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A Fuzzy-Based Assessment of LNG-Fuelled Ships' Impact on Maritime Logistics

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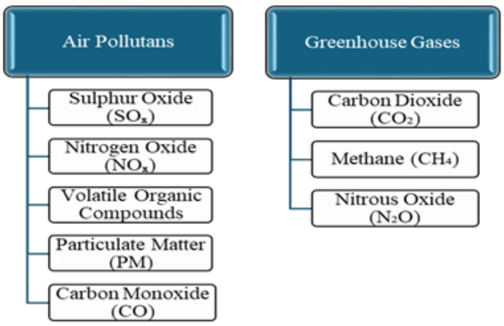
Abstract: In light of stringent emission reduction policies set by the International Maritime Organization (IMO) and the European Union (EU), LNG-fuelled ships (LFS) have emerged as a significant medium-term solution for the maritime industry. This study employs the Fuzzy Delphi Method to evaluate environmental, technological, economic, legal, and social factors identified through an extensive literature review, while the Fuzzy DEMATEL Method is used to determine cause-and-effect relationships based on expert assessments. Findings reveal that **F11** "*Operation Cost*" and **F14** "*Sailing Pattern*" are the most influential factors in the adoption of LFS. Additionally, key considerations include **F15** "*Bunkering Network*", **F3** "*Engine Type*", **F4** "*Unburned Methane Emissions*", **F1** "*Exhaust Emissions (NOx, SOx, PM, CO_2)",* and **F5** "*Safety Concerns*". Beyond addressing operational and economic challenges, LFS contribute significantly to mitigating maritime pollution, protecting marine ecosystems, and combating climate change. This study provides valuable guidance for LNG ship investors and maritime stakeholders, facilitating the transition to LNG-powered fleets in compliance with IMO regulations.

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

1. INTRODUCTION

Despite being regarded as an environmentally friendly mode of transport, the rising volume of maritime traffic has intensified air pollution from ship emissions (Yao et al., 2023). Exhaust gases, including greenhouse gases (CO_2, CH_4) and air pollutants (SO_x, NO_x, PM), presented in Figure 1, contribute to global warming, acid rain, and air quality degradation, posing significant risks to human health (Xu & Yang, 2020; EPA, 2024; Arıcan et al., 2022).

Figure 1. Exhaust Emissions from Ships

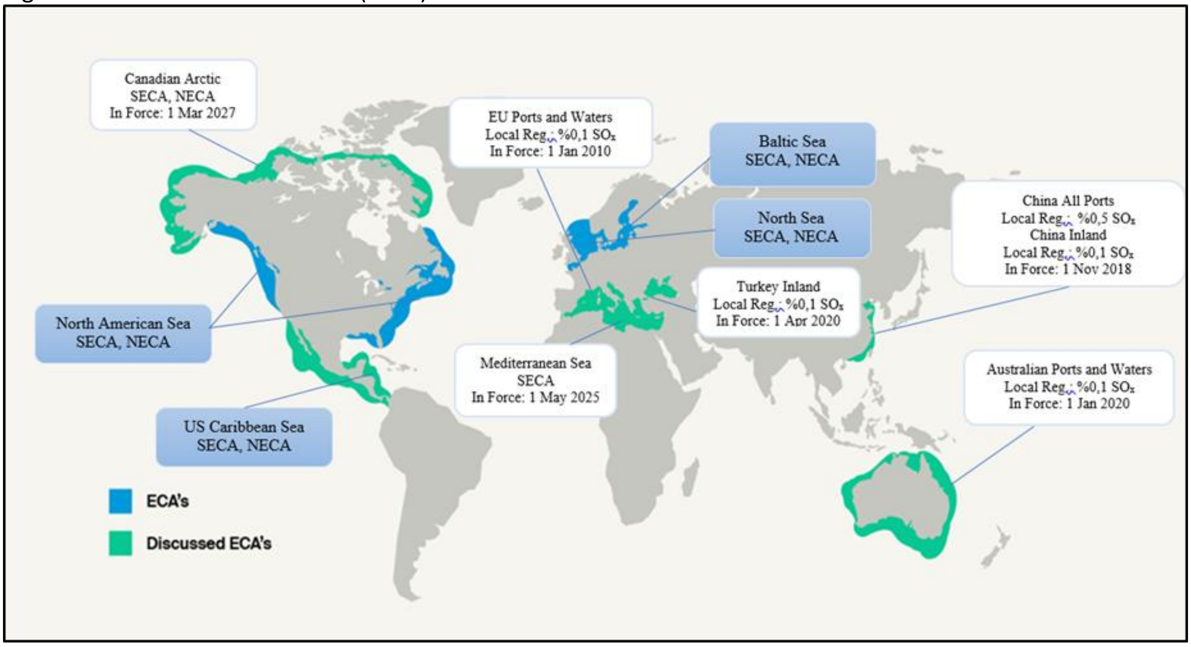


Under MARPOL 73/78 Annex VI, the IMO set a global sulfur oxide (SO_x) emission limit of 0.5% m/m by 2020 and 0.1% m/m in Emission Control Areas (ECAs) by 2015 (Vuskovic et al., 2023). Additionally, Tier III regulations, effective from 2016, mandate an approximately 80% reduction in NO_x emissions for ships operating in ECAs compared to Tier II standards (Lee et al., 2020).

IMO-designated ECAs have stricter emission limits under MARPOL Annex VI, aiming to reduce SO_x, NO_x, and PM emissions globally and regionally. While SECA regions focus on SO_x reduction and NECA regions on NO_x, ECAs target reductions in all three pollutants (Sari et al., 2023; Arıcan et al., 2022). The existing ECAs, presented in Figure 2 include the Baltic Sea, North Sea, North American coastlines, and the US Caribbean Sea (IMO Report, 2023).

In 2022, MEPC 79 designated the Mediterranean Sea as a SO_x-ECA, effective from 1 May 2025. Additionally, in 2024, MEPC 82 approved the designation of Canadian Arctic Waters and the Norwegian Sea as ECAs for NO_x, SO_x, and PM, with enforcement starting on 1 March 2027 (Clean Arctic Alliance, 2024).

Figure 2. Emission Control Areas (ECAs)



GHG emissions from ships peaked in 2023 at around 36.8 billion tonnes CO_2, an increase of 1.1% compared to 2022 (Nubli and John, 2022). In 2023, the maritime sector also accounts for 3% of total global CO_2 emissions (Oh et al., 2024; Yao et al., 2024; Unal et al., 2022).

IMO targets a 40% reduction in GHG emissions from ships by 2030 (compared to 2008) and aims for net-zero emissions by 2050 (Li & Yang, 2024; Balcombe et al., 2021). Similarly, the EU seeks an 80% reduction in the GHG intensity of maritime fuels by 2050 (Ramsay et al., 2023)

In this context, a series of rules have been put into force by IMO and the EU for the reduction of greenhouse gas emissions in the maritime sector, the scope and requirements of which are specified in Table 1 (SEA-LNG Report, 17 December 2024; IMO, 2024).

IMO and EU emission regulations have driven shipowners to seek compliant fuel alternatives. Options include switching from heavy fuel oil (HFO) to MGO, MDO, LSD, or ULSD to improve fuel quality or using scrubbers to achieve equivalent emission reductions (Wang & Notteboom, 2014; Sohn & Jung, 2022). Alternatively, compliance can be met by adopting LNG-fueled engines (Rahimi et al., 2020; Faber, 2017).

