“Cost-Benefit Analysis of Using LNG as a Fuel for Vessels”

Project report submitted to the School of Maritime Management, Indian Maritime University
in partial fulfilment for the requirements for the award of degree of

MASTER OF BUSINESS ADMINISTRATION

In

INTERNATIONAL TRANSPORTATION AND LOGISTICS MANAGEMENT

Submitted by

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CHENNAI CAMPUS

MAY 2025

DECLARATION

I, **Mohammad Faizan Khan, Reg. No.2303305027** student of **School of Maritime Management, Indian Maritime University**, pursuing **MBA in International Transportation and Logistics Management** hereby declare that submission of this project report titled **"Cost-Benefit Analysis of Using LNG as a Fuel for Vessels"** - has been prepared by me towards the partial fulfilment of the Master of Business Administration in Port shipping Management under the supervision of **Dr .Lekha Ravi** Assistant Professor SMM, Indian Maritime University, Chennai Campus. I also declare that this project report is my original work and has not been copied from any other report previously submitted for the award of any degree, fellowship or other in the similar title.

Faizan Khan

Place: Chennai

Date: 27|05|2025

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CERTIFICATE

This is to certify that this project report entitled " **Cost-Benefit Analysis of Using LNG as a Fuel for Vessels** " submitted to the School of Maritime Management, Indian Maritime University, Chennai Campus in partial fulfilment of the requirement for awarding the degree, MBA in International Transport and Logistic Management (ITLM) is a genuine work of **Mohammad Faizan Khan (Reg No. 2303305027).**

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iii

ACKNOWLEDGMENT

First and foremost, I would like to thank God the Almighty who has granted countless blessings, knowledge and opportunity to complete this project to its fullest.

I would like to thank my parents for the moral support and cooperation throughout the programme. My heartfelt and sincere thanks to, **Dr. B Swaminathan**, Associate professor Head SMM, Indian Maritime University, Chennai Campus who gave me the golden opportunity to do this wonderful project on the topic "**Cost-Benefit Analysis of Using LNG as a Fuel for Vessels**". I pay him my deep sense of gratitude for guiding me.

I would like to express my deep sense of gratitude of **Dr. Lekha Ravi** Assistant Professor SMM, Indian Maritime University, Chennai Campus. For his esteemed guidance and expert suggestions in each step of the project, alleviating inspiration, encouraging and kind supervision in the completion of my project.

I am also thankful to faculty members, library staffs, my friends and my well-wishers who were very cooperative during my project in providing appropriate guidance and support without whom this project would not have been completed successfully.

Mohammad Faizan Khan

ABSTRACT

The global maritime industry, responsible for transporting nearly 90% of the world's trade, is under increasing pressure to adopt environmentally sustainable practices due to the significant pollution caused by conventional marine fuels such as Heavy Fuel Oil (HFO) and Marine Gas Oil (MGO). These traditional fuels emit high levels of sulfur oxides (SOx), nitrogen oxides (NOx), carbon dioxide (CO_2), and particulate matter (PM), contributing to climate change and air pollution. In response, the International Maritime Organization (IMO) has introduced stringent regulations, including the IMO 2020 sulfur cap and long-term decarbonization targets for 2030 and 2050

This study presents a comprehensive cost-benefit analysis of LNG as a marine fuel, evaluating it against conventional options like HFO and MGO. The research methodology adopts a mixed-method approach, combining quantitative analysis such as financial modeling and emissions calculations, with qualitative insights drawn from industry case studies, regulatory reviews, and expert opinions. Key evaluation metrics include fuel cost comparison, capital and operational expenditures, regulatory compliance, and environmental impact. Data is drawn from credible international sources, including the International Maritime Organization (IMO), DNV, Lloyd's Register, and real-world case studies on LNG-powered vessels.

The findings suggest that although LNG requires significantly higher initial investment — with retrofitting costs ranging from $10 to $20 million and larger cryogenic fuel storage systems — it becomes economically competitive over an 8–12 year period due to lower operational and maintenance costs and avoidance of emissions-related penalties. For new ship constructions and high-utilization vessels, particularly those operating along established LNG bunkering routes in Europe, Asia-Pacific, and North America, LNG emerges as a cost-effective and regulation-compliant option.

In conclusion, LNG represents a transitional marine fuel that balances regulatory compliance, environmental responsibility, and long-term operational cost advantages. The study underscores the need for coordinated policy support, infrastructure development, and international cooperation to fully realize the benefits of LNG and support its integration into the global maritime fuel ecosystem.

TABLE OF CONTENTS

Table of figures

CHAPTER 1

(Introduction to the Cost-benefit Analysis of Using LNG as a Fuel for Vessels)

1.0 Introduction to the Cost-benefit Analysis of Using LNG as a Fuel for Vessels

The global shipping industry is a crucial pillar of international trade, transporting nearly 90% of the world's goods. Cargo ships, including container vessels, bulk carriers, and oil tankers, play an essential role in the global supply chain. However, this industry is also a significant contributor to environmental pollution due to its reliance on conventional marine fuels such as Heavy Fuel Oil (HFO) and Marine Gas Oil (MGO). These fuels are known to produce high levels of sulfur oxides (SOx), nitrogen oxides (NOx), particulate matter (PM), and carbon dioxide (CO_2), which contribute to air pollution, acid rain, and climate change.

In response to these environmental concerns, the International Maritime Organization (IMO) has implemented strict regulations to limit emissions from the maritime sector. The IMO 2020 sulfur cap mandates that the sulfur content in marine fuels must not exceed 0.5% globally and 0.1% in Emission Control Areas (ECAs). Additionally, the IMO 2030 and 2050 targets aim to reduce greenhouse gas (GHG) emissions by 40% by 2030 and 70% by 2050, compared to 2008 levels. These regulatory changes have forced ship-owners and operators to explore alternative fuel options that can comply with these stringent environmental requirements while maintaining operational efficiency and cost-effectiveness.

Among the alternative fuels being considered, Liquefied Natural Gas (LNG) has emerged as a promising solution. LNG is a cryogenically stored natural gas that, when used as a marine fuel, offers significant reductions in emissions. Compared to HFO and MGO, LNG virtually eliminates SOx emissions, reduces NOx emissions by up to 85%, and lowers CO_2 emissions by approximately 25%. Moreover, LNG-powered engines generally produce less particulate matter, improving air quality in port areas and along shipping routes. These advantages make LNG an attractive option for ship-owners looking to comply with IMO regulations and reduce their environmental footprint.

Despite its benefits, the adoption of LNG as a marine fuel is not without challenges. The high capital costs associated with retrofitting existing vessels or constructing new LNG-powered ships pose a significant financial burden. Additionally, the availability of LNG bunkering infrastructure is still developing, with limited refueling stations in key maritime regions. Furthermore, concerns over methane slip—the unburned release of methane during LNG combustion—have raised questions about LNG's overall impact on climate change. These factors highlight the need for a comprehensive cost-benefit analysis to determine whether the advantages of LNG outweigh its economic and operational challenges.

This study aims to provide an in-depth cost-benefit analysis of using LNG as a fuel for cargo ships, focusing on key factors such as fuel costs, environmental compliance, infrastructure investment, engine retrofitting, and operational efficiency. By evaluating these aspects, this research will offer insights into the economic viability and long-term sustainability of LNG in the shipping industry. The findings will assist ship-owners, policymakers, and maritime stakeholders in making informed decisions about the future of LNG adoption and its role in the transition to cleaner and more sustainable marine fuel solutions.

1.2 **Maritime Industry Introduction**

Sea transport systems in today's shipping market have evolved into three separate but closely connected segments: bulk shipping, liner shipping and specialized shipping. Although these segments belong to the same industry, each carries out different tasks and has a very different character. Large homogeneous parcels such as iron ore, coal and grain are carried by the bulk shipping industry, small parcels of general cargo are carried by the liner shipping industry and specialised cargoes shipped in large volumes are transported by the specialized shipping industry. These three cargo streams create demand for bulk transport, liner transport and specialized transport. A major distinction is drawn between the fleets of ships owned by companies moving their cargo in their ships and the ships owned by independent shipowners and chartered to the cargo owners. The bulk shipping industry carries large parcels of raw materials and bulky semi-manufactured. This is a very distinctive business. Bulk vessels handle few transactions, typically completing about six voyages with a single cargo each year, so the average revenue depends on a dozen of negotiations per ship each year. In addition, service levels are usually low so little overhead is required to run the ships and organize the cargo.

Figure 1 about (liner shipping) Source: https://www.marineregions.org/sources.php

The liner service transports small parcels of general cargo, which includes manufactured and semi-manufactured goods and many small quantities of bulk commodities. Because there are so many parcels to handle on each voyage, this is an organization-intensive business. In addition, the transport leg forms part of an integrated production operation, so speed, reliability and high service levels are important. With so many transactions the business relies on published prices, though nowadays the prices are negotiated with major customers as part of service agreement. Specialized shipping services transport difficult cargoes of which the five most important are cars, forest product, refrigerated cargo, chemicals and liquified gas. These trades fall somewhere between bulk and liner. Service provides in these trades invest in specialized ships and offer higher service levels than bulk shipping.

