diesel oil (MDO), SO_X emissions and PM emissions grew over the period (partly driven by the entry into force in 2015 of several Emission Control Areas associated with limits on the sulfur content of fuels). • There was an increase in the production of LNG engine production in 2001+, where there are 4 LNG characteristics with primary specific fuel consumption (SPF) levels as follows: o LNG-Otto Slow Speed (dual fuel), 148 g/kWh (LNG) and 0.8 g/kWh (pilot fuel) o LNG-Otto Medium Speed, 156 g/kWh o LNG-Diesel (dual fuel), 135 g/kWh (LNG), and 6.0 g/kWh (pilot fuel) o Lean Burn Spark Ignited (LBSI), 156 g/kWh

The use of LNG as fuel was initially only a proposal, which was seen in the First IMO GHG Study. And as petroleum reserves were depleted, LNG was developed as a ship fuel. It can be seen in the Fourth GHG Study, where in 2018, the dominance of HFO as ship fuel was 78%, while the rest was MDO and LNG. From the issuance of the Second IMO GHG Study to the Fourth IMO GHG Study, the use of LNG as LNG fuel has been proven to reduce GHG emissions, but methane emissions due to methane slip in LNG combustion have increased. In the Second IMO GHG Study, the LNG implementation scenario is based on the Special Report on Emission Scenario (SRES). This scenario compiled by the Intergovernmental Panel on Climate Change (IPCC) in 2000 covers the main drivers of future emissions, from demographics to technological and economic developments[37]. Some of these scenarios discussed in the second IMO GHG study are:

1. A1FI scenario, where economic growth is very fast, and technological developments include the intensification of fossil fuels.
2. A1T scenario, where the economic growth is very fast, and the technology of non-fossil energy sources are available.
3. A1B scenario, where economic growth is very fast, and technological developments are balanced between fossil fuels and non-fossil energy intensifying.
4. A2 scenario, where the world economy is highly heterogeneous and technological change is more fragmented and slower.
5. B1 scenario, where the world economy converges, the world population is the same, and clean technologies and energy source efficiency are introduced.
6. B2 scenario, where the world focuses on local economic solutions, environmental sustainability, and wider technological diversity than scenario B1.

In the third IMO GHG study, the LNG usage scenario was used in the ECA. The Baltic Sea, North Sea, North American, and US Caribbean sea areas are included in the ECA in the Third IMO GHG Study 35). The strategy used in this case is based on the Shared Socioeconomic Pathways (SSP) and Representative Concentration Pathways (RCPs) techniques. To predict the trajectory of GHG concentrations, Representative Concentration Pathways (RCPs), an updated version of The Special Report on Emissions Scenarios (SRES), project an increase in global radiation by 2100. This method represents a climate-based study, not an estimate or policy recommendation[38]. The RCP scenarios in the third IMO GHG Study are RCP2.6 (CO_2 emissions began to decline in 2020), RCP4.5 (CO_2 emissions start to decline in 2040), RCP6 (CO_2 emissions begin to fall in 2080), RCP8.5 (CO_2 emissions continue to increase)[39]. Shared Socioeconomic Pathways (SSPs) are projections of anticipated world socioeconomic trends during 2100 by taking policy recommendations to address GHG emissions[40]. The SSP scenarios in the third IMO GHG study are SSP1 (low challenges to mitigation and adaptation), SSP3 (High challenges to mitigation and adaptation), SSP4 (low challenges to mitigation, high challenges to transformation), SSP5 (high challenges to mitigation, low challenges to transformation)[41]. In the fourth IMO GHG Study scenario, LNG is applied on a smaller technical scale, namely to the combustion engine.

Moreover, in Fourth IMO GHG Study 2020[12], 4

technologies were screened out as potential GHG abatement technologies to improve energy efficiency or carbon intensity. The screened technologies consist of four different types, including 23 energy-saving technologies, 4 use of renewable energy (e.g., wind engine, solar panels), 16 use of alternative fuels (e.g., LNG, hydrogen, ammonia), and speed reduction. Applying all viable mitigation strategies chosen to all newly built ships started in 2025, CO_2 emissions reductions in 2050 can meet both the mid-term and long-term levels of the target. Alternative fuels will generate approximately 64% of overall CO_2 reductions by 2050. The marginal abatement cost curve (MACC) is heavily influenced by the expected costs of zero-carbon fuels, as seen in Fig. 2.

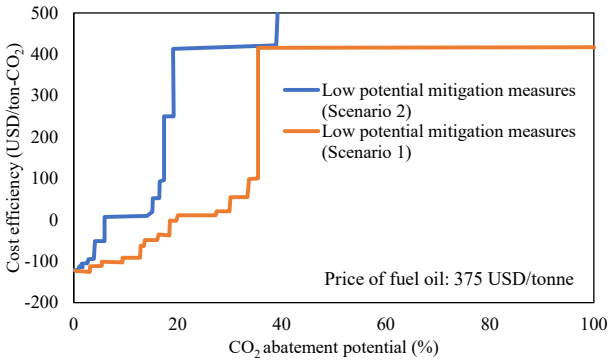


Fig. 2.: Marginal abatement cost curve for 2050[36].