While low-sulfur fuels (LSD, ULSD) and distillates (MGO, MDO) meet sulfur regulations, their high costs and rising demand create price volatility and supply concerns (Parfomak et al., 2019; Kuang et al., 2023). This drives shipowners toward alternative fuels and technologies to further reduce CO_2 and NO_x emissions (Salarkia & Golabi, 2023; Pekşen & Alkan, 2015). Additionally, LSD and ULSD are incompatible with HFO-fueled engines, as their low lubricity can cause failures in critical components like fuel pumps and injectors (Sharafian et al., 2019).

Exhaust gas cleaning systems effectively reduce SO_x emissions and can be used with HFO, offering a cost advantage despite high technological expenses (Dereli, 2018; Cassar et al., 2021). However, their high installation and maintenance costs, along with limited effectiveness in reducing NO_x and CO_2 emissions, pose disadvantages (Salarkia & Golabi, 2023; Tekeli et al., 2024). In contrast, LNG is considered a key alternative due to its lower cost compared to other fuels (Bayraktar, 2016) and its ability to significantly reduce SO_x, NO_x, PM, and CO_2 emissions (Tuswan et al., 2023; Stewart & Wolosz, 2015; Livaniou et al., 2022).

LFSs reduce SO_x emissions by 90-95% (Ghadikolaei et al., 2016), particulate matter (PM) by nearly 100% (Abdelmalek & Guedes Soares, 2023), NO_x by 85-90% (Merien-Paul et al., 2019), and CO_2 emissions by 15-20% (Burel et al., 2013; Herdzik, 2013). Additionally, LNG use lowers CO_2 emissions, benefiting financial outcomes under the EU Emissions Trading System (EU ETS) and FuelEU Maritime Regulation, which come into effect in 2024 and 2025, respectively. This offers environmental cost savings, enhancing stakeholder benefits (Karatuğ et al., 2023; Lehtoranta et al., 2023).

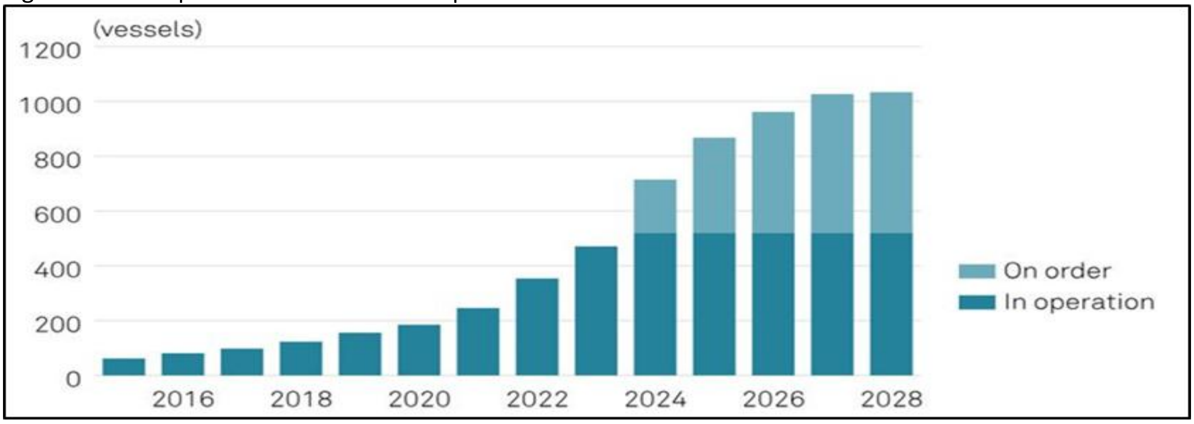
Table 1. Regulations Driving Shipping Industry Decarbonisation

REGULATOR	SCOPE/ INSTRUMENT	GEOGRAPHICAL COVERAGE/ APPLICATION	MECHANISM	IN FORCE
IMO/EEDI Energy Efficiency Design Index	TtW/ CO_2	World Wide / Newbuilding Ships	Measuring energy efficiency based on CO_2 emissions per unit of cargo carried on board ships (tonne-mile)	January 2013
IMO/EEXI Energy Efficiency Existing Ship Index	TtW/ CO_2	Worldwide / 400 GT and Above Existing Vessels	Measure current energy efficiency based on CO_2 emissions per unit of cargo carried on board	November 2022
IMO/CII Carbon Intensity Indicator	TtW/ CO_2	Worldwide / All Ships	Vessels A, B, C, D and E, cargo carrying capacity and the amount of CO_2 emitted in grams per nautical mile	January 2023
EU/ EU ETS	TtW / CO_2 from 2024; CH_4 and N_2O from 2026	Intra-EU voyages and 50% of international voyages calling at EU ports	Emission Payment	January 2024
EU/ FuelEU Maritime	WtW/ CO_2, CH_4 & N_2O	Intra-EU routes 100%, extra-EU routes 50% 5000 GT and above	Greenhouse gas intensity limit for energy used on ships	January 2025

Active LFSs currently account for more than 2% of the global shipping fleet. Including those on order, this percentage increases to 4% by number of vessels and 6% by deadweight tonnage (DWT) (SEA-LNG, 8 October 2024).

In 2010, 21 LFSs were in service, mostly smaller vessels operating regionally, while today this number has increased to 590 worldwide, including the world's largest containerships (SEA-LNG, 2024).

Figure 3. Development of LNG Fuelled Ships Worldwide



In addition, 564 vessels are on order and the total number of LFSs is expected to reach 1,154 by the end of 2028, as shown in Figure 3 for the development of LFSs worldwide (DNV, 2024).

LNG fuel plays a key role in the energy transition towards net-zero emissions by 2050 for the global shipping industry (Abdelmalek & Guedes Soares, 2023; Tuswan et al., 2023).

While LNG does not fully mitigate GHG emissions due to unburned methane in some engines (Pavlenko et al., 2020; Balcombe et al., 2021), it serves as a transitional fuel, offering immediate environmental benefits and paving the way for future renewable marine fuel developments (Baresic & Rehmatulla, 2024; Lindstad et al., 2020).

LFSs, which began with a small fleet in the 2010s and have expanded rapidly in recent years, remain a key part of maritime transport amidst increasingly stringent exhaust emission regulations by the IMO and EU. Analysing the impact of LFS fleets on maritime transport, based on expert opinions and the latest emission regulations, is crucial to addressing the existing gap in the literature.

This study aims to assess the impact of LFSs on maritime transport, considering environmental, technological, economic, commercial, legal, and social factors identified through literature, using the Fuzzy Delphi Method. It also examines interrelationships among these factors with the Fuzzy DEMATEL Method. By analysing the effects of stricter IMO and EU regulations and the growth of LFS fleets, the study provides insights for maritime enterprises and LFS investors, addressing the 'chicken-egg problem' in alternative fuel adoption. Additionally, it highlights areas for economic and environmental improvements in LFS fleets, contributing to global emission reduction and marine environment protection.

This paper is structured as follows: Section 1.1 reviews the literature on LFSs, highlighting their advantages and disadvantages. Section 2 outlines the methodologies, including the Fuzzy Delphi Method to identify LFS impact factors and the Fuzzy DEMATEL Method to explore cause-and-effect relationships. Section 3 presents the findings, followed by a discussion of their implications. Finally, Section 4 concludes with key insights and recommendations for future research on LFS adoption and greener maritime transport solutions.

