Analysing the Impact of LNG Fuelled Ships on Maritime Transport by Fuzzy Delphi Method

M.Sc.Orçun TOPRAKÇI[1] **PhD.Ozan Hikmet ARICAN**[2]

[1] Kocaeli University, Maritime Business and Management, Kocaeli, Turkiye, orcun402386@gmail.com, https://orcid.org/0009-0004-0491-5133

[2] Kocaeli University, Maritime Business and Management, Kocaeli, Turkiye, ozanhikmet.arican@kocaeli.edu.tr, https://orcid.org/0000-0003-2061-6112

Abstract: In light of the stringent measures imposed by the International Maritime Organization (IMO) and the European Union (EU) with the objective of curbing exhaust emissions in accordance with zero emission targets, liquefied natural gas (LNG)-fuelled vessels are regarded as the optimal solution for the medium term by ship owners and maritime enterprises. The proliferation of these vessels is rapidly escalating. The present study aims to analyse the effects of LNG-fuelled ships on maritime transport in terms of environmental, technological, economic, commercial, legal and social factors determined by the literature research using the Fuzzy Delphi Method. The findings of this study demonstrate that the most significant factors influencing the adoption and development of LNG-fuelled ships in maritime transport are as follows: *bunkering network, machinery type, unburned methane emission, exhaust emission (NOx, SOx, PM, CO_2), safety, operation cost* and *sailing pattern*. The study will evaluate the impact of IMO regulations on the adoption of LNG-fuelled ships by maritime enterprises and the development of LNG-fuelled ship fleets on maritime transport. The findings will serve as a valuable reference point for LNG ship investors.

Key Words: Exhaust Emission, Exhaust Emission Regulation, LNG Fuelled Ships, Maritime Transport, Fuzzy Delphi

1. INTRODUCTION

Despite the environmental benefits of maritime transport, the increase in ship traffic has resulted in a rise in environmental concerns due to emissions (Pekşen and Alkan, 2015).In accordance with MARPOL 73/78 Annex VI, the International Maritime Organization (IMO) has set targets to limit global SO_x emissions to 0.5% m/m by 2020 and 0.1% m/m in ECA regions from 2015 (Vuskovic et al., 2023). The implementation of the Tier III standard in 2016 has resulted in a 80% reduction in NO_x emissions in ECA regions (Lee et al., 2020). The release of greenhouse gases and air pollutants into the atmosphere from exhaust gases has been identified as a contributing factor to global warming, acid rain, and the degradation of air quality (Celikaslan and Kılıc, 2023).

In 2023, the total greenhouse gas emissions from ships amounted to 36.8 billion tonnes of CO_2, representing an increase of 1.1% compared to the previous year (Nubli and John, 2022). In the same year, the maritime sector accounted for 3% of the global CO_2 emissions (Oh et al., 2024).

In accordance with the most recent research, the International Maritime Organization (IMO) has set itself the objective of reducing greenhouse gas (GHG) emissions from ships by 40 per cent by 2030 compared to 2008, with a further target of reaching net zero by 2050 (Li and Yang, 2024), (Balcombe et al., 2021). The European Union (EU) has set itself a similarly ambitious target, aiming to reduce the GHG intensity of marine fuels by 80 per cent by 2050 (Ramsay et al., 2023).

The implementation of emission restriction measures by the International Maritime Organization (IMO) and the European Union (EU) has prompted the maritime industry to explore the use of alternative fuels that are compatible with these restrictions. The adoption of Marine Gas Oil (MGO), Marine Diesel Oil (MDO), Low Sulphur Diesel (LSD), Ultra Low Sulphur Diesel (ULSD), or scrubber systems in lieu of Heavy Fuel Oil (HFO) has been identified as a potential means of achieving emission reduction. Alternatively, LNG fuelled engines are preferred to comply with IMO standards (Wang and Notteboom, 2014), (Sohn and Jung, 2022).

Despite the fact that LSD, ULSD and distillate fuels meet sulphur requirements, concerns regarding high cost and availability create uncertainties (Kuang et al., 2023). This has prompted the search for alternative fuels and increased the need for additional technologies for CO2 and NOx reduction (Salarkia and Golabi, 2023). Additionally, the low lubricity of LSD and ULSD has the potential to result in equipment failure in HFO-compatible machinery (Sharafian et al., 2019).