Roll-on/roll-off (RORO or ro-ro) ships are cargo ships designed to carry wheeled cargo, such as cars, motorcycles, trucks, semi-trailer trucks, buses, trailers, and railroad cars, that are driven on and off the ship on their own wheels or using a platform vehicle, such as a self-propelled modular transporter. This is in contrast to lift-on/lift-off (LoLo) vessels, which use a crane to load and unload cargo. RORO vessels have either built-in or shore-based ramps or ferry slips that allow the cargo to be efficiently rolled on and off the vessel when in port. While smaller ferries that operate across rivers and other short distances often have built-in ramps, the term RORO is generally reserved for large seagoing vessels. The ramps and doors may be located in the stern, bow, or sides, or any combination thereof. Types of RORO vessels include ferries, cruiseferries, cargo ships, barges, and RoRo service for air/ railway deliveries. New automobiles that are transported by ship are often moved on a large type of RORO called a pure car carrier (PCC) or pure car/truck carrier (PCTC).

Elsewhere in the shipping industry, cargo is normally measured by tonnage or by the tonne, but RORO cargo is typically measured in lanes in metros (LIMs). This is calculated by multiplying the cargo length in metres by the number of decks and by its width in lanes (lane width differs from vessel to vessel, and there are several industry standards). On PCCs, cargo capacity is often measured in RT or RT43 units (based on a 1966 Toyota Corona, the first mass-produced car to be shipped in specialised car-carriers and used as the basis of RORO vessel size. 1 RT is approximately 4m of lane space required to store a 1.5m wide Toyota Corona) or in car-equivalent units (CEU). The largest RORO passenger ferry is MS Color Magic, a 75,100 GT cruise ferry that entered service in September 2007 for Color Line. Built in Finland by Aker Finnyards, it is 223.70 m (733ft,11 in) long and 35 m (114 ft 10 in) wide, and can carry 550 cars, or 1,270 lane meters of cargo. The RORO passenger ferry with the greatest car-carrying capacity is Ulysses (named after a novel by James Joyce), owned by Irish Ferries. Ulysses entered service on 25 March 2001 and operates between Dublin and Holyhead. The 50,938 GT ship is 209.02 m (685 ft 9 in) long and 31.84 m (104 ft 6 in) wide, and can carry 1,342 cars/4,101 lane meters of cargo. Most modern merchant ships can be placed in one of a few categories, such as:

Primary maritime transport types	
Image	**Description**
	**Bulk carriers** ("bulkers") are cargo ships used to transport bulk cargo items such as ore or food staples (rice, grain, etc.) and similar cargo. They can be recognized by the large box-like hatches on their deck, designed to slide outboard for loading. A bulk carrier could be either dry or wet. Most lakes are too small to accommodate bulk ships, but a large fleet of lake freighters has been plying the Great Lakes and St. Lawrence Seaway of North America for over a century.

Primary maritime transport types	
Image	**Description**
	**Container ships** are cargo ships that carry their entire load in truck-sized containers, in a technique called containerization. They form a common means of commercial intermodal freight transport. Informally known as "box boats," they carry the majority of the world's dry cargo. Most container ships are propelled by diesel engines and have crews of between 10 and 30 people. They generally have a large accommodation block at the stern, directly above the engine room.
	**Cruise ships** are passenger ships used for pleasure voyages, where the voyage itself and the ship's amenities are considered an essential part of the experience. Cruising has become a major part of the tourism industry, with millions of passengers each year as of 2006. The industry's rapid growth has seen nine or more newly built ships catering to a North American clientele added every year since 2001, as well as others servicing European clientele. Smaller markets such as the Asia-Pacific region are generally serviced by older tonnage displaced by new ships introduced into the high growth areas. On the Baltic Sea, ports are connected by **cruiseferries**.
	A **multi-purpose** ship (sometimes called a general cargo ship) is used to transport a variety of goods, from bulk commodities to break bulk and heavy cargoes. To provide maximum trading flexibility they are usually geared (supplied with cranes), and modern examples are fitted for the carriage of containers and grains. Generally they will have large open holds and tweendecks to facilitate the carriage of different cargoes on the same voyage. The crew will be highly competent in the securing of break

Primary maritime transport types	
Image	**Description**
	bulk cargoes and the ship will be equipped with various lashings and other equipment for sea fastening.
	An **ocean liner** is a passenger ship designed to transport people from one seaport to another along regular long-distance maritime routes according to a schedule. Ocean liners may also carry cargo or mail, and may sometimes be used for other purposes. Ocean liners are usually strongly built with a high freeboard to withstand rough seas and adverse conditions encountered in the open ocean, having large capacities for fuel, food and other consumables on long voyages. These were the main stay of most passenger transport companies, however, due to the growth of air travel, the passenger ships saw a steady decline. Cruise ships later filled the void and are primarily used by people who still have a love of the sea and offer more amenities than the older passenger ships.
	**Refrigerated ships** (usually called reefers) are cargo ships typically used to transport perishable commodities which require temperature-controlled transportation, mostly fruits, meat, fish, vegetables, dairy products and other foodstuffs.
	**Roll-on/roll-off ships** are ships designed to transport wheeled cargo such as automobiles, trailers or railway carriages. RORO (or ro/ro) vessels have built-in ramps which allow the cargo to be efficiently "rolled on" and "rolled off" the vessel when in port. While smaller ferries that operate across rivers and other short distances still often have built-in ramps, the term RORO is generally reserved for larger ocean-

Primary maritime transport types	
Image	**Description**
	going vessels, including pure car/truck carrier (PCTC) ships.
	**Tankers** are cargo ships for the transport of fluids, such as crude oil, petroleum products, liquefied petroleum gas (LPG), liquefied natural gas (LNG) and chemicals, also vegetable oils, wine and other food. The tanker sector comprises one third of the world tonnage.
	A **barge** is a flat-bottomed boat, built mainly for river and canal transport of heavy goods. Most barges are not self-propelled and need to be moved by tugboats or towboats pushing or towing them. Barges on canals (towed by draft animals on an adjacent towpath) established the conditions supporting the early Industrial Revolution in both Europe and the American Northeast but later after they made possible steam locomotive prime movers riding iron rails – after both could grow (and mature) to become commonplace and capable – contended with the railways and were outcompeted in the carriage of people, light freight, and high value items due to the higher speed, falling costs, and route flexibility of rail transport. Carriage of bulk goods also gradually lost ground to freight railways as train capacity and speeds continued to climb. Even underpowered early rail networks could usually reach places only an outrageously expensive canal might be built,[5] and once Iron T-rails and higher powered locomotives became possible, the far cheaper to build railways were unfettered and independent upon water sources, whilst mostly unplagued by the seasonal problems (restricted by icing) of temperate latitude canals which suffered ice and freshet flooding damages with dreary regularity. When floods did affect railways,

Primary maritime transport types	
Image	**Description**
	restoration of services was usually comparatively rapid.
	**Cable layer** is a deep-sea vessel designed and used to lay underwater cables for telecommunications, electricity, and such. A large superstructure, and one or more spools that feed off the transom distinguish it. Modern cable layers are equipped with advanced dynamic positioning systems (DPS) to maintain precise control during cable deployment, even in rough sea conditions. These vessels often feature specialized equipment such as remotely operated vehicles (ROVs) to assist with underwater cable positioning, inspections, and repairs.
	**Coastal trading vessels**, also known as **coasters**, ships used for trade between locations on the same island or continent. They are often small and of shallow draft, and sometimes set up as self-dischargers.
	A **dredger** (sometimes also called a dredge) is a ship used to excavate in shallow seas or fresh water areas with the purpose of gathering up bottom sediments and disposing of them at a different location, such as for gold exploration.

Primary maritime transport types	
Image	**Description**
	**Ferries** are a form of transport, usually a boat or ship, but also other forms, carrying (or *ferrying*) passengers and sometimes their vehicles. Ferries are also used to transport freight (in lorries and sometimes unpowered freight containers) and even railroad cars. Most ferries operate on regular, frequent return services. A foot-passenger ferry with many stops is sometimes called a waterbus or water taxi. Ferries form a part of the public transport systems of many waterside cities and islands, allowing direct transit between points at a capital cost much lower than bridges or tunnels. Many of the ferries operating in Northern European waters are roll-on/roll-off ships.
	A **tugboat** is a boat used to manoeuvre, primarily by towing or pushing, other vessels (see shipping) in harbours, over the open sea or through rivers and canals. They are also used to tow barges, disabled ships, or other equipment like towboats.
	**Open hatch general cargo ships** are designed to transport forest products, bulk cargos, unitized cargoes, project cargoes and containers.