3.2 Potential GHG emission reduction of LNG-fuelled ship

Several emission parameters are used as benchmarks in calculating GHG and pollutant emissions. Carbon dioxide (CO_2), nitrogen oxides (NOx), sulfur oxides (NOx), particulates (PM), carbon monoxide (CO), methane (CH_4), nitrous oxide (N_2O), and non-methane volatile organic compounds (NMVOC) are IMO standardized GHG and pollutant emission factors[35]. This systematic review examines previous research findings on the possibility of reducing GHG emissions by using LNG fuel on various types of ships compared to conventional ship fuels.

This study focuses on three specific types of emissions: PM_{10}, NOx, and SOx. These are considered to be significant contributors to air pollution. Among the nitrogen oxides, which are known to deplete the ozone layer, seven molecules are considered to be the most important: nitric oxide (NO), nitrous oxide (N_2O), dinitrogen dioxide (N_2O_2), dinitrogen trioxide (N_2O_3), nitrogen dioxide (NO_2), dinitrogen tetraoxide (N_2O_4), and dinitrogen pentoxide (N_2O_5)[42,43]. These are nitrogen and oxygen molecules present in the lower atmosphere. Sulfur oxide, or SOx, is formed when fuels containing sulfur are burned and is extremely harmful to the lungs and human respiratory system. It is a compound of sulfur and oxygen molecules in the lower atmosphere[44]. Particulate matter (PM), or airborne particulate matter, refers to solid materials released into the atmosphere, such as dust, dirt, soot, smoke, and liquids[44]. PM_{10} and $PM_{2.5}$ are the two standards used to monitor particles. PM_{10} refers to particles larger than 10 microns, while $PM_{2.5}$ refers to particles smaller than 2.5 microns. These are considered to be significant indicators of air quality. Table 2 shows the latest research and project developments regarding LNG comparison with conventional ship fuel.

Table 2. The latest research and project developments regarding LNG comparison with conventional ship fuel.

Vessel types	Research/project review	Potential GHG emission reduction (%) compared to conventional fuel		
		NOx	SOx	PM_{10}
Container feeder (800 TEU)[45]	Three ships in the Netherlands were used in research on using LNG as fuel with 3 LNG supplies. • LNG from Peakshaver Rotterdam: a North Sea gas pipeline. • LNG from Peakshaver Rotterdam, a Russian gas pipeline • Qatar LNG ship supplying the energy source Data is taken from annual politicians in the range of 2011 – 2015.	75.7	99.2	65.1
Harbor tug (80 T)[45]		85.0	66.7	86.8
Inland ship (110×11.5 m)[45]		66.0	52.9	63.8
Ro-Ro cargo ferry (DWT 6759)[46]	The research was carried out on a hybrid LNG-battery vessel operating with 2 Wärtsilä 34DF engines and 1,050 V, 546 kWh Corvus Energy Storage System (ESS). Emissions compared to 9L34DF twin engine.	92.0	99.9	93.0
Ro-Ro vessel[47]	A thorough analysis of how LNG, LBG (liquid biogas fuel), methanol, and bio-methanol compare in terms of their environmental performance over their entire life	93.1	99.9	95.4

	cycles. Data on tank to propeller comparison with HFO.			
High-speed craft (87.85 x 24.46 m)[48]	Case study on the use of LNG on fast ships sailing from the port of Hurghada (Egypt) to Doba (Saudi Arabia).	80.7	92.2	97.3
Bit Viking. Chemical tanker (DWT 25000)[49,50]	The first LNG-powered tanker conversion project in the world. The main engine was changed from two Wärtsilä 46 engines with six cylinders each to Wärtsilä 50DF engines with updated control systems.	90	100	100
Cruise ships[51]	Research assumptions regarding the potential use of LNG as a fuel on ships at the Port of Heraklion (Greece). The ship's condition is in 3 conditions, cruising, maneuvering, and hoteling. Emission potential results are compared between LNG and MDO.	88.7	99.1	96.6
Ropax[51]		83.6	99.1	96.5
Container Ships [51]		85.7	97.3	97.6
Vehicle Ships[51]		83.5	100	100
General Cargo[51]		85.7	99.0	96.6
Container ship (800+ TEU)[52]	Research on assumptions regarding the potential use of LNG as a fuel on ships at Bitung Port (Indonesia). The limitation of this research is the machine that is assumed to use LNG is the auxiliary engine used while at the port (96 hours).	94.6	89.3	84
Oil/Chemical Tanker (DWT 6970)[53]	A case study of a tanker using a MAS STX 6L 32/40 main engine with a power of 2880 kW. In this perspective, LNG uses a liquid carbonate fuel cell compared to emissions from MDO.	99	99	99
Container ship (DWT 33106)[54]	The Isle Bella ship is a dual-fuel ship with the Sister ship (Parla del Caribe) operating on the Puerto Rican trade route.	91	98	99
Passenger Ferry (GT 57565)[54]	The Viking Grace ship is a passenger ship with a capacity of 2800 passengers operating on the trans-Baltic route	80	100	90
Platform Supply vessel (DWT 6013)[55]	The Viking Energy vessel is a platform supply vessel that has been operating to supply oil and gas platforms in the North Sea	90	100	100
Tugboat (DWT 150)[55]	The Borgøy vessel is an LNG-fuelled ship operating at the Statoil Karate terminal	92	100	98
Gas carrier (DWT 3604[55]	From the SABIC Wilton site in Teesside, United Kingdom, to manufacturing facilities in North-West Europe and Scandinavia, LEG is transported there by the ship Coral Star.	85	100	100
Inland container ship (348 TEU)[55]	The Innovation and Networks Executive Agency (INEA) and Lloyd's Register Marine teamed up to convert the Eiger – Nordward vessel to run on 99% LNG (1% diesel)	80	98	95