1.1. Background

Many studies have been conducted in the literature on the use of LFS in maritime transport. Changes in exhaust emission values were calculated by modelling LFS types and cost analyses were made according to the calculated exhaust emission values. The advantages and disadvantages of LFS have been revealed in the studies.

Schinas and Butler (2016) developed a methodology to evaluate policy initiatives promoting LNG as a marine fuel, analysing international regulations, regional initiatives, and commercial factors influencing LNG adoption. Jasper Faber (2017) assessed the drivers and barriers to LNG use, highlighting environmental regulations and price differences as key drivers, while LNG availability in ports and technical standards were major barriers. Faber also conducted a quantitative analysis of LNG adoption in EU ports. Chen et al. (2018) evaluated the feasibility of investing in a new LNG-fuelled chemical ship, emphasizing the environmental and economic advantages of LNG over distillate fuels, influenced by factors like LNG-HFO price differences, ECA operation rates, and supply costs.

Bayraktar (2016) analysed the economic benefits of replacing a cruise ship's diesel engine with a dual-fuel propulsion system, concluding that the investment would pay off in about 10 years and meet upcoming emission restrictions in ECAs. Moreira (2016) evaluated the pollutant emissions of HFO, MGO, and LNG-fuelled container ships with Selective Catalytic Reduction (SCR), finding that LNG was the most economical and environmentally clean fuel.

Dereli (2018) examined exhaust emissions, their negative impact on the environment and human health, and efforts to reduce these effects, including emission limit values and methods for achieving them. The study also provided technical details on converting single-fuel engines to dual-fuel systems capable of using LNG. Lindstad et al. (2020) explored LNG’s role as a transition fuel in reducing carbon emissions in maritime transport, emphasizing that LNG can only be effective when paired with advanced dual-fuel engine technology to minimize global warming impacts.

Balcombe et al. (2021) compared the environmental life cycle and costs of LNG as a marine fuel with HFO, MDO, methanol, and renewable fuels, finding that LNG improves air quality, reduces fuel costs, and offers moderate climate benefits. However, methane emissions in certain engines were noted as a barrier to decarbonization goals. Similarly, Salarkia and Golabi (2023) analysed LNG's environmental and economic advantages, concluding that LNG offers significant regional and global benefits with low emissions compared to MGO, MDO, and HFO/Scrubber, making it the most suitable fuel for IMO 2020 requirements.

The literature review reveals frequent discussions on the technical and economic advantages and disadvantages of LFSs, as well as various studies on their adoption. However, no studies were found that evaluate the effects of LFS on maritime trade from multiple perspectives or examine the interrelationships of these effects in light of the increasingly stringent IMO and EU emission regulations.

This study aims to fill the literature gap by evaluating the impact of LNG-fuelled ships on maritime transport, both in the current context and under future IMO and EU regulations, based on the advantages and disadvantages of LNG-fueled ships and expert opinions from maritime professionals.

2. MATERIAL AND METHODS

2.1. Research Methodology

The adoption of LFSs as an alternative to comply with increasingly stringent IMO regulations has led to a range of impacts. A thorough literature review has identified both the benefits and challenges of LNG as a transitional fuel across environmental, economic, technological, commercial, legal, and social dimensions. This study applies the Fuzzy DEMATEL method to analyze the interdependencies among these criteria and utilizes the Fuzzy Delphi method to evaluate their relative importance in the transition to LNG

2.2. Fuzzy Delphi Method

The traditional Delphi method involves collecting expert opinions through multiple survey rounds to establish consensus on complex issues (Hsu & Sandford, 2007). However, the necessity of repeated surveys to ensure consistency may lead to respondent fatigue and negatively impact participation (Ma et al., 2011). Fuzzy Set Theory, introduced by Zadeh in 1955, provides a framework for handling uncertainty and converting expert evaluations into quantitative data (Bouzon et al., 2016; Alqahtani et al., 2023). The integration of Fuzzy Set Theory with the Delphi method enhances the efficiency of the process by reducing the number of survey rounds and the overall research duration while improving the clarity and precision of expert assessments (Bui et al., 2020).

As in the studies conducted by Alqahtani et al., 2023; Mohammadfam et al., 2022; Rafieyan et al., 2022; Yusof et al., 2022; Alghawli et al., 2022, the Fuzzy Delphi Method consists of Creating the Fuzzy Delphi Questionnaire, Determining the Average Fuzzy Evaluation Scores, Determining the Most Effective Criteria.

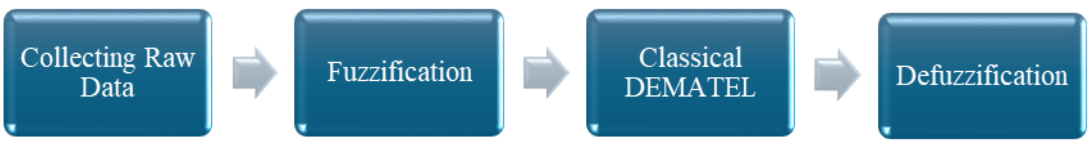
2.2. Fuzzy DEMATEL Method

Originally developed by Gabus et al. in 1972, the DEMATEL method is designed to analyze the interdependencies among variables (Mohammadfam et al., 2022). Similar to the Delphi method, it relies on expert evaluations and utilizes Trigonometric Fuzzy Numbers (TFN) to transform linguistic assessments into fuzzy values, thereby minimizing uncertainty and enhancing consensus. Lin's adaptation of DEMATEL to a fuzzy environment in 2008 further advanced its applicability (Wu & Lee, 2007). The Fuzzy DEMATEL approach effectively determines cause-and-effect relationships by examining the interactions between criteria and sub-criteria.

The DEMATEL method, which utilizes pairwise comparisons to analyze relationships in decision-making processes, provides a significant advantage over alternative techniques (Akyuz & Celik, 2015). The Fuzzy DEMATEL approach has been extensively employed across various domains, including risk assessment, security management, and human resource management.

Fuzzy Logic-Based DEMATEL is formulated by integrating data into the Classical DEMATEL framework following the processes of ‘Defuzzification’ and ‘Clarification’ (Giri et al., 2022). In this study, the Fuzzy DEMATEL method is implemented in accordance with the steps outlined in Figure 4.

Figure 4. Fuzzy DEMATEL Method



The Fuzzy Delphi method provides a comprehensive assessment of influential factors through expert opinions, while the DEMATEL method visualizes cause-effect relationships to identify key drivers or barriers. Shanta et al. (2024) and Ruano et al. (2023) highlighted that combining Fuzzy Delphi and Fuzzy DEMATEL enhances multi-criteria decision-making, especially in criteria identification and impact analysis. This methodological synergy strengthens the study, which is why both methods were employed.

3. RESULTS AND DISCUSSION

A comprehensive literature review identified six main factors affecting the maritime trade of LFS: environmental, technological, economic, commercial, legal, and social. Based on these findings, 35 sub-factors were determined and presented in Table 2.

Table 2. Main and Sub Factors Determined According to Literature Research.