Exhaust gas cleaning systems have been shown to be effective in SO_x reduction and can be used in conjunction with HFO. Although the low cost of HFO is advantageous, the high installation and maintenance costs and the

failure to fully meet NO_x and CO_2 emissions are disadvantages (Dereli, 2018). LNG is regarded as the most significant alternative fuel due to its reduced cost and the capability to decrease SO_x, NO_x, PM, and CO_2 emissions (Tuswan et al., 2023), (Stewart and Wolosz, 2015).

LNG-powered ships have been shown to reduce SO_x emissions by 90-95%, PM emissions by almost 100%, NO_x emissions by 85-90%, and CO_2 emissions by 15-20% (Abdelmalek and Guedes Soares, 2023), (Herdzik, 2013). Moreover, the utilisation of LNG has been demonstrated to reduce CO2 emissions and offer financial benefits under the EU Emissions Trading Scheme (EU ETS), which came into effect in 2024, and the impending FuelEU Maritime Regulation, scheduled for implementation in 2025 (Karatuğ et al., 2023).

LNG has been identified as playing a pivotal role in enabling the maritime sector to achieve its 2050 net zero target (Tuswan et al., 2023). However, it is important to note that LNG does not offer a complete solution for greenhouse gas (GHG) mitigation, primarily due to the emission of unburned methane (Balcombe et al., 2021). Nevertheless, LNG does provide immediate environmental benefits and serves as a transitional fuel for the transition to renewable marine fuels (Baresic and Rehmatulla, 2024).

LNG-fuelled ships, which commenced operations with a modest number of vessels in the early 2010s and have undergone substantial expansion in recent years, persist in their role within the maritime transport sector despite the continuous updates, tightening and expansion of exhaust emission gas restrictions promulgated by the International Maritime Organization (IMO) and the European Union (EU). In this context, it is imperative to analyse the impact of LNG-fuelled ship fleets on maritime transport in light of the latest updated emission rules, informed by expert opinions, in order to address the existing lacuna in the extant literature.

The objective of this study is to analyse the effects of LNG-fuelled ships on maritime transport using the Fuzzy Delphi Method. This analysis will consider environmental, technological, economic, commercial, legal and social factors determined by a thorough literature review.

2. BACKGROUND

A substantial corpus of research has been dedicated to the analysis of LNG-fuelled ships. This research has encompassed the calculation of exhaust emission changes, stratified by ship type, and cost analyses. The merits and drawbacks of LNG-fuelled ships have been thoroughly debated within the academic literature.

In order to promote LNG as a marine fuel, Schinas and Butler (2016) analysed policy initiatives supporting the use of alternative technologies and developed a methodology to estimate the market impacts of these initiatives. In their study, regulatory frameworks, commercial characteristics and barriers favouring the use of LNG are addressed. Jasper Faber (2017) qualitatively analysed the drivers and barriers affecting LNG adoption and examined the development of the LNG market in the EU. According to Faber, environmental regulations and price differentials have the potential to increase demand for LNG, while issues such as port availability, technical standards and second-hand prices act as barriers to adoption.The economic and environmental superiority of LNG was determined by parameters such as price differentials, operation rate, new ship value and procurement costs (Chen et al., 2018). The possibility of investing in LNG-powered ships was tested with new chemical ship investment.

Bayraktar (2016) conducted an analysis of the economic benefits of converting the diesel engine system of a cruise ship into a dual fuel system, concluding that the investment can be recouped within a decade. The study also emphasised the system's compliance with the latest emission restrictions. In a similar vein, Moreira (2016) calculated the emissions of HFO, MGO and LNG fuelled ship models equipped with SCR, determining that LNG is the most economical and clean fuel.

Dereli (2018) conducted a comprehensive examination of the detrimental impacts of exhaust emissions on the environment and human health. The study also involved a detailed discussion of the methodologies developed to mitigate these effects and the emission limits that have been established. Additionally, the study provides a comprehensive overview of the technical intricacies involved in the conversion of single-fuel machines into dual-fuel machines. Lindstad et al. (2020) investigated the conditions under which LNG can be used as a transition fuel to reduce carbon emissions in maritime transport and ways to ensure the lowest global warming impact, and stated that LNG can only be effective with dual-fuel diesel engines.