A comprehensive study found that using LNG as a fuel source in the maritime industry can significantly reduce emissions of harmful pollutants compared to traditional fuel sources. Specifically, Nitrogen Oxide (NOx), Sulfur Oxide (SOx), and PM_{10} particulate matter emissions can be reduced significantly. After carefully analyzing and considering low GHG emissions in Table 2, the best recommendation for LNG implementation is for large oceangoing vessels, such as container ships and tankers. LNG significantly reduces GHG emissions compared to traditional marine fuels, emitting lower NOx, SOx, PM_{10}, and particulate matter levels. By utilizing LNG as a marine fuel, these types of ships can contribute to a substantial decrease in GHG emissions and help mitigate the environmental impact of the shipping industry while complying with increasingly stringent emission regulations.

This information is supported by data from the International Maritime Organization (IMO), which has analyzed the emissions from burning Heavy Fuel Oil (HFO), Marine Diesel Oil (MDO), and LNG as fuels for shipping. This data can be found in Table 3 of the IMO's findings. Overall, using LNG as a fuel source in the maritime sector can significantly contribute to reducing the environmental impact and improving air quality.[35,56].

Table 3. Emission factors for fuel combustion based on IMO.

Emission substances	Emission factor (g/g fuel)		
	HFO	MDO	LNG
NOx	0.093	0.087	0.008
SOx	0.049	0.003	Trace
PM	0.007	0.001	Trace

4. Overview of currently operating LNG-fuelled ship

Currently, a growing number of LNG-fuelled ships are in operation worldwide. These ships can be classified into three main categories: 100% LNG-fuelled, dual-fuel, and LNG-ready. 100% LNG-fuelled ships use LNG as their sole fuel source, while dual-fuel ships are capable of running on both LNG and traditional marine fuels. LNG-ready ships are vessels that have been designed to be converted to run on LNG at a later date.

The majority of LNG-fuelled ships currently in operation are located in ECAs. These ships are typically operated by major shipping companies, such as Carnival Corporation and Royal Caribbean Cruises, and are used for a variety of purposes, including cruise ships, container ships, and ferries.

Along with stringent pollution rules, LNG-fuelled ships have increased both new ship construction and conversion operations, with the most transportation mode being offshore, tugs, dan ferries[57]. Table 4 briefly overviews several LNG-fuelled vessels and their operational shipping routes. Table 4 shows examples of LNG-fuelled ships that operate in ECAs. The emission control area is a shipping area with more stringent controls to minimize emissions from ships (SOx, NOx, PM) under MARPOL regulations Annex VI[58]. Currently, there are 4 ECAs: the North Sea, the Baltic Sea, the US Caribbean Sea, and the North American[35,59]. Fig. 3 shows the currently operating ECAs.

Table 4. LNG-fuelled vessels and operational route area.

LNG-fuelled Ship	Type	Year	Operational route area
Glutra (IMO 9208461)[17]	Ro-Ro cargo	2000	North sea
Isla Bella (IMO 9680841)[54]	Container ship	2015	US Caribbean sea
Viking Grace (IMO 9606900)[54]	Passenger Ferry	2013	Baltic sea
Viking Energy (IMO 9258442)[54]	PSV	2003	North sea
Borgøy (IMO 9662112)[54]	Tugboat	2014	North sea
Coral Energy (IMO 9617698)[54]	LNG carrier	2013	Baltic sea
Coral Star (IMO 9685499)[54]	Gas carrier	2014	North sea
Creole Spirit (IMO 9681687)[60]	LNG tanker	2016	South East Asia
Sajir (IMO 9708784)[61]	Container ship	2020	Baltic sea
Bit Viking (IMO 9309239)[49]	Chemical tanker	2012	North sea
MTS Argonon (IMO 9552903)[62]	Inland chemical tanker	2011	Rotterdam area (inland)
Eiger Nordwand (MMSI 244660203)[55]	Inland container ship	2013	Rotterdam area (inland)
Coral Sticho (IMO 9685504)[63]	Inland LPG tanker	2012	North sea
Abel Matutes (IMO 9441130)[63]	Passenger ship	2014	Balearic sea
RPG Stuttgart (ENI: 2337160)[63]	Inland tanker barge	2016	Rotterdam area (inland)
Green rhine (IMO 9665009)[63]	Inland tanker	2013	North sea
Coral star (IMO 9685499)[63]	LPG tanker	2014	North sea
Greenland (IMO 9734264)[63]	Cement carrier	2015	Baltic sea