Primary maritime transport types	
Image	**Description**
	**Semi-submersible heavy-lift ships** often move particularly large, heavy, or bulky goods that other ships cannot handle well. Such off-size goods include ship hulls, premade construction materials, other seagoing vessels, power plant components, cast ste

Figure 2 Sources (about types of ship): https://www.ship-technology.com/features/largest-ships-in-the-world/

1.3 Statement of the Problem

The global shipping industry faces increasing pressure to reduce its environmental impact while maintaining economic viability. Traditional marine fuels such as Heavy Fuel Oil (HFO) and Marine Gas Oil (MGO) have long been the primary energy sources for cargo ships, but they contribute significantly to greenhouse gas (GHG) emissions, sulfur oxides (SOx), nitrogen oxides (NOx), and particulate matter (PM). These emissions have severe consequences, including air pollution, ocean acidification, and climate change.

To address these environmental concerns, the International Maritime Organization (IMO) has introduced stringent regulations, such as the IMO 2020 sulfur cap and the IMO 2030 and 2050 decarbonization targets. These regulations require shipowners and operators to transition to cleaner fuel alternatives to comply with emission reduction mandates. Among the available options, Liquefied Natural Gas (LNG) has emerged as a promising alternative due to its potential to significantly reduce SOx, NOx, and CO_2 emissions.

However, despite its environmental benefits, the adoption of LNG as a marine fuel presents several economic, technical, and operational challenges. These include:

- High Initial Investment Costs – Retrofitting existing vessels to run on LNG or constructing new LNG-powered ships requires substantial financial investment.

- Infrastructure Limitations – The global LNG bunkering infrastructure is still under development, leading to concerns about the availability of refueling stations along major shipping routes.
- Methane Slip – The incomplete combustion of LNG can lead to methane leakage, a potent greenhouse gas with a significantly higher global warming potential than CO_2.
- Economic Viability – LNG prices fluctuate depending on market conditions, and shipowners must evaluate whether LNG provides long-term cost savings compared to traditional fuels.
- Operational Considerations – LNG-powered engines require specialized training for crew members, and there are uncertainties regarding long-term maintenance and efficiency.

Given these challenges, there is a critical need for a comprehensive cost-benefit analysis to determine whether LNG is a viable alternative fuel for cargo ships. This study aims to evaluate the economic feasibility, environmental impact, regulatory compliance, and operational efficiency of LNG adoption in the maritime sector. By analysing both the benefits and limitations of LNG, this research will provide data-driven insights to help shipowners, policymakers, and industry stakeholders make informed decisions about the future of LNG as a marine fuel.

1.4 Objective

The primary objective of this study is to conduct a comprehensive cost-benefit analysis of using Liquefied Natural Gas (LNG**)** as a fuel for cargo ships, focusing on economic, environmental, technical, and operational aspects. The specific objectives of the project are:

By addressing these objectives, this project aims to offer data-driven insights to help decision-makers in the shipping industry evaluate the potential of LNG as a viable alternative fuel for cargo ships while balancing economic and environmental considerations.

1. To evaluate the economic feasibility of LNG as a marine fuel in comparison to conventional marine fuels such as HFO and MGO, including operational and maintenance costs.
2. To assess the environmental benefits of LNG adoption, focusing on reductions in CO_2, SOx, NOx, and particulate matter emissions.

3. To analyze the impact of infrastructure development and regulatory policies on the cost-benefit ratio of LNG-powered shipping.

1.5 Scope of the Study

This study focuses on the cost-benefit analysis of using Liquefied Natural Gas (LNG) as a fuel for cargo ships, covering economic, environmental, regulatory, and operational aspects. It specifically examines container ships, bulk carriers, and oil tankers, comparing LNG with Heavy Fuel Oil (HFO), Marine Gas Oil (MGO), and Low-Sulfur Fuel Oil (LSFO).

Key areas of analysis include fuel cost comparisons, capital and operational expenditures, emission reductions, regulatory compliance (IMO 2020, 2030, 2050), LNG bunkering infrastructure, and operational challenges. The study focuses on major shipping regions such as Europe, North America, Asia-Pacific, and the Middle East while considering global market trends.

The research covers historical data from the past decade and future projections for the next 10-20 years, aligning with international decarbonisation goals. While alternative fuels like hydrogen and ammonia are briefly mentioned, they are not the primary focus.

1.6 Research Methodology

This study adopts a comprehensive and systematic approach to evaluating the cost-benefit analysis of using Liquefied Natural Gas (LNG) as a fuel for cargo ships. The research methodology consists of the following key components

1) Research Design

The study follows a mixed-method approach, incorporating both quantitative and qualitative analyses.

- Quantitative Analysis: Involves financial modelling, cost comparisons, and environmental impact calculations based on emission reduction data.
- Qualitative Analysis: Focuses on regulatory compliance, infrastructure availability, and operational challenges through case studies and industry reports.

This dual approach ensures a comprehensive evaluation of both economic and non-economic factors influencing LNG adoption.

2) Data Collection Methods

To ensure accuracy and reliability, the study gathers data from multiple sources:

A. Secondary Data Collection

1) Industry Reports and Market Studies – Data from maritime organizations such as:

- International Maritime Organization (IMO)
- International Energy Agency (IEA)
- Society for Gas as a Marine Fuel (SGMF)
- DNV (Det Norske Veritas) and Lloyd's Register

2) Cost and Fuel Price Data – Historical and current price trends for LNG, HFO, and MGO from sources like:
   - Platts and Argus Media (fuel price reporting agencies)
   - Port authorities and LNG bunkering suppliers

3) Regulatory Frameworks and Compliance Reports – Analysis of IMO 2020, IMO 2030, and IMO 2050 regulations and their impact on LNG adoption.

4) Shipbuilding and Retrofitting Costs – Data from shipyards, LNG engine manufacturers (e.g., MAN Energy Solutions, Wärtsilä), and financial reports from shipping companies.

B. Primary Data Collection (If Applicable)

If feasible, primary data collection may include:

- Interviews with industry experts, shipowners, and fuel suppliers to gain insights into the challenges and feasibility of LNG adoption.
- Surveys with shipping companies to understand their perceptions of LNG as a marine fuel.

3) Data Analysis Techniques

1) Cost-Benefit Analysis (CBA)

- Fuel Cost Comparison: Evaluate LNG vs. HFO and MGO based on historical and projected price trends.
- Capital Expenditure (CAPEX) and Operational Expenditure (OPEX) Analysis: Assess the cost of retrofitting ships vs. building new LNG-powered vessels.
- Return on Investment (ROI) Calculation: Determine the financial viability of LNG-powered ships over different operational lifespans.

2) Environmental Impact Assessment

- Analyze SOx, NOx, CO_2, and particulate matter (PM) reduction potential using emission factor data.
- Evaluate concerns related to methane slip and its impact on greenhouse gas emissions.

3) Regulatory and Compliance Assessment

- Compare LNG's compliance with IMO environmental regulations vs. conventional marine fuels.
- Assess potential future policy incentives and carbon taxation impacts on LNG adoption.

4) Scenario Analysis & Sensitivity Testing

- Model different fuel price scenarios (e.g., high LNG prices vs. declining HFO prices).
- Evaluate risks and uncertainties related to LNG infrastructure expansion and global adoption.

1.7 Limitations of the study

While this study aims to provide a comprehensive evaluation, certain limitations exist:

- Dependence on secondary data: Market trends and technological developments may change over time.
- LNG price fluctuations: Future price variations could impact the cost-benefit conclusions.
- Infrastructure uncertainties: LNG bunkering network expansion is not uniform worldwide.
- Exclusion of other alternative fuels: While briefly mentioned, fuels like hydrogen and ammonia are not analyzed in depth.

CHAPTER 2

(LITERATURE REVIEW)

2.0 LITERATURE REVIEW

1. Life cycle emission and cost assessment for LNG-retrofitted vessels: the risk and sensitivity analyses under fuel property and load variations (Hadi Taghavifar a) , (Lokukaluge P. Perera) the Arctic University of Norway, Tromsø, Norway b SINTEF Digital, Oslo, Norway

Sources: https://d.docs.live.net/7d6bc2c23102bba9/Desktop/Pictures

Review: The study "Life Cycle Emission and Cost Assessment for LNG-Retrofitted Vessels: The Risk and Sensitivity Analyses under Fuel Property and Load Variations" by Hadi Taghavifar and Lokukaluge P. Perera provides a comprehensive evaluation of the environmental and economic impacts of retrofitting ships with LNG propulsion. Through detailed life cycle assessment (LCA) and cost analysis, the research investigates how variations in fuel properties and vessel load conditions influence emissions and total cost of ownership. The authors employ sensitivity and risk analysis to reveal critical factors affecting LNG's viability as a marine fuel. The study highlights LNG's potential to reduce greenhouse gas emissions but underscores the importance of considering operational uncertainties and retrofit costs in decision-making. It is a valuable contribution for stakeholders exploring sustainable marine fuel alternatives.