Balcombe et al. (2021) conducted a comprehensive environmental life cycle and cost comparison of LNG with HFO, MDO, methanol and renewable fuels, concluding that LNG enhances air quality and reduces costs, though methane emissions are high in certain engines. In a separate study, Salarkia and Golabi (2023) examined the

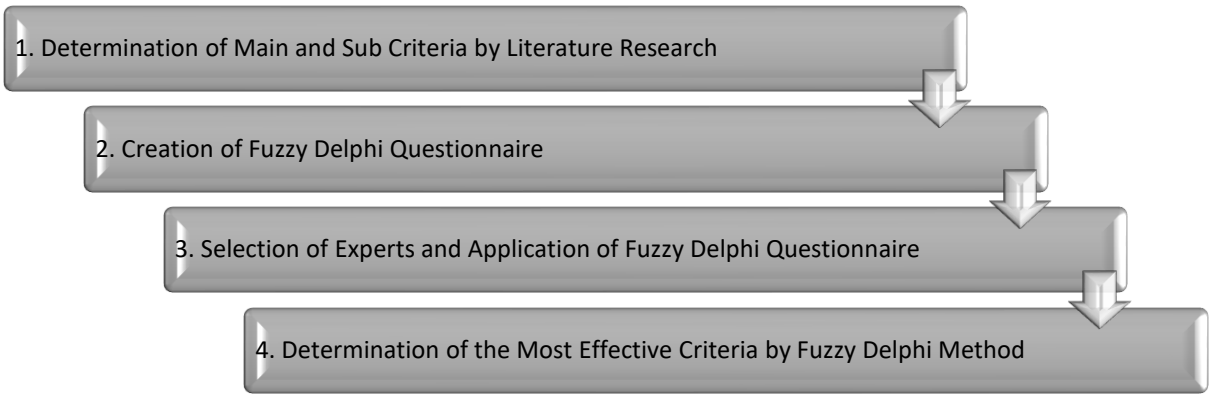
environmental and economic advantages of LNG, emphasising that LNG offers environmental benefits with low emissions compared to MGO, MDO and HFO/Scrubber fuels and is the most suitable fuel for IMO 2020 requirements.

In this context, the present study will address the existing lacuna in the extant literature by evaluating the advantages and disadvantages of LNG-fuelled ships and their impact on maritime transport in both the present and future contexts. This evaluation will be informed by the latest IMO and EU rules, as well as the opinions of experts who play an active role in maritime transport activities.

3. METHODOLOGY

In the context of the IMO's increasingly stringent regulations, the utilisation of LNG-fuelled ships as an alternative maritime transport solution has given rise to a range of observations regarding their environmental, economic, technological, commercial, legal and social impacts. A comprehensive review of the extant literature has facilitated the identification of both the advantages and disadvantages of LNG as a bunker fuel across these diverse domains. To ascertain the most significant and effective criteria identified from this body of literature, the Fuzzy Delphi method was employed in the study. Research Methodology is presented in Figure 1.

Figure 1: Research Methodology



Source: Author

The traditional Delphi method is a consultative approach that aims to achieve consensus on complex issues by collecting expert opinions. This method is applied through successive survey rounds (Hsu and Sandford, 2007).However, consecutive surveys to ensure the consistency of expert opinions and pressures to change opinions may create negativity (Ma et al., 2011). Fuzzy Set Theory, developed by Zadeh in 1955, offers the possibility to reflect uncertainty and convert expert language into quantitative values (Bouzon et al., 2016), (Alqahtani et al., 2023). This theory has been integrated into the Delphi method, reducing the number of interviews and research time and enabling more comprehensive communication of expert judgements (Bui et al., 2020).

4. RESULTS

4.1. Determination of Main and Sub Factors

A comprehensive review of the literature was conducted in order to ascertain the factors affecting the maritime trade of LNG-fuelled ships. These factors were then classified into six groups: environmental, technological, economic, commercial, legal and social. The findings obtained from this review are presented in Table 1, which details 35 sub-factors.

Table 1: Main and Sub Factors Determined According to Literature Research.