Ecodelta (IMO 9822619)[63]	Hopper dredger	2018	Rotterdam area
Shetland (IMO 9852004)[63]	Cement carrier	2019	North sea
Samuel de Champlainlain (IMO 9234408)[64]	Hopper dredger	2017	English Channel area
Rem eir (IMO 9668647)[65]	Offshore supply ship	2014	North sea

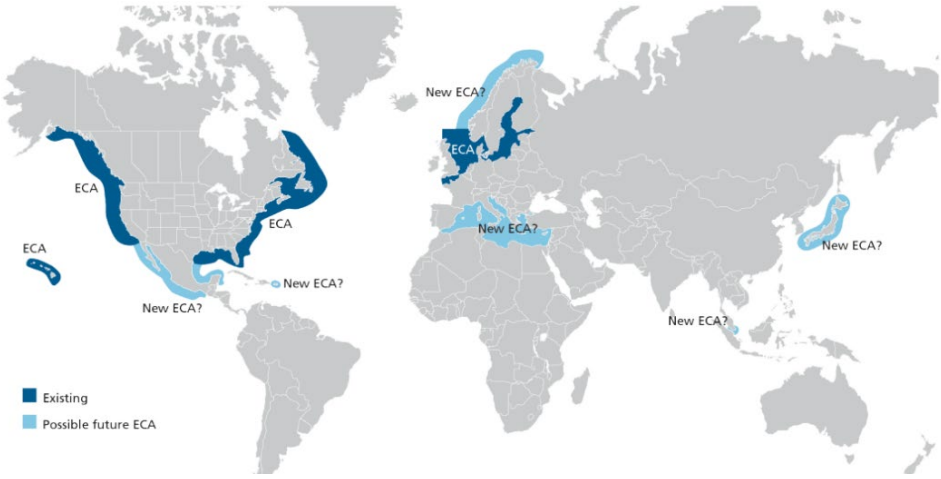


Fig. 3.: Currently and proposed emission control area[35].

Vessels operating on ECA routes must qualify for Tier III emissions or at least reduce NOx by approximately 80% from Tier II[66]. Based on previous studies regarding the potential for reducing GHG emissions from LNG-fuelled vessels, it has been proven that LNG-fuelled vessels are an alternative solution to be more intensely applied in ECA areas. There was a significant increase in LNG-fuelled vessels from 2010 to 2022, as seen in Fig. 4. 175 LNG-fuelled vessels were in service, 145 were LNG-ready, and 195 were in the order phase in 2022[19]. LNG-ready, or more precisely LNG fuel ready, is a classification of ships whose ship design, structure, and geometry can be adapted to the concept of an LNG-fuelled ship, including the necessary equipment and safety elements related to the location of the tank and hazardous areas can be accommodated following the Guidelines of Gas Fuelled Vessels [67]. An example of this type of vessel is the MV Sajir which was converted to an LNG-fuelled vessel in 2020 [61]. Fig. 5 shows some examples of LNG-fuelled vessels for different types of vessels.

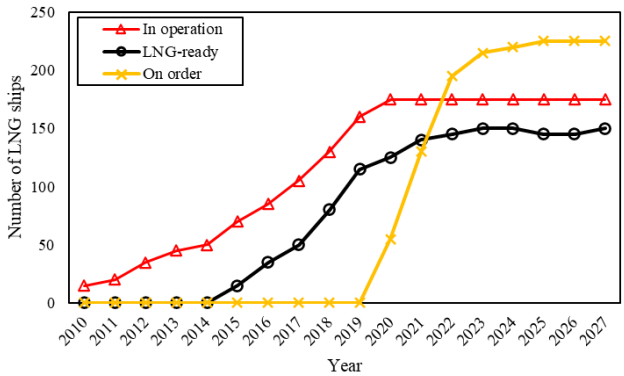


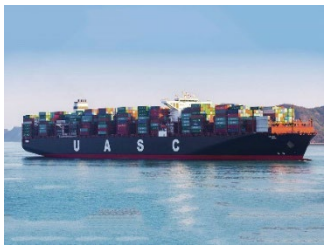
Fig. 4.: The number of LNG vessels operating globally from 2010 - 2022, with an estimate for the period until 2027[19].