Main Factors	Code	Factors	Referances
Environmental	C1	Exhaust Emission (NOx, SOx, PM, CO2)	Pekşen and Alkan, 2015;
	C2	Air Pollution	Sohn and Jung, 2022
	C3	Global Warming	Xu and Yang, 2020
	C4	Environmental Pollution Caused by LNG Accidents	Nubli and John., 2022;
Technological	C5	Ship Design and Location of Fuel Tank	Stewart and Wolosz, 2015;
	C6	Type Of Engine	Balcombe et al., 2021; Karatuğ
	C7	Unburned Methane	Kuittinen et al., 2023; Tuswan
	C8	Capacity Loss Ratio	Tuswan et al., 2023; Salarkia
	C9	Safety Issues Such as Flammability	Molitor et al., 2012; Peng et al., 2021; Celikaslan and Kılıc,
	C10	Security Issues	Wang and Notteboom, 2014; Bruzzone and Sciomachen,
	C11	Fuel and Lubricating Oil Consumption	Merien-Paul et al., 2019; Sari
	C12	Retrofitting Tendecy	Parfomak et al., 2019; Baresic
	C13	Needless of Abatement Systems such as Scrubber	Dereli, 2018; Tekeli et al.,
Economical	C14	LNG Fuel System Capital Cost	Bayraktar, 2016; Wang et al.,
	C15	LNG Fuel Delivery Cost	Bayraktar, 2016; Dereli, 2018; Wang et al., 2021; He et al.,
	C16	Operation Cost	Faber, 2017; Chen et al., 2018
	C17	Possible Environmetal Cost	Xu and Yang, 2020
	C18	Cost Savings	Karatuğ et al.,2023; Lehtoranta
	C19	Infrastructure	Parfomak et al., 2019; Yao et
	C20	Maintenance Cost	Faber, 2017; Merien-Paul et
Commercial	C21	Sailing Pattern	Faber, 2017; He et al., 2024
	C22	Bunkering Network	Rahimi et al., 2020; Peng et al.,
	C23	LNG Distribution Network	Schinas and Butler, 2016
	C24	LNG Source	Bruzzone and Sciomachen,
	C25	Availibity to Ship Types	Kuang et al., 2023; Oh et al.,
	C26	Cargo Space Loss	Salarkia and Golabi, 2023
	C27	Operation Standarts	Stewart and Wolosz, 2015
	C28	Competitivness	Wang and Notteboom, 2014;
Legal	C29	Emission Reg. MARPOL Annex VI	Vuskovic et al., 2023; Oh et al.,
	C30	LNG Bunkering Regulation	Peng et al., 2021; Bruzzone
	C31	Regulations on Gas Fueled Ships_ IGF Code	Cassar et al., 2021; Ha et al.,
	C32	Regulatory Gap	Ha et al., 2022
Social	C33	Social Public Awareness	Wang and Notteboom, 2014;
	C34	Public Perception	Wang and Notteboom, 2014;
	C35	Contribution of Government	Wang and Notteboom, 2014;

Fuzzy Delphi method was applied to determine the most important factors affecting the maritime trade of LFS and Fuzzy DEMATEL method was applied to reveal the relationships between these factors and the results are explained in detail in the following subsections.

3.1. The Universe and the Sample of the Study

This study targets maritime enterprises involved in maritime transport activities, encompassing all stakeholders affected by the research problem.

The sample consists of maritime enterprises using LFSs. A guided sampling method was used to select participants who best represent the research problem. Given the need for expertise, the sample includes individuals with at least 10 years of professional experience in LNG and LFS, primarily holding roles such as operations manager, fleet manager, technical manager, captain, and chief engineer.

3.2. Ranking Factors Affecting Maritime Transport Based on the Fuzzy Delphi Method

In determining the most influential factor, the importance ranking values and expert consensus values of each factor were calculated with the formulas used in Alqahtani et al. (2023), Mohammadfam et al. (2022), Rafieyan et al. (2022) Yusof et al. (2022), Alghawli et al. According to the calculations, the most important factors are presented in Table 3. The most important factors (F1, F2, F3….. F_n) were ranked again for the Fuzzy DEMATEL study and shown 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	Bunkering Network
F16	Operation Standards
F17	Competition
F18	LNG Fuel Transfer Rules

3.3. Determining Cause-and-Effect Relationships Among Factors Affecting Maritime Transport Based on the Fuzzy DEMATEL Method

In this section, the most important factors identified by the Fuzzy Delphi Method were extracted for the Fuzzy DEMATEL study as shown in Table 3 and then presented to the experts as a double-matrix questionnaire to analyse the cause-effect relationships between the factors. After the expert opinions were collected as linguistic data, the data were analysed using 'OnlineOutput MCDM Software'. According to the results of data analyses, influential-relationship map was created and presented in Figure 5.

According to the vertical vector value, F1, F3, F4, F7, F9, F12, F15, F18 are considered as cause variables, while F2, F5, F6, F8, F10, F11, F13, F14, F16, F17 are considered as effect variables. And they are presented in Table 4.

Figure 5. Influence-Relationship Map Found by Fuzzy DEMATEL Method.