2. An environmental cost-benefit analysis of LNG as a maritime fuel in the Arctic 9Ryan Thomas Holmes) (A thesis submitted for the degree of PhD at the University of St Andrews)

Sources: https://research-repository.st-andrews.ac.uk/bitstream/handle/10023/29479/Thesis-Ryan-Holmes-complete-version.pdf?sequence=2&isAllowed=y

Review: The PhD thesis "An Environmental Cost-Benefit Analysis of LNG as a Maritime Fuel in the Arctic" by Ryan Thomas Holmes critically examines the trade-offs of adopting liquefied natural gas (LNG) as an alternative marine fuel in the sensitive Arctic region. The research provides a balanced evaluation of LNG's environmental benefits—such as reductions in SOx, NOx, and particulate matter—against its lifecycle greenhouse gas emissions, especially methane slip. Through a cost-benefit framework, the study also considers regulatory, economic, and operational implications, highlighting the complex interplay between environmental protection and commercial viability. Holmes' work offers valuable insights for policymakers and maritime stakeholders assessing sustainable fuel transitions in ecologically vulnerable zones.

3. Cost-benefit analysis of emission reduction techniques: a case for container vessel **(**Emir Ejder) (Çağlar Karatuğ) (**Yasin Arslanoğlu)** Received 08 Jun 2022, Accepted 07 Feb 2024, Published online: 16 Feb 2024

Sources: https://www.tandfonline.com/doi/abs/10.1080/20464177.2024.2317511

Review: The article "Cost-Benefit Analysis of Emission Reduction Techniques: A Case for Container Vessel" by Emir Ejder, Çağlar Karatuğ, and Yasin Arslanoğlu presents a practical evaluation of various emission reduction strategies for container ships. The study compares methods such as alternative fuels, energy efficiency measures, and exhaust gas cleaning systems by analyzing their environmental impact and economic feasibility. Using real operational data, the authors conduct a detailed cost-benefit analysis to identify the most effective solutions for reducing emissions while maintaining commercial competitiveness. The paper offers valuable insights for shipowners and regulators aiming to balance compliance with IMO regulations and operational cost-efficiency in the context of sustainable maritime transport.

4. Concept design and cost–benefit analysis of pile-guide mooring system for an offshore LNG bunkering terminal. (Author links open overlay panelSeongn
yeob Lee [a], Choonghee Jo [b], Bjørnar Pettersen [c], Hyun Chung [a], San Kim [a], Daejun Chang)

Sources:https://www.sciencedirect.com/science/article/abs/pii/S0029801818301136

Review: The study "Concept Design and Cost–Benefit Analysis of Pile-Guide Mooring System for an Offshore LNG Bunkering Terminal" by Seongn Yeob Lee, Choonghee Jo, Bjørnar Pettersen, Hyun Chung, San Kim, and Daejun Chang explores an innovative mooring solution to support offshore LNG bunkering operations. The paper presents a conceptual design of a pile-guide mooring system, emphasizing its technical feasibility, operational stability, and adaptability to varying environmental conditions. Through a detailed cost–benefit analysis, the authors demonstrate that the proposed system offers economic and logistical advantages over traditional mooring methods, particularly in enhancing safety, reducing downtime, and supporting LNG infrastructure expansion. This research is a significant contribution to offshore LNG terminal design and maritime infrastructure development.

5. Economic feasibility of LNG fuel for trans ocean-going ships: A case study of container ships

Reference: https://so04.tci-thaijo.org/index.php/MTR/article/view/248055#:~:text=https%3A//doi.org/10.33175/mtr.2021.248055

Review: The study "Economic Feasibility of LNG Fuel for Trans Ocean-Going Ships: A Case Study of Container Ships" assesses the viability of LNG as a marine fuel for long-distance container shipping. By analyzing factors such as fuel costs, retrofitting expenses, operational performance, and emissions compliance, the paper provides a thorough cost-benefit comparison between LNG and conventional marine fuels. The findings suggest that while LNG can offer long-term savings and environmental benefits—especially under stricter emission regulations—its economic feasibility heavily depends on variables such as fuel price volatility, infrastructure availability, and voyage patterns. The case study highlights both the opportunities and challenges of adopting LNG for large-scale, ocean-crossing container vessels.

6. A cost-benefit analysis of fuel-switching vs. hybrid scrubber installation: A container route through the Chinese SECA case. (Author links open overlay panel), (Lixian Fan), (Bingmei Gu), (Meifeng Luo)

Reference: https://www.sciencedirect.com/science/article/abs/pii/S0967070X19308832

Review: The study "A Cost-Benefit Analysis of Fuel-Switching vs. Hybrid Scrubber Installation: A Container Route Through the Chinese SECA Case" by Lixian Fan, Bingmei Gu, and Meifeng Luo examines two key compliance strategies with sulfur emission control area (SECA) regulations along a container shipping route in China. The research compares the economic and environmental impacts of switching to low-sulfur fuel versus investing in hybrid scrubber systems. Through detailed modeling and scenario analysis, the authors evaluate factors such as fuel costs, capital investment, maintenance, and regulatory compliance. The results reveal that while fuel-switching offers lower upfront costs and operational simplicity, hybrid scrubbers can provide long-term financial advantages under certain fuel price and operational conditions. The paper offers practical guidance for shipowners navigating SECA regulations and investment decisions.

7. Emission reduction and cost-benefit analysis of the use of ammonia and green hydrogen as fuel for marine applications. (Yunfan Wu), (Aiguo Chen), (Hua Xiao), (Marco Jano-Ito b), (Mustafa Alnaeli b), (Mohammad Alnajideen b), (Syed Mashruk b), (Agustin Valera-Medina)

Reference: https://www.sciencedirect.com/science/article/pii/S2949720523000437

Review: The study "Emission Reduction and Cost-Benefit Analysis of the Use of Ammonia and Green Hydrogen as Fuel for Marine Applications" by Yunfan Wu, Aiguo Chen, Hua Xiao, Marco Jano-Ito, Mustafa Alnaeli, Mohammad Alnajideen, Syed Mashruk, and Agustin Valera-Medina investigates the environmental and economic viability of using ammonia and green hydrogen as alternative marine fuels. The research provides a comparative assessment of emissions reductions, particularly CO_2 and NO_x, as well as the lifecycle costs associated with fuel production, storage, and onboard use. The authors highlight that while both fuels show significant potential in decarbonizing maritime transport, ammonia offers more feasible storage and handling advantages, whereas green hydrogen requires substantial infrastructure development. The study underscores the importance of regulatory support and technological advancements to make these zero-carbon fuels competitive, offering strategic insights for future marine fuel transitions.

8. Numerical analysis of economic and environmental benefits of marine fuel conversion from diesel oil to natural gas for container ship. Published: 24 November 2020. (Ahmed G. Elkafas, Mohamed M. Elgohary & Mohamed R. Shouman)

Sources: https://link.springer.com/article/10.1007/s11356-020-11639-6

Review: The study "Numerical Analysis of Economic and Environmental Benefits of Marine Fuel Conversion from Diesel Oil to Natural Gas for Container Ship" by Ahmed G. Elkafas, Mohamed M. Elgohary, and Mohamed (last name not fully listed) provides a detailed simulation-based evaluation of converting container ships from diesel oil to natural gas fuel. Using numerical modeling, the authors assess both the economic and environmental implications of this fuel switch. The results indicate that natural gas significantly reduces emissions of SOx, NOx, CO_2, and particulate matter, aligning with IMO environmental regulations. Economically, the study shows that although initial conversion costs are high, long-term fuel savings and reduced emissions-related penalties enhance overall feasibility.

The paper offers practical insights into fuel transition strategies for achieving greener maritime operations.

9. A cost-benefit analysis of fuel-switching vs. use MGO: A CHINA-Europe container route case. (ZhongHao Zhang and Ding Liu). (Published under licence by IOP Publishing Ltd)

Sources: https://iopscience.iop.org/article/10.1088/1755-1315/831/1/012008/meta

Review: The study "A Cost-Benefit Analysis of Fuel-Switching vs. Use of MGO: A China-Europe Container Route Case" by ZhongHao Zhang and Ding Liu, published by IOP Publishing Ltd, investigates two key compliance strategies for meeting sulfur emission regulations on the China–Europe container route. The paper compares the economic and environmental performance of fuel-switching strategies—such as using LNG or installing scrubbers—against the continued use of marine gas oil (MGO). Through detailed route-specific modeling and cost-benefit analysis, the study concludes that while MGO ensures straightforward regulatory compliance, fuel-switching options can offer better long-term economic and environmental returns under favorable market and policy conditions. The findings provide critical insights for shipowners and operators making fuel strategy decisions in response to emission control area (ECA) requirements.