Glutra (IMO 9208461), the first 100% LNG-fuelled ship[68)]

Creole Spirit (IMO 9681687), the world's most efficient LNG ship[65)]

Isla Bella (IMO 9680841), the world's first LNG-powered containership[65)]

Rem eir (IMO 9668647), the world's largest LNG-powered platform supply vessel[65)]



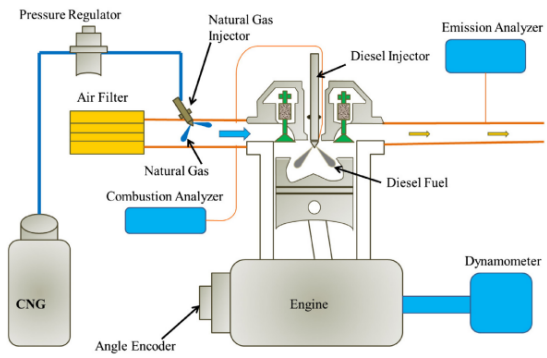
Sajir (IMO 9708784), one of the ship conversion projects with LNG-ready qualification[61)]

Abel Matutes (IMO 9441130), passenger ship LNG-powered retrofitted[69)]

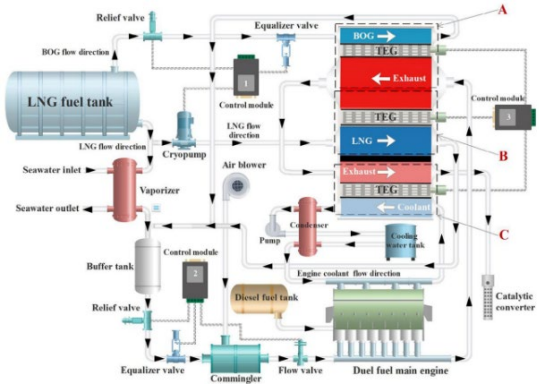
Fig. 6.: Several representative applications of LNG-fueled ships.

There are natural gas-powered ships that use CNG and LNG. These forms of fuel have different specifications and treatments. LNG is natural gas cooled to cryogenic temperatures (-162°C), which converts it into a liquid state. LNG usually consists of methane (CH4) as the main component, higher than CNG, with a methane content of around 95-99%. LNG is stored and transported in special cryogenic tanks and vessels maintaining very low temperatures. CNG is natural gas compressed to high pressure (usually around 200-250 bar) without liquefaction. CNG has a lower energy density than LNG due to its uncompressed form. It offers about 25-30% of the energy content of the same volume of natural gas in the gaseous state. CNG is stored and transported in high pressure cylinders or tanks. These storage systems must withstand high pressures and require safety features such as pressure relief devices and adequate ventilation[70,71)].

The very different tank specifications are the most important difference in the application of LNG and CNG. CNG tanks are bigger and heavier than LNG tanks to contain the same fuel mass. It is because the CNG tank must withstand enormous gas pressure[72)]. CNG tanks are divided into 4 types based on the material type 1 (all metal), type 2 (metal lines reinforced by composite wrap), type 3 (metal liner reinforced by composite wrap around the cylinder), and type 4 (plastic / fully wrapped tank). Meanwhile, the LNG tank is designed to minimize heat transfer with double wall insulation[73)]. Another difference is the fueling system of a different main engine. This difference can be seen in Fig. 6[74,75)].



a) CNG dual fuel



b) LNG dual fuel

Fig. 6.: Typical schematic diagram of CNG and LNG dual-fuel engine[74,75)].

5. Critical issues of LNG-Fuelled ships

The essential concerns for future research were discussed based on a synthesis of studies in each cluster. LNG is rapidly being viewed as a viable alternative fuel for ships because of its GHG emissions compared to

existing marine fuels. However, several major concerns and challenges must be addressed to fully achieve the promise of LNG-fuelled ships in lowering GHG emissions.

LNG is projected to have very high prospects and problems in future low-emission fuel use. One of the major issues is the insufficient infrastructure for LNG fuel supply. While LNG is widely used as a fuel for land-based transportation and power generation, there are currently just a few LNG bunkering facilities for ships. It makes switching to LNG fuel difficult for ship operators because they may have to travel long distances to refill. Another crucial issue is the expensive expense of adapting existing ships to use LNG fuel. Some ship operators may be unable to afford the process because it can be expensive and time-consuming. Furthermore, there are no defined standards for LNG-fuelled ships, which may confuse shipbuilders and operators.

In this section, other critical issues in developing LNG-fuelled ships. The discussion aims to assess the problems of constructing LNG-fuelled ships, including the environmental issue of significant methane slip in Section 4.1. Section 4.2 will briefly analyze the current geopolitical crisis' impact, and Section 4.3 will discuss the risk of the LNG bunkering process.