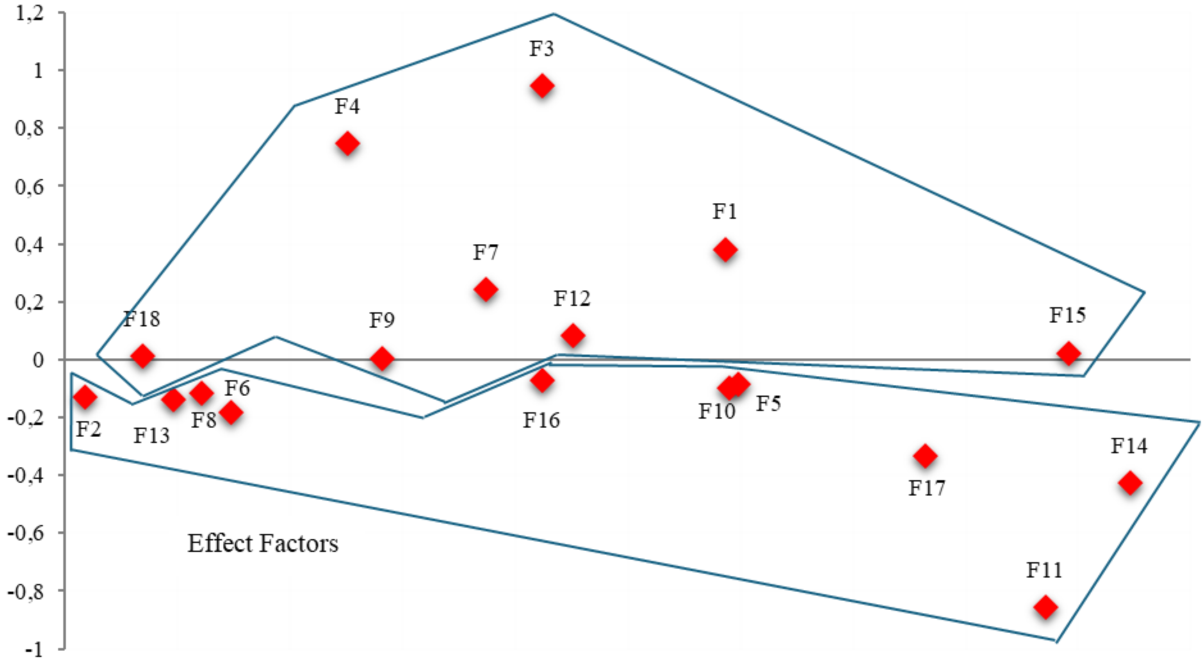


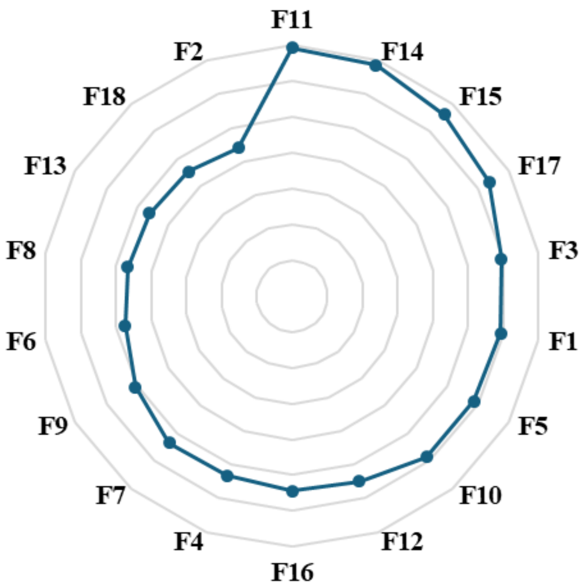
Table 4. Cause and Effect Classification of Criteria

Code	Criteria name	Cause-Effect
F1	Exhaust Emission (NOx, SOx, PM, CO2)	Cause
F3	Machine Type	Cause
F4	Unburned Methane Gas	Cause
F7	Fuel and Lubricating Oil Consumption	Cause
F9	LNG Fuel Capital Cost	Cause
F12	Cost Savings	Cause
F15	Bunkering Network	Cause
F18	LNG Fuel Transfer Rules	Cause
F2	Air Pollution	Effect
F5	Safety Issues	Effect
F6	Security Issues	Effect
F8	Exhaust Cleaning System Requirement	Effect
F10	LNG Fuel Sales Price	Effect
F11	Operation Cost	Effect
F13	Maintenance Cost	Effect
F14	Sailing Pattern	Effect
F16	Operation Standards	Effect
F17	Competition	Effect

Then the weights of the criteria were found by using the standard weighting formulae with the vector values obtained from the programme.

According to this ranking, **F11** "Operation Cost", **F14** "Sailing Pattern", **F15** "Bunkering Network", **F17** "Competition", **F3** "Machine Type", **F1** "Exhaust Emission (NOx, SOx, PM, CO_2)", **F5** "Safety Issues" and **F10** "LNG Fuel Delivery Cost" have been identified as the most important factors in the impact of LFS on maritime transport. A graphical representation of the ranking of all factor weights is presented in Figure 6.

Figure 6. Ranking of Factor Weights.



This study examines the impact of LNG-fueled fleets on maritime transport amid increasingly stringent exhaust emission regulations since their initial adoption in 2016 with a limited number of vessels. Based on expert opinions, the research provides insights, particularly from environmental, economic, and commercial perspectives.

The study's findings indicate that the most critical factors influencing the impact of LNG-fueled ships on maritime transport are **F11** "Operational Cost", **F14** "Sailing Pattern", **F15** "Bunkering Network" **F17** "Competition", **F3** "Engine Type', **F1** "Exhaust Emissions (NO_x, SO_x, PM, CO_2)", **F5** "Safety Issues" and **F10** "LNG Fuel Delivery Cost". Additionally, effect-relationship calculations reveal that **F3** "Engine Type" **F4** "Unburned Methane Gas" **F1** "Exhaust Emissions (NO_x, SO_x, PM, CO_2)" and **F7** "Fuel and Oil Consumption" are the most influential causal variables, indicating their significant role in shaping the impact factors within the system.

The variation in NO_x and unburned methane emissions from LNG-fueled ships depending on engine type poses a challenge to the greenhouse gas regulations introduced by the IMO and EU in pursuit of zero-emission targets. Notably, Comer et al. (2024) highlight that the high global warming potential of unburned methane emissions from LNG engines could undermine the environmental advantages of LNG unless mitigated through technological advancements. Additionally, the EU's FuelEU Maritime regulations, effective from January 1, 2025, and the EU ETS payments set to commence in 2026, may offset the environmental and economic benefits of LNG-fueled ships in terms of NO_x, SO_x, PM, and CO_2 reductions, as noted by Karatuğ et al. (2023).

Livaniou et al. (2022) and Wang and Notteboom (2014) highlight that the substantial reduction in NO_x, SO_x, PM, and CO_2 emissions compared to conventional fuels offers a key advantage for LNG-fueled ships operating within IMO-designated ECAs. Additionally, the extent of a ship's voyage within ECAs plays a crucial role in determining operational costs.

Merien-Paul et al. (2019) and Moreira (2016) indicate that the higher efficiency of LNG-fueled engines results in reduced fuel and lubricating oil consumption, leading to lower operational costs. Additionally, the cleaner combustion process and enhanced engine longevity contribute to lower maintenance expenses compared to conventional heavy fuel diesel engines.

In this context, the factors **F3** "Machine Type", **F4** "Unburned Methane Gas", **F1** "Exhaust Emission (NOx, SOx, PM, CO_2)" and **F7** "Fuel and Oil Consumption", which are found to be the most influential causal variables, significantly affect freight prices depending on the geographical regions, operation and maintenance costs of LFS and the maritime enterprises that own these ships.

According to the effect-relationship calculations made within the scope of the study, the fact that **F11** "Operation Cost", **F14** "Sailing Pattern" and **F13** "Maintenance Cost" are among the most affected outcome variables is in line with this situation. At the same time, **F11** and **F14** were found to be the most important factors according to the weighting calculations.

The F17 "Competition" factor, identified as a significantly impacted outcome variable, has gained importance amid tightening IMO and EU emission regulations and ongoing technological advancements. Following the implementation of the 2020 IMO sulphur standards, LNG has become more competitive against low-sulphur fuels, with its market price varying by region (He et al., 2024). Additionally, efforts to enhance LNG-fueled engine designs, particularly in reducing unburned methane emissions, have intensified technological competition among major marine engine manufacturers. As highlighted by Yao et al. (2024), the increasing global adoption of LNG-fueled ships due to regulatory measures has also fueled competition in shipbuilding, maritime operations, and port infrastructure.

The expansion of LNG refueling infrastructure is crucial for the growth of the sector, aligning with the significance of the **F15** 'Bunkering Network' factor identified through weighting calculations (Peng et al., 2021). As noted by He et al. (2024), LFS owners and operators must consider the availability of LNG bunkering facilities when planning ship routes and port calls. These vessels tend to navigate routes that offer both convenient access to refueling points and competitive LNG fuel prices.

Palaios et al. (2024) and Bruzzone and Sciomachen (2023) highlight that the ongoing Russia-Ukraine conflict has significantly disrupted gas supply and pricing, particularly in Europe. This aligns with the study's findings, where Factor **F10** "LNG Fuel Delivery Cost" emerges as one of the most critical and impacted variables.