10. How can LNG-fuelled ships meet decarbonisation targets? An environmental and economic analysis. (Paul Balcombe), (Iain Staffell), (Ivan Garcia Kerdan)

Reference: How can LNG-fuelled ships meet decarbonisation targets? An environmental and economic analysis

Review: The study "How Can LNG-Fuelled Ships Meet Decarbonisation Targets? An Environmental and Economic Analysis" by Paul Balcombe, Iain Staffell, and Ivan Garcia Kerdan critically assesses the role of LNG in achieving maritime decarbonisation goals. The authors conduct a comprehensive life cycle analysis (LCA) of LNG as a marine fuel, including upstream emissions and methane slip, and compare its performance against conventional fuels and emerging zero-carbon alternatives. Economically, the study evaluates operational costs, infrastructure investment, and long-term regulatory implications. The results suggest that while LNG offers immediate emissions reductions, especially for SOx, NOx, and particulates, its long-term viability as a decarbonisation solution is limited unless paired with carbon capture or renewable bio-LNG. The paper provides key insights for policymakers and industry stakeholders navigating the complex transition to low- and zero-emission shipping.

11. Cost-benefit analysis of ships NOx Emission Control Areas (NECA) along China's coastal area.

Sources: https://doi.org/10.1016/j.marpolbul.2025.117830

Review: The study "Cost-Benefit Analysis of Ships NOx Emission Control Areas (NECA) Along China's Coastal Area" evaluates the economic and environmental impacts of implementing NOx emission regulations under NECA policies in China. By assessing various compliance measures—such as engine modifications, adoption of selective catalytic reduction (SCR) systems, and switching to low-NOx fuels—the study quantifies the associated costs against the public health and environmental benefits from reduced nitrogen oxide emissions. The analysis shows that while compliance entails significant upfront and operational costs for shipowners, the long-term benefits in terms of improved air quality, reduced healthcare costs, and regulatory alignment outweigh the expenditures. The study supports NECA implementation as a cost-effective policy for sustainable maritime development along China's rapidly industrializing coastline.

12. Real option analysis for environmental compliance: LNG and emission control areas. (Michele Acciar)

Sources: https://doi.org/10.1016/j.trd.2013.12.007

Review: The study "Real Option Analysis for Environmental Compliance: LNG and Emission Control Areas" by Michele Acciaro explores the strategic decision-making process for shipowners considering LNG adoption in response to Emission Control Area (ECA) regulations. Using real option analysis (ROA), the research captures the value of managerial flexibility under uncertainty—such as fluctuating fuel prices, evolving regulations, and technological advancements. The study demonstrates that LNG investments, while capital-intensive, can be more attractive when accounting for the option to delay, expand, or abandon based on future market and policy developments. Acciaro's work offers a dynamic framework that moves beyond static cost-benefit models, providing valuable insights for maritime stakeholders managing long-term environmental compliance risks.

13. Cost-Benefit Analysis in the Assessment of LNG Ship Bunkering Station on Inland Waterway Port. (JiaRong Jiang1)

Sources: https://www.atlantis-press.com/proceedings/msea-22/125982752

Review: The study "Cost-Benefit Analysis in the Assessment of LNG Ship Bunkering Station on Inland Waterway Port" by JiaRong Jiang evaluates the economic viability and environmental advantages of establishing an LNG bunkering station at an inland waterway port. The research analyzes construction and operational costs against benefits such as reduced emissions, improved fuel supply reliability, and potential attraction of LNG-fueled vessels. The findings indicate that, despite significant initial investments, LNG bunkering infrastructure can deliver long-term economic and environmental gains by supporting cleaner fuel adoption in inland shipping. This study offers practical insights for port authorities and policymakers aiming to promote sustainable inland waterway transport through LNG infrastructure development.

14. Primer on the Cost of Marine Fuels Compliant with IMO 2020 Rule

Reference: ORNL: Primer on the Cost of Marine Fuels Compliant with IMO 2020 Rule

Review: This primer discusses the cost implications of various marine fuels compliant with the International Maritime Organization's (IMO) 2020 sulfur cap. It highlights that LNG retrofit can be cheaper than using Very Low Sulfur Fuel Oil (VLSFO) or High Sulfur Fuel Oil (HSFO) with scrubbers in certain price scenarios. The document emphasizes that choosing LNG can make sense from a commercial and cost perspective, especially when considering long-term operational savings and environmental compliance. However, it also points out that the initial investment for LNG retrofitting and the development of adequate bunkering infrastructure are significant considerations.

15. Marine LNG Engine

Reference: Marine LNG Engine

Review: This article provides an overview of marine LNG engines, discussing their operational principles, environmental benefits, and economic considerations. It notes that LNG engines can reduce fuel costs due to the lower price of natural gas compared to traditional marine fuels. Additionally, LNG engines produce fewer emissions, helping ship operators comply with international environmental regulations. However, the article also mentions challenges such as the need for specialized infrastructure and the current limited availability of LNG bunkering facilities.

16. LNG-fuelled fishing vessels: A systems engineering approach. (Sepideh Jafarzadeh)

Sources: https://doi.org/10.1016/j.trd.2016.10.032

Review: The study "LNG-Fuelled Fishing Vessels: A Systems Engineering Approach" by Sepideh Jafarzadeh applies a holistic systems engineering methodology to evaluate the design, operation, and environmental impact of fishing vessels powered by LNG. The research integrates technical, economic, and environmental factors to optimize fuel system configurations while ensuring regulatory compliance and operational efficiency. The study highlights LNG's potential to reduce harmful emissions significantly in the fishing sector, a traditionally hard-to-abate segment. By addressing challenges such as fuel storage, safety, and cost implications, the paper provides a comprehensive framework for transitioning fishing fleets towards cleaner energy solutions.

17. The Cost and Environmental Impact of LNG versus Conventional Marine Fuels

Reference: Shiprope: The Costs and Benefits of Converting Ships to LNG

Review: This article compares the cost and environmental impact of LNG with conventional marine fuels such as HFO and MGO. It finds that LNG can reduce fuel costs by 10-15% when carbon pricing is factored in. Additionally, LNG offers significant environmental benefits, including reductions in CO_2, SOx, and NOx emissions. The study also notes that while LNG has a higher upfront cost due to the need for specialized engines and storage systems, maintenance savings resulting from cleaner combustion can lead to an overall cost advantage over the vessel's operational life.

18. Life-cycle cost analysis of an innovative marine dual-fuel engine under uncertainties. (Khanh Q. Bui)

Sources: https://doi.org/10.1016/j.jclepro.2022.134847

Review: The study "Life-Cycle Cost Analysis of an Innovative Marine Dual-Fuel Engine Under Uncertainties" by Khanh Q. Bui investigates the economic viability of adopting advanced dual-fuel engines in maritime vessels. By incorporating uncertainties such as fuel price fluctuations, maintenance costs, and regulatory changes, the research uses probabilistic modeling to evaluate the total cost of ownership over the engine's life cycle. The findings suggest that, despite higher initial investment, dual-fuel engines offer significant long-term cost savings and emissions benefits, especially when flexibility in fuel choice is valued. This analysis provides valuable insights for shipowners and operators considering cleaner propulsion technologies under uncertain market and policy conditions.

19. Environmental and economical benefits of changing from marine diesel oil to natural-gas fuel for short-voyage high-power passenger ships. (A A Banawan, M M El Gohary, and I S Sadek)

Reference: https://journals.sagepub.com/doi/abs/10.1243/14750902JEME181

Review: The study by A.A. Banawan, M.M. El Gohary, and I.S. Sadek examines the environmental and economic benefits of converting short-voyage, high-power passenger ships from marine diesel oil (MDO) to natural gas fuel. The findings reveal significant emission reductions, including a 72% decrease in nitrogen oxides, 91% reduction in sulfur oxides, 85% less particulate matter, and a 10% drop in carbon dioxide emissions. Economically, the switch to LNG leads to substantial cost savings, with fuel consumption expenses falling by 39% and maintenance costs decreasing by 40%. Overall, the study demonstrates that using natural gas as a marine fuel for these vessels offers a promising pathway to cleaner and more cost-effective maritime operations.

CHAPTER 3
(Analytics)

3.0 Introduction of Marine Fuel

The global maritime industry plays a vital role in international trade, transporting approximately 90% of the world's goods. However, the sector is also a significant contributor to environmental pollution, primarily due to the widespread use of conventional marine fuels such as Heavy Fuel Oil (HFO) and Marine Gas Oil (MGO). These fuels are associated with high levels of sulfur oxides (SOx), nitrogen oxides (NOx), carbon dioxide (CO_2), and particulate matter emissions, which have severe environmental and health impacts.

In response to growing environmental concerns and international regulations—such as the International Maritime Organization's (IMO) 2020 sulfur cap—there has been an increasing demand for cleaner and more sustainable fuel alternatives. Among the emerging options, Liquefied Natural Gas (LNG) has gained significant attention as a transitional marine fuel. LNG offers the potential to significantly reduce emissions, lower operational costs, and comply with current and future environmental regulations.