5.1 Environmental problem of high methane slip

It is a well-established fact that using liquefied natural gas (LNG) as a fuel source in engines can result in the release of methane, a greenhouse gas that has a global warming potential of 28, according to the IPCC's Fifth Assessment Report. This release of unburned fuel that escapes into the atmosphere is referred to as methane slip. To minimize this leakage, the BOG reliquefaction procedure is employed in LNG-powered transportation systems to regulate the temperature of storage tanks[76,77]. The cause of methane slip is usually attributed to two factors: the presence of dead volume, which can manifest as gaps between the components of the cylinder unit, and incomplete combustion, which can occur in the coldest regions of the combustion chamber when the engine is running[78]. Engines that use a lean burn spark ignition (LBSI) and have methane slip are typically classified as IMO category III engines and feature low-pressure injection before compression[79]. To accurately reflect the methane emission factors from marine engines, Pavlenko et al.[57] use energy-based emission factors (EF_e) values that consider changes in methane slip between engine technology. The following CH_4 EF_e values apply to engines running on LNG: LBSI (4.1 g/kWh), LNG-Diesel (0.20 g/kWh), LNG-Otto SS (2.5 g/kWh), and LNG-Otto MS (5.5 g/kWh). Depending on engine load, actual methane emissions from these engines could be higher or lower. Due to this, and as previously mentioned, a low load adjustment factor that is lower than the main engine's 20% MCR is used.

Following a review of the literature on various LNG-fuelled ships, the study estimated 10% CO_2 emission reduction offset by methane slip, which is the key value. The GHG emission from engines using methane as fuel was set at zero to generate emission estimates, although there are still uncertainties regarding the methane slip that can be decreased with technological improvement by 2050[36]. Furthermore, the expansion of the LNG-fuelled fleet, which includes both converted and newbuild vessels, has resulted in faster methane emissions growth than LNG itself when compared to other GHG emissions[36]. Several studies have criticized the existence of methane slip. Pavlenko et al.[57], in the study of the international council on clean transportation (ICCT), even demonstrated that the use of LNG as ship fuel is not viable for both HPDF and LPDF engines, which are most frequently used in LNG-fuelled ships, for the 20-year global warming potential (GWP) assessment. The benefits of using LNG can only be felt after 100 years of use, and even then, only 15% when compared to MGO. Moreover, Felayati et al.[80] mentioned that detecting methane emissions in the exhaust port reveals that these emissions decrease during the scavenging process. The fraction of methane emissions during scavenging is significantly smaller compared to the overall concentration of total HC emissions in the experimental results. At low load conditions, the contribution of the scavenging process to the formation of HC emissions in a diesel/natural gas dual-fuel engine is lower than that of the combustion process.

LNG and other alternative energies still have constraints in their use, so efforts to reduce global warming are constrained, such as high investment costs for solar-powered ships, ineffective sails for wind-powered ships, and methane slip on LNG-powered ships. However, the use of LNG is the most economically profitable. It is evident from the many engine manufacturers that choose this energy as a substitute for conventional fuel. Several steps and technologies have been taken to reduce methane slip.

The New Energy and Industrial Technology Development Organization (NEDO) has developed technology for methane oxidation catalysts (MOC) and developed more cost-effective machines to reduce methane slip by 70% over six years[81]. Fig. 7 shows the methane oxidation catalysts developed by NEDO. Meanwhile, the MAN energy solution uses exhaust gas recirculation (EGR) technology installed in the MAN ME-GI engine to ensure the methane slip produced is in the safe range of 0.2-0.3 gr/kWh[82].

The employment of modern combustion technologies, such as low-pressure lean burn engines, which can reduce methane slip by up to 90%, is one answer to this problem. Another option is SCR systems, which can cut methane emissions by up to 99%. It is crucial to highlight, however, that these solutions are not without their own set of issues. Low-pressure lean burn engines are more complex and expensive than typical engines, and SCR systems necessitate frequent maintenance and can add significant

expense to a ship's operation.

As previously stated, methane slip is a serious problem that must be addressed in LNG-powered ships. While technological developments can help to alleviate the problem, more research and development is required to create cost-effective and practical solutions. Additionally, the marine industry should be more aware of this issue and collaborate to discover methods to prevent methane slip.

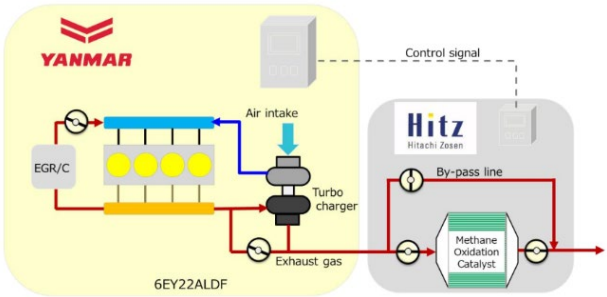


Fig. 7.: Methane oxidation catalysts from NEDO[82].

5.2 Influence of geopolitical impact

The growth of LNG-powered ships is not immune to geopolitical influences. These factors can considerably impact LNG supply and demand, as well as companies' capacity to invest in new projects.

Political unrest in LNG-producing countries can cause industrial uncertainty, making it difficult for corporations to plan and invest in new LNG-powered ships. Conflicts and civil wars can also cause disruptions in LNG production and shipping, resulting in supply shortages and price rises. Economic penalties imposed on LNG-producing countries by countries or international organizations can also impede companies' capacity to trade and transport LNG.