Finally, **F5** "Safety Issues" and **F6** "Security Issues" are critical concerns in maritime transport, requiring enhanced standards, regulations, training, and materials due to LNG's chemical properties. As Xie et al. (2022) stated, although LNG is non-toxic and has a narrow flammability range, its cryogenic nature poses risks during transport, transfer, and usage, potentially leading to rapid phase transitions. These can result in hazards such as flammable vapor clouds, flash fires, fireballs, and explosions. Additionally, while no major incidents have been recorded, LNG's structural properties necessitate careful evaluation regarding potential security vulnerabilities.

This study distinguishes itself by incorporating expert insights from professionals actively engaged in maritime transport, assessing the advantages and disadvantages of LNG-fueled ships, and evaluating their impact on maritime transport both presently and in the future under the latest IMO and EU regulations.

The findings highlight the significance of factors such as Operation Cost, Sailing Pattern, Bunkering Network, Competition, Machinery Type, Unburned Methane Emission, Exhaust Emission (NOx, SOx, PM, CO_2), Safety Issues, and LNG Fuel Delivery Cost in the use of LFS in maritime transport. The effect-relationships of these factors align with previous studies, showing that Operation Cost and Sailing Pattern are strongly influenced by factors like Bunkering Network, Machinery Type, Unburned Methane Emission, Exhaust Emissions, and Safety.

4. CONCLUSION

This study analyzes the environmental, technological, economic, commercial, legal, and social impacts of LFS fleets on maritime transport, considering IMO and EU exhaust emission regulations. Based on literature and expert opinions, 35 factors related to LFS were identified, and 18 key factors were selected using the fuzzy Delphi method. The cause-effect relationships among these factors were examined using the DEMATEL method.

The research findings indicate that LFS reduce operational and maintenance costs, offering environmental savings based on geographical regions. They also enhance competition by aligning with IMO and EU emission targets. LFS present an economic alternative in ECA regions, meeting current regulations with appropriate machinery, and are considered key to achieving zero-emission targets in the medium term. Their adoption contributes to regulatory compliance, reduces maritime pollution, and supports the global shift toward sustainable shipping.

The study's limitations include geographical variations in LFS adoption and the evolving nature of regulations. Future research could explore emission rules, green fuels, LFS development, cargo types, or regional impacts on environmental pollution.

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REFERENCES

Abdelmalek, M., & Guedes Soares, C. (2023). Review of Risk Analysis Studies in the Maritime LNG Sector. Journal of Marine Science and Application, 22(4), 693-715. https://doi.org/10.1007/s11804-023-00376-0

Akyuz, E., & Celik, E. (2015). A fuzzy DEMATEL method to evaluate critical operational hazards during gas freeing process in crude oil tankers. Journal of Loss Prevention in the Process Industries, 38, 243-253. https://doi.org/10.1016/j.jlp.2015.10.006

Alghawli, A. S. A., Al-khulaidi, A. A., Nasser, A. A., AL-Khulaidi, N. A., & Abass, F. A. (2022). Application of the Fuzzy Delphi Method to Identify and Prioritize the Social-Health Family Disintegration Indicators in Yemen. International Journal of Advanced Computer Science and Applications, 13(5).

Alqahtani, F. M., Noman, M. A., Alabdulkarim, S. A., Alharkan, I., Alhaag, M. H., & Alessa, F. M. (2023). A New Model for Determining Factors Affecting Human Errors in Manual Assembly Processes Using Fuzzy Delphi and DEMATEL Methods. Symmetry, 15(11), 1967. **https://doi.org/10.3390/sym15111967**

Arıcan, O. H., Arslan, O., & Unal, A. U. (2023). The importance of CATZOC in passage planning and prioritization of strategies for safe navigation. Marine Science and Technology Bulletin, 12(4), 445-458.

Arıcan, O. H., Unal, A., Arslan, O., & Bamyacı, M. (2022). A Dry Cargo Coaster Tonnage Selection Model for Shipping Companies in Turkey. Kent Akademisi, 15(4), 1651-1669.

Balcombe, P., Staffell, I., Kerdan, I. G., Speirs, J. F., Brandon, N. P., & Hawkes, A. D. (2021). How can LNG-fuelled ships meet decarbonisation targets? An environmental and economic analysis. Energy, 227, 120462. https://doi.org/10.1016/j.energy.2021.120462

Baresic, D., & Rehmatulla, N. (2024). Exploring the Factors Leading to Diffusion of Alternative Fuels Using a Socio-Technical Transition Approach—A Case Study of LNG as a Marine Fuel in Norway. Fuels, 5(4), 574-606. https://doi.org/10.3390/fuels5040032

Bayraktar, M. (2016). Hizmetteki bir Geminin Sıvılaştırılmış Doğalgaz (LNG) Yakıtlı bir Gemi Makinesiyle Donatılmasının Ekonomik Analizi (Master's thesis, Dokuz Eylul Universitesi (Turkey).

Bouzon, M., Govindan, K., Rodriguez, C. M. T., & Campos, L. M. (2016). Identification and analysis of reverse logistics barriers using fuzzy Delphi method and AHP. Resources, conservation and recycling, 108, 182-197. https://doi.org/10.1016/j.resconrec.2015.05.021

Bruzzone, A., & Sciomachen, A. (2023). Simulating Operating Performance of Alternative Configurations of LNG Bunkering Stations. Sustainability, 15(13), 9940. https://doi.org/10.3390/su15139940

Bui, T. D., Tsai, F. M., Tseng, M. L., & Ali, M. H. (2020). Identifying sustainable solid waste management barriers in practice using the fuzzy Delphi method. Resources, conservation and recycling, 154, 104625. https://doi.org/10.1016/j.resconrec.2019.104625

Burel, F., Taccani, R., & Zuliani, N. (2013). Improving sustainability of maritime transport through utilization of Liquefied Natural Gas (LNG) for propulsion. Energy, 57, 412-420. https://doi.org/10.1016/j.energy.2013.05.002

Cassar, M. P., Dalaklis, D., Ballini, F., & Vakili, S. (2021). Liquefied natural gas as ship fuel: A maltese regulatory gap analysis. Transactions on Maritime Science, 10(01), 247-259. https://hrcak.srce.hr/258061

Clean Arctic Alliance.2024.LNG: The Threat to the Arctic from Liquified Natural Gas as a Shipping Fuel.Access Date:13 December 2024. **https://cleanarctic.org/** campaigns/the-arctic-climate-crisis/lng-the-threat-to-the-arctic-from-liquified-natural-gas-as-a-shipping-fuel/

Chen, S., Zheng, S., & Zhang, Q. (2018). Investment decisions under uncertainty on LNG-powered vessels for environmental compliance. Journal of Shipping and Trade, 3, 1-19. https://doi.org/10.1186/s41072-018-0031-4

Comer, B., Beecken, J., Vermeulen, R., Sturrup, E., Paschinger, P., Osipova, L., ... & Verbeek, R. (2024). Fugitive and Unburned Methane Emissions from Ships (Fumes). ICCT Report.