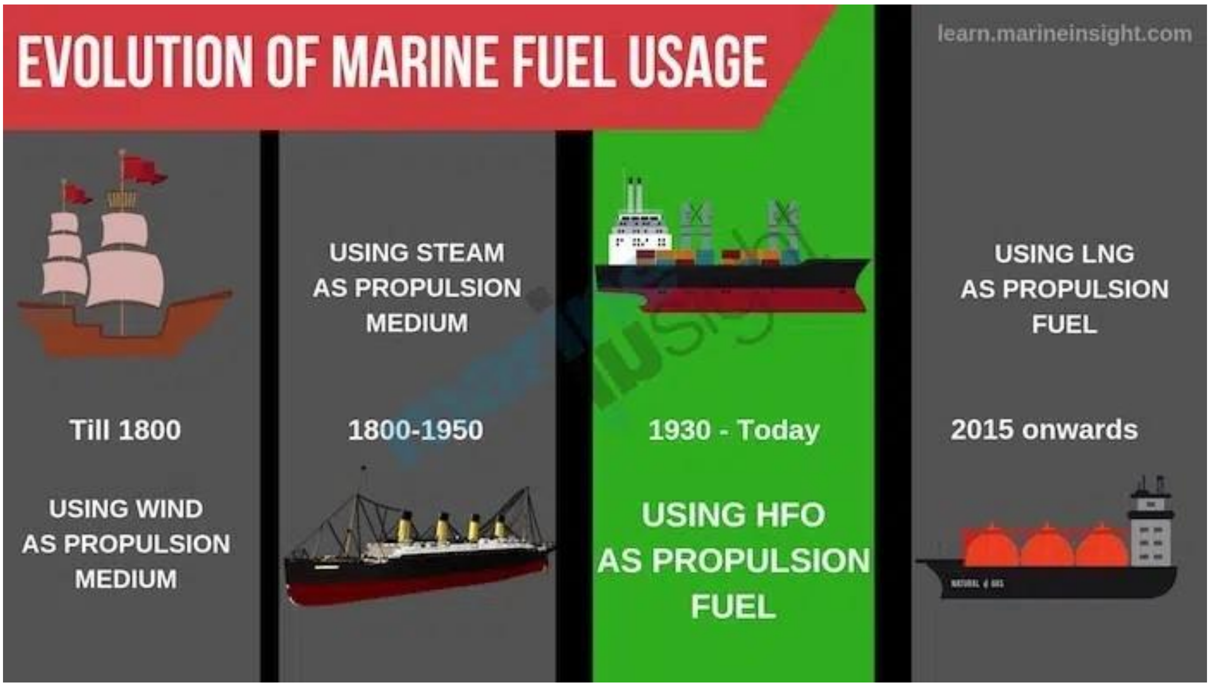

Figure 3 (about evolution of marine fule usage)
https://www.researchgate.net/figure/Evaluation-of-marine-fuel-usage-1_fig1_349278876

3.2 Different types of Marine Fuel:

1. **Heavy Fuel Oil (HFO)**

Heavy Fuel Oil (HFO), also referred to as residual fuel oil or bunker fuel, is a dense, viscous byproduct obtained during the final stages of crude oil refining. It is composed mainly of long-chain hydrocarbons and contains impurities such as sulfur, nitrogen, vanadium, and other heavy metals. Due to its low cost and high energy content, HFO has long been the dominant fuel used in the global shipping industry, particularly for powering large ocean-going vessels such as tankers, bulk carriers, and container ships.

Economically, HFO has been a favorable option for ship operators because of its relatively low price compared to distillate fuels like Marine Gas Oil (MGO). This cost advantage has played a crucial role in keeping shipping expenses manageable and international trade competitive. However, the financial benefits of HFO are counterbalanced by its environmental impact.

From an environmental perspective, the combustion of HFO is associated with the release of high levels of harmful pollutants, including sulfur oxides (SOx), nitrogen oxides (NOx), carbon dioxide (CO_2), particulate matter (PM), and black carbon. These emissions contribute to air pollution, acid rain, and global warming, posing serious risks to both environmental and human health. In particular, SOx emissions have been a primary concern due to their role in forming fine particulate matter, which can lead to respiratory and cardiovascular diseases.

In response to these concerns, the International Maritime Organization (IMO) implemented the IMO 2020 regulation, which mandates a global sulfur cap of 0.5% in marine fuels, significantly lower than the previous limit of 3.5%. Ships operating in Emission Control Areas (ECAs) face even stricter limits, with a maximum sulfur content of 0.1%. These regulatory changes have forced ship operators using HFO to adopt alternative compliance measures, such as installing exhaust gas cleaning systems (scrubbers) or switching to low-sulfur fuels like VLSFO or LNG.

Despite its declining use, HFO remains relevant in the marine fuel landscape, especially on vessels that are equipped with scrubbers. These systems allow ships to continue burning high-sulfur fuel while removing harmful emissions before they are released into the atmosphere. However, the high capital and maintenance costs of scrubbers, along with the growing pressure for sustainable shipping practices, have led to increased interest in cleaner fuel alternatives.

In conclusion, while Heavy Fuel Oil has been a cornerstone of maritime energy for decades due to its economic advantages, its environmental drawbacks and regulatory challenges are accelerating a shift toward cleaner and more sustainable marine fuels.

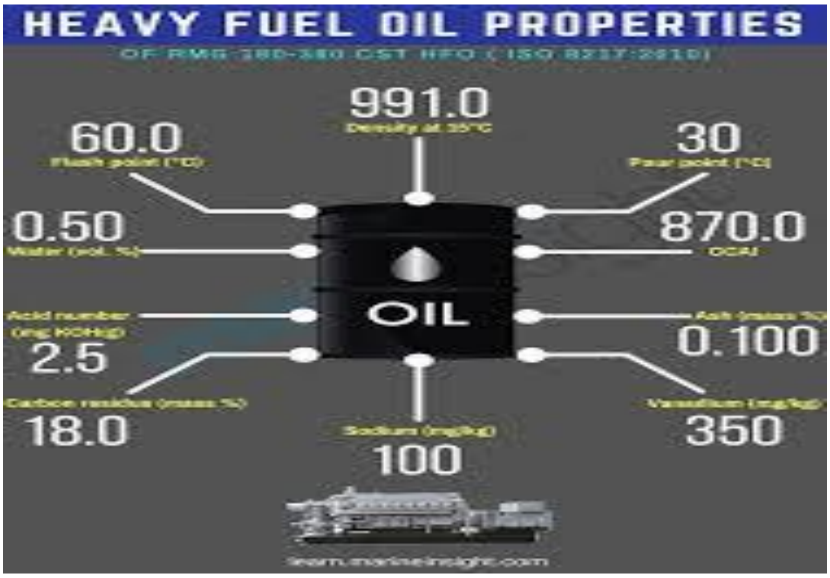

Figure4 (about heavy fuel oil properties)
https://www.forbes.com/sites/nishandegnarain/2020/08/14/what-is-heavy-fuel-oil-and-why-is-it-so-controversial-five-killer-facts/

2. **Marine Gas Oil (MGO)**

Marine Gas Oil (MGO) is a type of distillate fuel commonly used in the maritime industry, particularly for vessels operating in coastal waters, Emission Control Areas (ECAs), and in auxiliary engines aboard ocean-going ships. Unlike Heavy Fuel Oil (HFO), which is a residual product of crude oil distillation, MGO is a refined product derived from the lighter fractions of crude oil, making it a cleaner and more environmentally friendly alternative.

Chemically, MGO is similar to diesel fuel and is composed of shorter-chain hydrocarbons with significantly lower levels of sulfur, heavy metals, and other impurities compared to HFO. This results in more complete combustion, leading to fewer emissions of sulfur oxides (SOx), nitrogen oxides (NOx), particulate matter (PM), and carbon dioxide (CO_2). Because of these characteristics, MGO has become the fuel of choice in regions with stringent emissions regulations, especially following the implementation of the IMO 2020 sulfur cap, which limits the sulfur content in marine fuels to 0.5% globally and 0.1% within ECAs.

Economically, MGO is more expensive than HFO, primarily due to its higher refining cost and greater demand in compliance-driven markets. However, its ease of use and compatibility with existing marine engines make it an attractive short- to medium-term solution for shipowners seeking to comply with environmental regulations without making major investments in new technologies or retrofitting engines. MGO does not require significant modifications to a ship's propulsion system or additional onboard equipment like scrubbers, unlike vessels using high-sulfur HFO.

In terms of storage and handling, MGO is also less complex than alternative fuels such as LNG. It can be stored and transported using conventional fuel infrastructure, which reduces logistical challenges. Furthermore, it poses fewer safety risks compared to cryogenic fuels and is readily available in most ports around the world, making it a highly accessible option.