MAIN FACTORS	CODE	FACTORS	REFERANCES
Environmental	C1	Exhaust Emission (NOx, SOx, PM, CO2)	Livaniou et al., 2022; Abdelmalek and Guedes Soares, 2023 Burel et al., 2013

	C2	Air Pollution	Sohn and Jung, 2022; Pekşen and Alkan, 2015
	C3	Global Warming	Xu and Yang, 2020; Çelikaslan and Kılıç, 2023
	C4	Environmental Pollution Caused by LNG Accidents	Nubli and John., 2022
Technological	C5	Ship Design and Location of Fuel Tank	Stewart and Wolosz, 2015; Parfomak et al., 2019
	C6	Type Of Engine	Balcombe et al., 2021; Karatuğ et al., 2023; Sharafian et al., 2019
	C7	Unburned Methane	Tuswan et al., 2023; Comer et al., 2024; Balcombe et al., 2021
	C8	Capacity Loss Ratio	Tuswan et al., 2023; Salarkia and Golabi, 2023
	C9	Safety Issues Such as Flammability	Peng et al., 2021; Molitor et al., 2012
	C10	Security Issues	Bruzzone and Sciomachen, 2023; Wang and Notteboom, 2014
	C11	Fuel and Lubricating Oil Consumption	Merien-Paul et al, 2019
	C12	Retrofitting Tendecy	Baresic and Rehmatulla, 2024; Parfomak et al., 2019
	C13	Needless of Abatement Systems such as Scrubber	Dereli, 2018
Economical	C14	LNG Fuel System Capital Cost	Wang et al., 2021; Bayraktar, 2016
	C15	LNG Fuel Delivery Cost	He et al., 2024; Wang et al., 2021; Dereli, 2018; Bayraktar, 2016
	C16	Operation Cost	Faber, 2017; Chen et al., 2018
	C17	Possible Environmetal Cost	Çelikaslan and Kılıç, 2023; Xu and Yang, 2020
	C18	Cost Savings	Karatuğ et al.,2023; Moreira, 2016
	C19	Infrastructure	Parfomak et al., 2019; Yao et al., 2024
	C20	Maintenance Cost	Faber, 2017; Merien-Paul et al., 2019
Commercial	C21	Sailing Pattern	He et al., 2024; Faber, 2017
	C22	Bunkering Network	Yao et al., 2024; Peng et al., 2021
	C23	LNG Distribution Network	Schinas and Butler, 2016
	C24	LNG Source	Bruzzone and Sciomachen, 2023
	C25	Availibity to Ship Types	Oh et al., 2024; Kuang et al., 2023
	C26	Cargo Space Loss	Salarkia and Golabi, 2023
	C27	Operation Standarts	Stewart and Wolosz, 2015
	C28	Competitivness	Wang and Notteboom, 2014; Yao et al., 2024
Legal	C29	Emission Reg. MARPOL Annex VI	Oh et al., 2024; Vuskovic et al., 2023
	C30	LNG Bunkering Regulation	Peng et al., 2021; Bruzzone and Sciomachen, 2023
	C31	Regulations on Gas Fueled Ships_ IGF Code	Ha et al., 2022
	C32	Regulatory Gap	Ha et al., 2022
Social	C33	Social Public Awareness	Lee et al. 2020; Wang and Notteboom, 2014
	C34	Public Perception	Lee et al. 2020; Wang and Notteboom, 2014
	C35	Contribution of Government	Li and Yang, 2024; Wang and Notteboom, 2014

4.2. Creation of Fuzzy Delphi Questionnaire

The fuzzy method employs a variety of fuzzy numbers to transform expert opinions from linguistic factors into fuzzy numbers, with Trigonometric Fuzzy Numbers (TFN) being the preferred option in this study. TFN is expressed as a function of three real numbers: the minimum possible value (a), the maximum possible value (b),

and the minimum possible value (c) (Alqahtani et al., 2023). The degree of influence of the criteria obtained as a result of the literature research is determined by a questionnaire created with the linguistic variables in Table 2.