The Ukraine-Russia war that started on February 24th, 2022, has caused an increase in commodity prices, including LNG. As a country rich in mineral commodities, Russia is the leader of a gas-exporting country. In 2021, of the 241.3 billion m^3 of gas exported by Russia, 84% will be piped[83]. This gas is distributed to Europe, the Balkans, Central Asia, and China. Fig. 8 shows the ranking of leading gas-exporting countries in billion cubic meters in 2021.

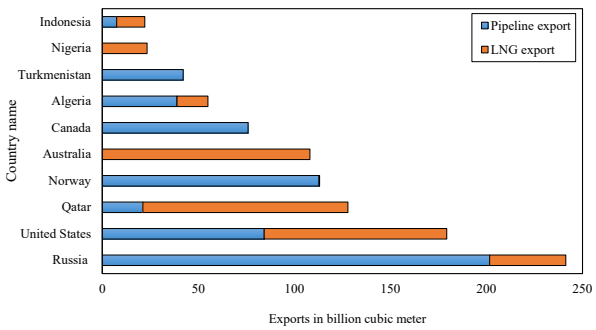


Fig. 8.: Leading gas exporting countries in 2021[83].

Nearly 42% of Europe's gas needs are assumed to be imported from Russia[84]. The gas distributed to Europe is used for civilians, industry, and others are converted into LNG for shipping fuel. Even some European countries have a high dependence on this gas type, such as France (USD 0.89 billion), Spain (USD 0.59 billion), the UK (USD 0.48 billion), Netherlands (USD 0.4 billion), Belgium (USD 0.39 billion), and Portugal (USD 0.17 billion)[85]. The ICIS East Asia Index and the ICIS TTF spot gas price for Europe have been up to $70/MMBtu[86]. With Russia steadily suspending the flow of natural gas since the start of the Ukraine war, Europe has shifted toward consuming high-cost liquefied natural gas (LNG). The spot market for LNG has also drifted away from Asian markets to European markets. Data obtained by the Anadolu Agency from Refinitiv, a provider of infrastructure and financial market information, show that Europe's LNG imports increased by 86% from June to August of 2022 compared to the same period in 2017. Despite the high costs, European nations are purchasing more LNG out of concern that the energy crisis brought on by the Ukraine-Russia war will leave them in the dark come the coming winter. The continuous increase in LNG prices and the termination of LNG infrastructure contracts between Russia and Europe can threaten the existence of LNG-fuelled ships as a long-term solution to reduce GHG emissions, considering that most LNG-fuelled ships in the world operate in European continents. IMO's vision to reduce GHG emissions by 2050 will be disrupted if this geopolitical conflict is not stopped immediately.

5.3 LNG bunkering process

The bunkering of LNG involves risk. The cryogenic LNG condition, which is at a temperature of -259.6°F and poses a risk to workers and nearby conventional steel structures or pipes, is one of the risk factors of the LNG bunkering process. Because they are dangerous and can create explosive clouds in small places, LNG vapors must be handled carefully when bunkering[87].

Adequate fire prevention equipment, certified personnel, and preventative techniques for all potential outcomes are necessary to reduce fire risk during the LNG bunkering process. Based on the likelihood that it will happen and the causes of the incident, the likelihood of this accident is examined. Making an event tree identification compilation is one of these analyses. Based on the causes of accidents, Fig. 9 illustrates an example of event tree identification in the LNG bunkering process[88].

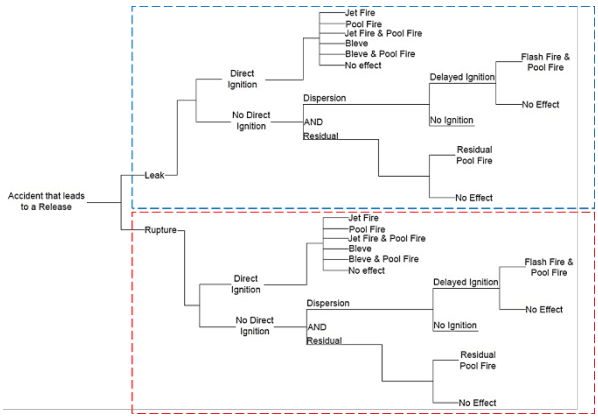


Fig. 9.: Event tree identification for LNG bunkering.

6. Overall Discussion

One of the proposed solutions to reduce GHG emissions in the shipping industry, as recommended by IMO, is the adoption of alternative fuels such as liquefied natural gas (LNG). Over the years, there has been a significant increase in the number of LNG-fueled vessels, both through new builds and conversion projects, from 2010 to 2022.

Among ship owners, the most common choice for utilizing LNG as a marine fuel is the installation of dual-fuel engines. This allows ships to operate on either LNG or traditional fuels, providing flexibility and reducing the reliance on conventional marine fuels. Large oceangoing vessels like container ships and tankers are particularly suitable for LNG implementation due to their size and energy requirements.