Despite its environmental advantages over HFO, MGO is still a fossil fuel and contributes to greenhouse gas emissions. As such, it is often viewed as a transitional fuel, helping the shipping industry move toward more sustainable energy sources like Liquefied Natural Gas (LNG), biofuels, methanol, or ammonia. Its role in the decarbonization of shipping is important, especially as the industry prepares for future regulations that may include carbon pricing and stricter emissions limits.

In conclusion, Marine Gas Oil (MGO) plays a crucial role in modern maritime operations, offering a balance between cleaner combustion and operational simplicity. While more expensive than HFO, its compliance with environmental standards and global availability position it as a practical fuel option in the ongoing transition to sustainable shipping.

3. Very Low Sulfur Fuel Oil (VLSFO)

Very Low Sulfur Fuel Oil (VLSFO) is a marine fuel specifically formulated to meet the International Maritime Organization (IMO) 2020 regulation, which mandates a global sulfur cap of 0.5% (down from 3.5%) in marine fuels. Introduced as a compliance solution to this regulation, VLSFO is a blended product composed of various refinery streams designed to reduce sulfur emissions while maintaining acceptable performance in marine engines.

VLSFO typically contains a sulfur content ranging from 0.3% to 0.5%, making it suitable for use without additional exhaust cleaning systems such as scrubbers. It is considered a compromise between traditional Heavy Fuel Oil (HFO) and more refined distillates like Marine Gas Oil (MGO). While it retains some of the residual characteristics of HFO, it is treated and blended to significantly reduce its sulfur content, thereby limiting SOx (sulfur oxides) emissions and helping ship operators comply with global environmental standards.

Unlike standardized fuels like HFO or MGO, VLSFO's chemical and physical properties can vary significantly depending on the blending process and refinery source. It is often a hybrid of residual and distillate fuel components, which can result in differences in viscosity, density, flash point, and stability. These variations have sometimes led to operational challenges such as:

- Incompatibility between different batches or sources of VLSFO.
- Stability issues, where asphaltenes may precipitate, leading to sludge formation.
- Catalytic fines, which can cause wear in engine components if not properly filtered.
- However, most of these issues can be mitigated through proper fuel handling, filtration, and compatibility testing.

Environmental Benefits:

From an environmental standpoint, VLSFO represents a major improvement over traditional HFO. By drastically lowering sulfur emissions, it reduces the formation of fine particulate matter and acid rain. This helps improve air quality around busy ports and shipping lanes, especially in coastal regions and Emission Control Areas (ECAs).

However, VLSFO still emits CO_2, NOx, and particulate matter, albeit at lower levels than HFO. It is therefore seen not as a long-term solution for decarbonization, but rather a compliance fuel to bridge the gap while the maritime industry transitions to cleaner alternatives like LNG, biofuels, methanol, or hydrogen-based fuels.

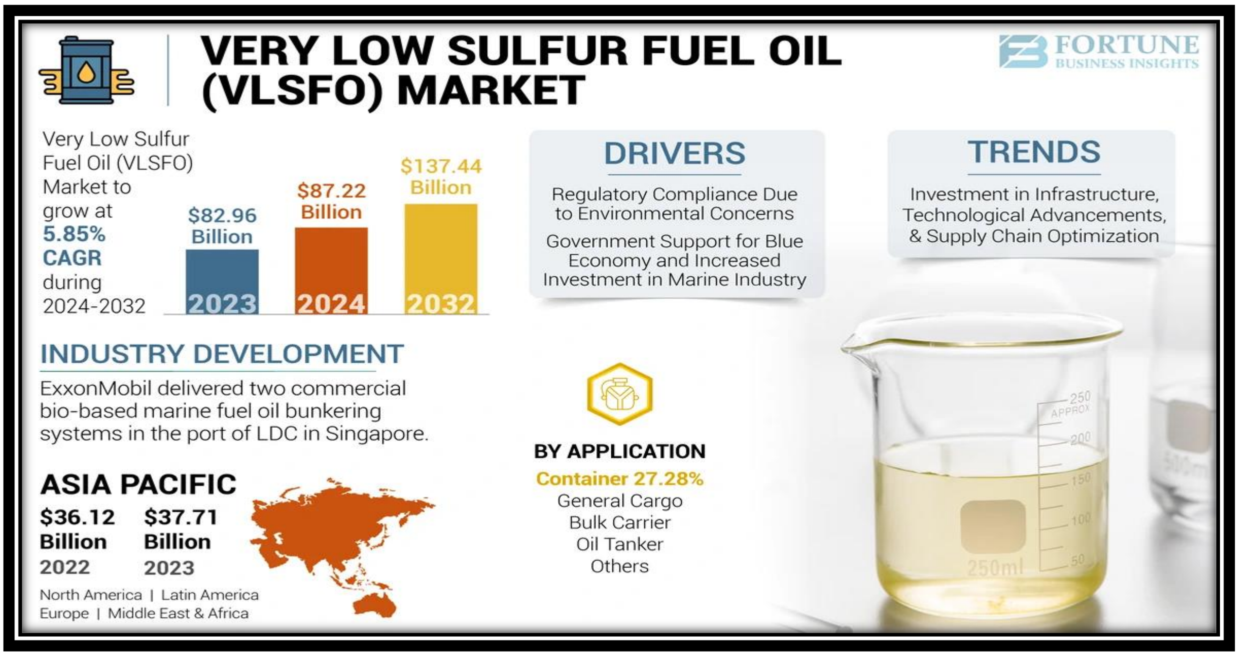

Figure 2(about very low sulfur fuel) sources:https://brickstone.africa/potential-of-low-sulphur-fuel-oil/

Economically, VLSFO is more expensive than high-sulfur HFO but cheaper than MGO and LNG. It does not require the installation of scrubbers or modifications to existing engines, making it a cost-effective and practical short-term solution for shipowners seeking compliance without significant capital expenditure. Its widespread availability and similarity in usage procedures to HFO also make it a convenient choice for many operators. However, VLSFO prices can be volatile, and as demand shifts towards cleaner fuels, its long-term competitiveness may decline. Additionally, as carbon pricing and emissions-related penalties become more prominent, VLSFO may become less attractive compared to fuels with lower greenhouse gas footprints.

3.3 Marine Fuel Regulation

Marine fuel regulations are critical in ensuring that shipping operations are conducted in a manner that is environmentally sustainable and safe. The International Maritime Organization (IMO) is the primary global body responsible for setting these standards. Under its MARPOL Annex VI, the IMO regulates air pollution from ships by setting limits on emissions such as sulfur oxides (SOx), nitrogen oxides (NOx), and particulate matter. One of the most significant regulations is the IMO 2020 Sulfur Cap, which came into effect on January 1, 2020. This regulation limits the sulfur content in marine fuels to 0.50% m/m globally, reduced from the previous 3.50%. Within Emission Control Areas (ECAs), such as the North American coast, the Baltic Sea, and the North Sea, a stricter limit of 0.10% m/m applies. To comply, ships may use low-sulfur fuel oils (LSFO), install scrubbers (exhaust gas cleaning systems), or switch to alternative fuels like LNG (Liquefied Natural Gas) and methanol.

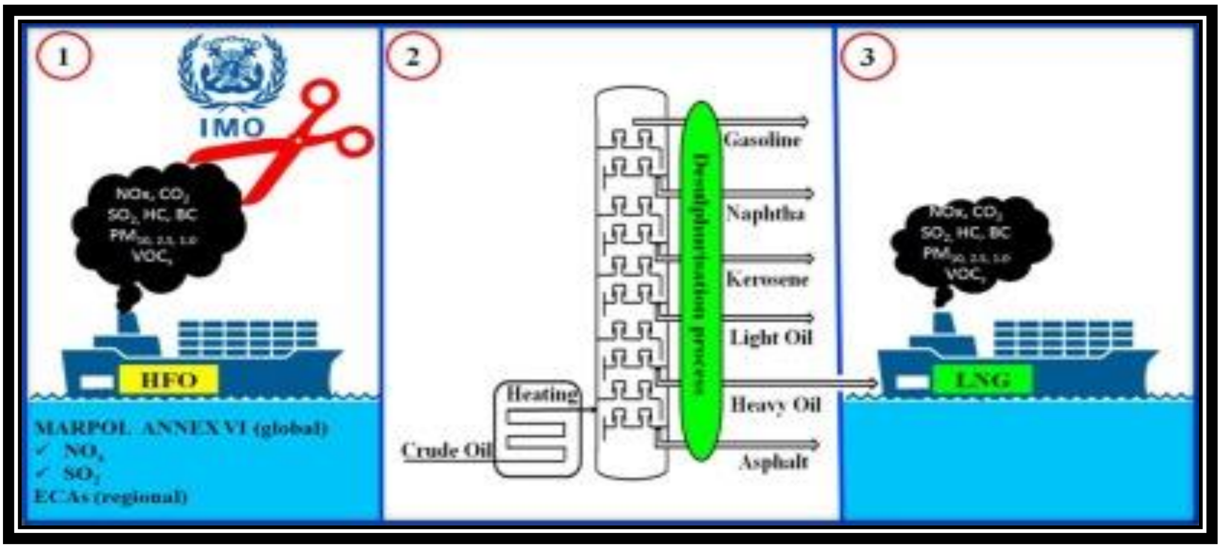

Figure 3(about Marpol) sources: https://brickstone.africa/potential-of-low-sulphur-fuel-oil/