Table 2: List of Linguistic Terms And Meanings

Symbols	Linguistic Variables	TFNs (a, b, c)
VL	Very Low Efficiency	(0,0,0.25)
L	Low Efficiency	(0, 0.25, 0.5)
M	Medium Efficiency	(0.25, 0.5, 0.75)
H	High Efficiency	(0.5, 0.75, 1)
VH	Very High Efficiency	(0.75, 1, 1)

Source: Mohammadfam et al. (2022)

4.3. Selection of Experts and Application of Fuzzy Delphi Questionnaire

The present study's sample consists of maritime enterprises engaged in maritime transport with LNG-fuelled ships. In selecting the sample, the guided sampling method was favoured, as it is considered the most effective approach in reflecting the research problem and observing the solution in its most typical manifestation. Given that completing the questionnaire requires expertise and experience, the sample was composed of individuals with a proven track record in the field of LNG-fuelled ships. The participants in the study were selected based on their extensive professional experience, ranging from 10 years in the field of LNG and LNG-fuelled vessels, to positions such as operations manager, fleet manager, technical manager, captain, and chief engineer. The distribution of the questionnaire to the experts was conducted electronically via email.

4.4. Determination of the Most Effective Criteria by Fuzzy Delphi Method

In the Fuzzy Delphi Method, the linguistic values obtained from the questionnaire were first converted into Trigonometric Fuzzy Numbers (TFN). Then, the average fuzzy evaluation score of the group decision for each factor was calculated, and the average fuzzy evaluation scores were converted into definite values by using the simple centre of gravity method. These values were then used to determine the order of importance of the factors. Factors with a score of 0.7 and above were deemed effective, while those with scores below this threshold were excluded from further consideration.

In order to ascertain the expert consensus, the distance between the fuzzy prediction values of the experts on each factor and the average fuzzy value of that factor for all experts was calculated as a percentage. For each factor, a limit of 75% was assessed based on expert agreement. Factors with less than 75% expert agreement were then ignored.

The Fuzzy Delphi Method was utilised to ascertain the most significant criteria, with the degree of importance and the intersection set on the consensus boundary determined as the primary factors. The most important criteria identified by the Fuzzy Delphi Method are presented in Table 3.

Table 3: The Most Important Factors Affecting Maritime Transport.

CODE	CRITERIA NAME
F1	Exhaust Emission (NOx, SOx, PM, CO2)
F2	Air Pollution
F3	Machine Type
F4	Unburned Methane Gas
F5	Safety Issues
F6	Security Issues
F7	Fuel and Lubricating Oil Consumption
F8	Exhaust Cleaning System Requirement
F9	LNG Fuel Capital Cost
F10	LNG Fuel Sales Price

F11	Operation Cost
F12	Cost Savings
F13	Maintenance Cost
F14	Sailing Pattern
F15	Refuelling Network
F16	Operation Standards
F17	Competition
F18	LNG Fuel Transfer Regulation

5. DISCUSSION AND CONCLUSION

This study analyses the impact of LNG fleets on maritime transport in the face of continuously updated and tightening exhaust emission restrictions since 2016, when the use of LNG fleets commenced with a small number of ships, based on expert opinions, and presents findings especially in environmental, economic and commercial terms.

The fact that LNG-fuelled ships emit different NO_x and unburned methane emissions (F4) depending on the engine type (F3) represents a challenge for the greenhouse gas emission rules issued and planned by the IMO and EU in line with zero emission targets in recent years. Of particular concern is the unburned methane emission in LNG engines, which, as highlighted by Comer et al. (2024), exhibits an unacceptably high power greenhouse gas effect. This poses a significant challenge to the environmental benefits of LNG-fuelled ships, unless measures are implemented to reduce these emissions through technological advancements in engine design. The introduction of the FuelEU Maritime rules by the EU, effective from 1 January 2025, aimed at curbing methane emissions, and the EU ETS payments, scheduled to be implemented by 2026, are poised to neutralise the environmental and environmental costs of LNG-fuelled ships associated with NOx, SOx, PM, and CO2, as outlined in the studies conducted by Karatuğ et al. (2023).

As stated in the studies conducted by Herdzik (2013) and Wang and Notteboom (2014), there is a significant reduction in NOx, SOx, PM, and CO2 emissions (F1) when compared to other conventional fuels. The findings of Herdzik (2013) and Wang and Notteboom (2014) demonstrate that LNG fuel, when utilised by compatible vessels, offers a substantial advantage to ships operating within Emission Control Areas (F18) as delineated by the International Maritime Organization (IMO).The distance traversed in ECAs is also a pivotal factor in determining the operational costs of a vessel.