LNG offers substantial environmental benefits over traditional marine fuels, resulting in lower emissions of NOx, Sox, and PM_{10}, and other pollutants. By utilizing LNG as a marine fuel, these types of ships can contribute to a significant reduction in GHG emissions and help mitigate the environmental impact of the shipping industry. This is especially crucial as emission regulations become increasingly stringent.

The use of LNG can lead to a significant decrease in NOx, SOx, and PM_{10} particulate matter emissions. If all viable mitigation strategies are applied to newly built ships starting in 2025, it is believed that CO_2 emissions reductions in 2050 can meet both the mid-term and long-term targets. This highlights the potential of LNG as a crucial component in achieving emission reduction goals in the shipping sector.

However, it's important to acknowledge that LNG implementation also presents both opportunities and challenges in future applications. On the positive side, there are economic benefits associated with conversion projects compared to constructing entirely new ships. The fuel cost savings over the vessel's lifetime and investments in LNG-fueled shipbuilding can provide favorable returns. These economic advantages make LNG an attractive option for ship owners.

Nevertheless, there are challenges that need to be addressed. One significant concern is the environmental issue of methane slip, which refers to the unintended release of methane during LNG combustion. Methane is a potent greenhouse gas, and its release could undermine the overall environmental benefits of LNG. Efforts are being made to develop and implement technologies and practices that minimize methane slip and ensure the environmental sustainability of LNG as a marine fuel.

Additionally, the unresolved geopolitical crisis can impact the future development of LNG-fueled ships. The availability and accessibility of LNG as a fuel source can be influenced by geopolitical factors, such as supply disruptions or political tensions in LNG-producing regions. These uncertainties pose challenges to the widespread adoption of LNG as a marine fuel and require careful consideration in future planning and decision-making processes.

7. Conclusion

The use of LNG as a marine fuel provides the potential to lower GHG emissions from ships dramatically. When compared to conventional fossil fuels, LNG burns cleaner and produces less SOx, PM, and NOx pollution. Furthermore, LNG-powered ships produce much less CO2 emissions than conventional fossil fuel-powered ships. The International Maritime Organization (IMO) has created rules and regulations for the safe handling and storage of LNG and the design and operation of LNG-powered ships. It is used to reduce greenhouse gas emissions from ships. The shipping sector can strive toward achieving the IMO target of decreasing GHG emissions from ships by at least 50% by 2050 by adopting LNG-fuelled ships and other alternative fuels.

As a result of reviewing the impact of the development of LNG-powered ships on greenhouse gas (GHG) emissions, several recommendations can be made. The number of vessels using LNG as fuel is rising and these ships can be classified as 100% LNG-powered, dual-fuel, or LNG-ready. Most of the LNG-powered fleet operates in Emission Control Areas (ECA), including the Baltic Sea, North Sea, North American, and US Caribbean Sea regions. The study has analyzed the most recent research and initiatives that explore the potential of using LNG as a ship fuel to lower GHG emissions through a systematic review of various sources. This review showed that LNG can significantly reduce NOx, SOx, and PM_{10} emissions compared to traditional ship fuels by 86.1%, 94.5%, and 92.7%, respectively.

LNG is projected to have very high prospects and problems in future uses as a low-emission fuel, such as methane slip on LNG-powered ships. There are uncertainties regarding the amount of methane slip that can be decreased with technological improvement by 2050. Besides that, the viability of LNG-fuelled ships as a

long-term strategy to reduce GHG emissions may be threatened by the ongoing rise in LNG costs and the termination of LNG infrastructure contracts between Russia and Europe.

Based on the systematic review described above, the authors recommend several factors regarding the application of LNG as the main fuel in the shipping business sector:

1. Based on the IMO GHG Study, it has been stated that LNG is an alternative future fuel that is more environmentally friendly, reducing SOx, NOx, and PM_{10} compared to conventional marine fuel. This could be a consideration for shipping companies to start implementing LNG as fleet fuel.
2. Many ship engine manufacturers have made engines with dual fuel capabilities, and this is intended so that LNG can be coherently applied as a companion fuel to accompany conventional marine fuel.
3. The implementation of LNG in dual fuel marine engine technology has been widely applied in gas carrier-type ships by utilizing BOG from the transported gas and channeled to the main engine.
4. Fleet owners must pay attention that applying LNG as ship fuel requires a special storage place different from conventional fuel. For new ships, it may be possible to place the LNG bunker tank in the ship's hull, even though construction requires quite a large space. This can be overcome by placing the LNG bunker tanks outside the ship deck with the addition of reinforcement construction, such as on the Isla Bella ship (IMO 9680841). This concept can also be applied to existing ships, both cargo ships such as tankers and bulk carriers, and passenger ships.
5. Shipping fleet companies must also consider critical issues in applying LNG as a marine fuel, such as using the latest technology to overcome methane slip and risk mitigation in the bunkering process and efforts to deal with geopolitical crises affecting LNG fuel prices.

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