Çelikaslan, Z., & Kılıç, A. (2023). Safety Precautions for The Use of LNG as Marine Fuel. Journal of Maritime Transport and Logistics, 4(1), 11-22. https://doi.org/10.52602/mtl.1037248

Dereli, D.2018.LNG applications in marine transport. Master's Thesis. İstanbul Teknik Üniversitesi. June 2018

Environmental Protection Agency.2024.Air Pollution: Current and Future Challenges.Access Date: 26 November 2024.https://www.epa.gov/clean-air-act-overview/air-pollution-current-and-future-challenges#PP

Faber, J.(2017).Analysis Of The LNG Market Development In The EU. Access date: 10.11.2024.https://transport.ec.europa.eu/document/download/6d764330-ca1a-43b3-ab9d-ac9ee3d24d7en?filename =2015-12-lng-lot3.pdf

Ghadikolaei, M. A., Cheung, C. S., & Yung, K. F. (2016). Study of performance and emissions of marine engines fueled with liquefied natural gas (LNG). Proceedings of 7th PAAMES and AMEC2016, 13, 14.

Giri, B. C., Molla, M. U., & Biswas, P. (2022). Pythagorean fuzzy DEMATEL method for supplier selection in sustainable supply chain management. Expert Systems with Applications, 193, 116396. https://doi.org/10.1016/j.eswa.2021.116396

Ha, S. M., Lee, W. J., Jeong, B., Choi, J. H., & Kang, J. (2022). Regulatory gaps between LNG carriers and LNG fuelled ships. Journal of Marine Engineering & Technology, 21(1), 23-37. https://doi.org/10.1080/20464177.2019.1572060

He, P., Jin, J. G., Pan, W., & Chen, J. (2024). Route, speed, and bunkering optimization for LNG-fueled tramp ship with alternative bunkering ports. Ocean Engineering, 305, 117957. https://doi.org/10.1016/j.oceaneng.2024.117957

Herdzik, J. (2013). Consequences of using LNG as a marine fuel. Journal of KONES, 20(2), 159-166.

Hsu, C. C., & Sandford, B. A. (2007). The Delphi technique: making sense of consensus. Practical assessment, research, and evaluation, 12(1). https://doi.org/10.7275/pdz9-th90

IMO.2024. EEXI and CII - ship carbon intensity and rating system.Access Date: 17 December 2024. https://www.imo.org/en/MediaCentre/HotTopics/Pages/EEXI-CII-FAQ.aspx

IMO.30 October 2023.List Of Special Areas, Emission Control Areas And Particularly Sensitive Sea Areas.Access Date: 21 November 2024. https://wwwcdn.imo.org/localresources/en/OurWork/ Circulars/Documents/MEPC.1Circ.778Rev.4%20%20Special%20Areas%20and%20Emission%20Control%20Areas%20(ECAs)%20under%20MARPOL%20(Secretariat).pdf

Karatuğ, Ç., Ejder, E., Tadros, M., & Arslanoğlu, Y. (2023). Environmental and Economic Evaluation of Dual-Fuel Engine Investment of a Container Ship. Journal of Marine Science and Application, 22(4), 823-836. https://doi.org/10.1007/s11804-023-00381-3

Karatuğ, Ç., Ceylan, B. O., Ejder, E., & Arslanoğlu, Y. (2023). Investigation and examination of LNG, methanol, and ammonia usage on marine vessels. In Decarbonization of Maritime Transport (pp. 65-85). Singapore: Springer Nature Singapore. https://doi.org/10.1007/978-981-99-1677-1_5

Kuang, L., Wang, J., Cui, Y., & Pan, B. (2023, March). Brief Analysis on The Current Situation of LNG Fuel Powered Ship and The Challenge of LNG Fuel Bunkering. In Proceedings of the 2nd International Conference on Information, Control and Automation, ICICA 2022, December 2-4, 2022, Chongqing, China. http://dx.doi.org/10.4108/eai.2-12-2022.2327980

Lee, H. J., Yoo, S. H., & Huh, S. Y. (2020). Economic benefits of introducing LNG-fuelled ships for imported flour in South Korea. Transportation Research Part D: Transport and Environment, 78, 102220. https://doi.org/10.1016/j.trd.2019.102220

Lehtoranta, K., Kuittinen, N., Vesala, H., & Koponen, P. (2023). Methane Emissions from a State-of-the-Art LNG-Powered Vessel. Atmosphere, 14(5), 825. https://doi.org/10.3390/atmos14050825

Li, D. C., & Yang, H. L. (2024). Economic feasibility of LNG-fuelled river ships: Carbon tax schemes perspective. Transportation Research Part D: Transport and Environment, 132, 104235. https://doi.org/10.1016/j.trd.2024.104240

Lindstad, E., Eskeland, G. S., Rialland, A., & Valland, A. (2020). Decarbonizing maritime transport: The importance of engine technology and regulations for LNG to serve as a transition fuel. Sustainability, 12(21), 8793. https://doi.org/10.3390/su12218793

Livaniou, S., Chatzistelios, G., Lyridis, D. V., & Bellos, E. (2022). LNG vs. MDO in marine fuel emissions tracking. Sustainability, 14(7), 3860. https://doi.org/10.3390/su14073860

Ma, Z., Shao, C., Ma, S., & Ye, Z. (2011). Constructing road safety performance indicators using fuzzy delphi method and grey delphi method. Expert systems with applications, 38(3), 1509-1514. https://doi.org/10.1016/j.eswa.2010.07.062

Merien-Paul, R. H., Enshaei, H., & Jayasinghe, S. G. (2019). Effects of fuel-specific energy and operational demands on cost/emission estimates: A case study on heavy fuel-oil vs liquefied natural gas. Transportation Research Part D: Transport and Environment, 69, 77-89. https://doi.org/10.1016/j.trd.2019.01.031

Mohammadfam, I., Khajevandi, A. A., Dehghani, H., Babamiri, M., & Farhadian, M. (2022). Analysis of factors affecting human reliability in the mining process design using Fuzzy Delphi and DEMATEL methods. Sustainability, 14(13), 8168. https://doi.org/10.3390/su14138168

Molitor, E., Bakosch, A., & Forsman, B. (2012). Feasibility Study on LNG Fuelled Short Sea and Coastal Shipping in the Wider Caribbean Region. SSPA SWEDE N AB: London, UK.

Moreira, P. (2016). Liquefied natural gas as an alternative fuel: a voyage-based model. Transport, Logistics: Int. J.

Nubli, H., & Sohn, J. M. (2022). CFD-based simulation of accidental fuel release from LNG-fuelled ships. Ships and Offshore Structures, 17(2), 339-358. https://doi.org/10.1080/17445302.2020.1827806

Oh, J., Kim, D., Roussanaly, S., & Lim, Y. (2024). Greenhouse gas emissions of shipping with onboard carbon capture under the FuelEU Maritime regulation: a well-to-wake evaluation of different propulsion scenarios. Chemical Engineering Journal, 498, 155407. https://doi.org/10.1016/j.cej.2024.155407

Parfomak, P. W., Frittelli, J., Lattanzio, R. K., & Ratner, M. (2019). LNG as a maritime fuel: prospects and policy. Congressional Research Service: Washington, DC, USA.

Park, K., Lempert, C., Abdullah, M., Katakura, S., Shigeyama, J., Roumen, T., & Baudisch, P. (2022, April). FoolProofJoint: Reducing Assembly Errors of Laser Cut 3D Models by Means of Custom Joint Patterns. In Proceedings of the 2022 CHI Conference on Human Factors in Computing Systems (pp. 1-12). https://doi.org/10.1145/3491102.3501919

Pavlenko, N., Comer, B., Zhou, Y., Clark, N., & Rutherford, D. (2020). The climate implications of using LNG as a marine fuel. Swedish Environmental Protection Agency: Stockholm, Sweden.