The enhanced efficiency of LNG-powered engines, reduced fuel consumption and diminished lubricating oil consumption (F7) (Merien-Paul et al., 2019), as deduced by the calculations of Moreira (2016), result in diminished costs. Moreover, LNG engines exhibit reduced maintenance costs (F13) in comparison to other heavy fuel diesel engines, attributable to the more efficient and unsoiled system and the longevity of the machine.

In this context, it is evident that these factors have a substantial impact on the freight prices (F11), contingent on the geographical regions, operation and maintenance costs of LNG-fuelled ships, and the maritime enterprises that possess these ships.

In addition, the competition factor (F17) has gained importance within the scope of tightening IMO and EU emission rules and technological advances. With the 2020 IMO sulphur standards coming into force, it is evident that LNG has increased its price competitiveness against low sulphur fuels, and as Wang et al. (2021) state, the selling price of LNG fuel (F10) varies according to geographical regions. Furthermore, ongoing research endeavours are focused on enhancing the engine types utilised in LNG-fuelled ships, where unburned methane emissions are particularly high. This has given rise to a state of technological competition among major marine engine manufacturers, who are striving to address the identified deficiencies. The tightening measures of IMO and EU have resulted in a rapid increase in the number of LNG-fuelled ships around the world in recent years, as well as an increase in competition in the shipbuilding sector and maritime businesses, especially ports, as stated by Yao et al. (2024).

Concurrent with the surge in the number of LNG-fuelled ships, the adequacy of LNG bunkering points has emerged as a pivotal factor in propelling the sector's advancement (Peng et al., 2021). The preeminence of the Bunkering Network (F15) as a crucial element in this context is consistent with this observation. As He et al.

(2024) have asserted, LNG-fuelled ship owners and operators must consider available suitable LNG bunkering points when determining routes (F14) and ports of call for their ships. These ships follow routes that provide easy access to LNG bunkering facilities and where the selling price of LNG fuel is favourable.

As Bruzzone and Sciomachen (2023) have observed, the ongoing Russia-Ukraine conflict has resulted in significant imbalances in gas supply (F9) and prices (F10), particularly for Europe. These imbalances are among the most salient factors identified in the study, and support the hypothesis that the conflict has had a substantial impact on the energy market.

Finally, Safety Issues (F5) and Security Issues (F6), which are among the most significant factors, are an issue that should be supported as standards, rules, training and materials in maritime transport due to the chemical properties of LNG. As Molitor et al. (2012) have asserted, although LNG fuel is not a toxic substance and the flammability lower-upper limit range is narrow, rapid phase transformation may occur in the event of leakage during transport, transfer and use of the fuel due to its cryogenic properties. This potential hazard can manifest in the form of flammable vapour clouds, flash fires, fireballs and explosions. Furthermore, although this has not yet been observed, it is a matter that should be evaluated, as LNG may also pose a security vulnerability due to its structural features that can cause major damage.

The findings indicate that factors such as operation cost, voyage and route planning, refuelling network, competition, machinery type, unburned methane emission, exhaust emission (NOx, SOx, PM, CO_2), safety issues, and LNG fuel sales price are of paramount importance in the utilisation of LNG-fuelled ships in maritime transport. As previously indicated by other studies, it has been determined that the most significant and influential factors in the role of LNG-fuelled ships in maritime transport are the refuelling network, the machinery type, unburned methane emission, exhaust emission (NOx, SOx, PM, CO_2), safety, operation cost and voyage and route planning.

The extant research results indicate that liquefied natural gas (LNG)-fuelled ships reduce operational costs depending on geographical regions and operation-maintenance costs, whilst concomitantly contributing to stakeholders with environmental savings. Concurrently, they increase competition in accordance with IMO and EU's stringent emission targets. LNG-fuelled ships thus offer an economic alternative in ECA regions by meeting the current rules with appropriate engine type choices, and are regarded as the most suitable option for zero emission targets in the medium term.

The geographical disparities in the adoption of LNG-fuelled ships and the prospective expansion of the regulatory framework constitute the study's limitations. This study serves as a foundation for future research in the context of emission regulations and the advancement of LNG-fuelled ships. Potential future research directions could encompass the analysis of specific cargo types or the assessment of regional impacts.

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