Pekşen, D. Y., & ALKAN, G. (2015). Alternatif Gemi Yakiti Lng; Net Bugünkü Değer Yöntemiyle Değerlendirilmesi. Deniz Ulaştırma İşletme Mühendisliği Anabilim Dalı Doktora Tezi.

Peng, Y., Zhao, X., Zuo, T., Wang, W., & Song, X. (2021). A systematic literature review on port LNG bunkering station. Transportation Research Part D: Transport and Environment, 91, 102704. https://doi.org/10.1016/j.trd.2021.102704

Rahimi, G., Dehghani, T., & Jokar, M. S. (2020). The Potential of Using LNG as a fuel in Marine Transport. World Journal of Environmental Biosciences, 9(1-2020), 39-44.

Rafieyan, A., Sarvari, H., Beer, M., & Chan, D. W. (2024). Determining the effective factors leading to incidence of human error accidents in industrial parks construction projects: Results of a fuzzy Delphi survey. International Journal of Construction Management, 24(7), 748-760. https://doi.org/10.1080/15623599.2022.2159630

Ramsay, W., Fridell, E., & Michan, M. (2023). Maritime energy transition: future fuels and future emissions. Journal of Marine Science and Application, 22(4), 681-692. https://doi.org/10.1007/s11804-023-00369-z

Ruano, M., Huang, C. Y., Nguyen, P. H., Nguyen, L. A. T., Le, H. Q., & Tran, L. C. (2023). Enhancing sustainability in Belize’s ecotourism sector: A fuzzy Delphi and fuzzy DEMATEL Investigation of Key Indicators. Mathematics, 11(13), 2816. https://doi.org/10.3390/math11132816

Salarkia, M., & Golabi, S. I. (2023). Liquefied Natural Gas (LNG): Alternative Marine Fuel Restriction and Regulation Considerations, Environmental and Economic Assessment. Energy Engineering and

Management, 10(4), 44-59. https://doi.org/10.22052/10.4.44

Sari, D. P., Tuswan, T., Muttaqie, T., Soetardjo, M., Murwatono, T. T. P., Utina, R., ... & Misbahudin, S. (2023). Critical Overview and Challenge of Representative LNG-Fuelled Ships on Potential GHG Emission Reduction. https://doi.org/10.5109/7151729

Schinas, O., & Butler, M. (2016). Feasibility and commercial considerations of LNG-fueled ships. Ocean Engineering, 122, 84-96. https://doi.org/10.1016/j.oceaneng.2016.04.031

SEA- LNG.8 October 2024.LNG-fuelled vessels accelerate to 6% of the global fleet.Access Date:23 December 2024.https://sea-lng.org/2024/10/lng-fuelled-vessels-accelerate-to-6-of-the-global-fleet/

SEA-LNG.2024.Global fleet.Access Date: 26 October 2024. https://sea-lng.org/why-lng/global-fleet/

SEA-LNG.17 December 2024. Shipping Industry Decarbonisation: Fuel Choice And The Costs Of Achieving Regulatory Compliance. Access Date: 19 January 2024. https://sea-lng.org/wp-content/uploads/2024/12/Cost-of-Compliance_Nov24_v4.pdf

Shanta, M. H., Choudhury, I. A., & Salman, S. (2024). Municipal solid waste management: Identification and analysis of technology selection criteria using Fuzzy Delphi and Fuzzy DEMATEL technique. Heliyon, 10(1). https://doi.org/10.1016/j.heliyon.2023.e23236

Sharafian, A., Blomerus, P., & Mérida, W. (2019). Natural gas as a ship fuel: Assessment of greenhouse gas and air pollutant reduction potential. Energy Policy, 131, 332-346. https://doi.org/10.1016/j.enpol.2019.05.015

Sohn, J. M., & Jung, D. (2022). Structural assessment of a 500-cbm liquefied natural gas bunker ship during bunkering and marine operation under collision accidents. Ships and Offshore Structures, 17(11), 2379-2395.https://doi.org/10.1080/17445302.2021.1996133

Stewart, R. D., & Wolosz, C. J. (2015). Development of the Adoption of Liquefied Natural Gas as a Fuel for Shipping on the Great Lakes. Transportation Research Record, 2479(1), 1-8. https://doi.org/10.3141/2479-01

Tekeli, M. M., Arici, S. S., Sezer, S. I., Akyuz, E., & Gardoni, P. (2024). Predicting Human Reliability for Shore-based LNG Bunkering Operation Process on Tanker Ships Using SLIM and Improved Z-numbers. Journal of Marine Science and Application, 1-13. https://doi.org/10.1007/s11804-024-00492-5

Tuswan, T., Sari, D. P., Muttaqie, T., Prabowo, A. R., Soetardjo, M., Murwantono, T. T. P., ... & Yuniati, Y. (2023). Representative application of LNG-fuelled ships: a critical overview on potential GHG emission reductions and economic benefits. Brodogradnja: An International Journal of Naval Architecture and Ocean Engineering for Research and Development, 74(1), 63-83. https://doi.org/10.21278/brod74104

Unal, A. U., Arslan, O., & Arıcan, O. H. (2022). Türkiye'de Ro-Ro taşımacılığının önemi ve geleceği hakkında örnek bir çalışma. Denizcilik Araştırmaları Dergisi: Amfora, 1(1), 60-79.

Vuskovic, B., Rudan, I., & Sumner, M. (2023). Fostering sustainable LNG bunkering operations: development of regulatory framework. Sustainability, 15(9), 7358. https://doi.org/10.3390/su15097358

Wang, S., & Notteboom, T. (2014). The adoption of liquefied natural gas as a ship fuel: A systematic review of perspectives and challenges. Transport Reviews, 34(6), 749-774. https://doi.org/10.1080/01441647.2014.981884

Wang, Y., Wright, L., & Zhang, P. (2021). Economic feasibility of LNG fuel for trans ocean-going ships: A case study of container ships. Maritime Technology and Research, 3(2), 202-222. https://doi.org/10.33175/mtr.2021.248055

Wu, W. W., & Lee, Y. T. (2007). Developing global managers' competencies using the fuzzy DEMATEL method. Expert systems with applications, 32(2), 499-507. https://doi.org/10.1016/j.eswa.2005.12.005

Xu, H., & Yang, D. (2020). LNG-fuelled container ship sailing on the Arctic Sea: Economic and emission assessment. Transportation Research Part D: Transport and Environment, 87, 102556. https://doi.org/10.1016/j.trd.2020.102556

Yao, S., Li, C., & Wei, Y. (2023). Design and optimization of a zero-carbon emission system integrated with the utilization of marine engine waste heat and LNG cold energy for LNG-powered ships. Applied Thermal Engineering, 231, 120976. https://doi.org/10.1016/j.applthermaleng.2023.120976

Yao, A. F., Sèbe, M., Virto, L. R., Nassiri, A., & Dumez, H. (2024). The effect of LNG bunkering on port competitiveness using multilevel data analysis. Transportation Research Part D: Transport and Environment, 132, 104240. https://doi.org/10.1016/j.trd.2024.104240

Yusof, N., Hashim, N. L., & Hussain, A. (2022, August). A review of fuzzy Delphi method application in human-computer interaction studies. In AIP Conference Proceedings (Vol. 2472, No. 1). AIP Publishing. https://doi.org/10.1063/5.0094417