The IMO has also introduced measures to reduce greenhouse gas emissions. Its Initial GHG Strategy (2018) aims to reduce the carbon intensity of international shipping by 40% by 2030 and 70% by 2050, using 2008 as the baseline. Two key mechanisms have been introduced: the Energy Efficiency Existing Ship Index (EEXI), which applies to ships over 400 gross tonnage, and the Carbon Intensity Indicator (CII), which measures CO_2 emissions per cargo ton-mile and rates ships from A to E. Ships rated poorly must take corrective actions. Fuel quality is governed by the ISO 8217:2017 standard, which defines various parameters to ensure marine fuels are safe and effective. These include viscosity, flash point (minimum 60°C to prevent fire), sulfur content, water content, and pour point (lowest temperature at which fuel flows). Marine fuels are generally categorized as distillate fuels (DMA, DMB) and residual fuels (RMG, RME), with distillates being cleaner and more refined.

The European Union has adopted Directive 2016/802, which aligns with IMO rules and requires ships at berth in EU ports to use fuel with ≤0.10% sulfur content. EU authorities conduct fuel sampling, logbook inspections, and even use remote sensing to monitor compliance. In the United States, marine fuel regulations are enforced by the Environmental Protection Agency (EPA) and the U.S. Coast Guard under the Clean Air Act. The U.S. also has ECAs similar to the IMO, and smaller vessels are required to use Ultra Low Sulfur Diesel (ULSD). Additionally, ports and some state agencies may impose further requirements to limit emissions and ensure cleaner maritime operations. Safety is also a priority.

The SOLAS (Safety of Life at Sea) convention requires marine fuels to have a minimum flash point of 60°C, ensuring safe storage and handling. Ships must keep bunker delivery notes (BDNs) and onboard samples to verify fuel quality. These safety and quality controls are essential to avoid accidents and maintain operational integrity.

To meet the various compliance requirements, vessels use different methods. These include switching to low-sulfur fuels, installing scrubbers, using alternative fuels like LNG or biofuels, and utilizing shore power (cold ironing) to reduce emissions while docked. Enforcement of these regulations is stringent. Port authorities and flag states perform inspections, check documentation, and test fuel samples. Non-compliance can result in severe consequences, such as hefty fines, vessel detentions, loss of certifications, and reputational damage to the shipping company. Overall, these rules and regulations form a comprehensive framework that ensures the maritime industry reduces its environmental footprint, enhances safety, and aligns with international sustainability targets. Adhering to marine fuel regulations is not only a legal requirement but also a crucial step toward a cleaner and more responsible global shipping industry.

3.4 Initiatives to Use LNG as a Marine Fuel

The initiative to use Liquefied Natural Gas (LNG) as a marine fuel is a significant development in the maritime industry’s efforts to reduce harmful emissions and comply with increasingly stringent environmental regulations. As international attention on climate change intensifies, the global shipping industry has been under pressure to transition toward cleaner fuels. One of the most promising alternatives to conventional marine fuels like Heavy Fuel Oil (HFO) is LNG, which burns cleaner and significantly reduces emissions of sulfur oxides (SOx), nitrogen oxides (NOx), carbon dioxide (CO_2), and particulate matter (PM).

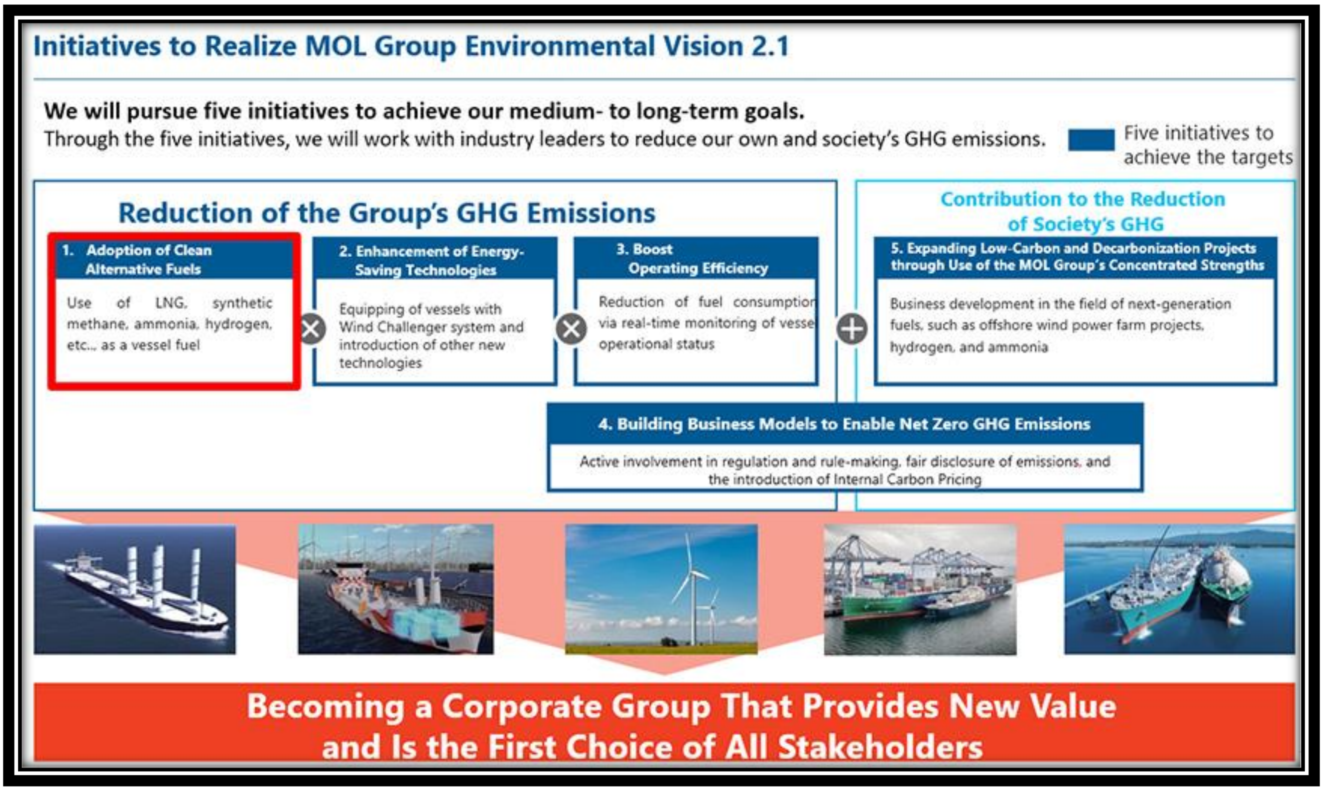

Figure 7 (initiatives to realize MOL group environmental vision) sources https://www.gminsights.com/industry-analysis/very-low-sulphur-fuel-oil-market

The push toward LNG began gaining momentum with the introduction of the IMO 2020 Sulfur Cap, which limits sulfur content in marine fuels to 0.50% m/m globally and 0.10% in Emission Control Areas (ECAs). LNG naturally contains virtually no sulfur, making it compliant with MARPOL Annex VI without the need for exhaust cleaning systems (scrubbers). Additionally, LNG reduces NOx emissions by up to 85%, CO_2 emissions by approximately 20-25%, and PM emissions by nearly 100% compared to traditional fuels. This has made it an attractive option for shipowners seeking both environmental and regulatory compliance. Several international initiatives have been launched to encourage the adoption of LNG. The International Maritime Organization (IMO), under its Initial GHG Strategy, is pushing for a 50% reduction in greenhouse gas emissions from ships by 2050. LNG is seen as a transitional fuel that can help the industry meet these mid-term targets while paving the way for future zero-carbon options like ammonia or hydrogen. To support this, the IMO has included LNG in its guidelines for alternative fuels and propulsion technologies.

National governments and ports around the world have also introduced various incentives to promote LNG. For example, ports in countries such as Singapore, the Netherlands, Norway, and South Korea offer discounted port fees, infrastructure grants, and financial support for LNG bunkering facilities and LNG-fueled vessels. The European Union has invested heavily in LNG infrastructure under programs like TEN-T (Trans-European Transport Network) and CEF (Connecting Europe Facility) to promote cleaner transport solutions, including maritime LNG. Furthermore, industry-led collaborations and partnerships have played a vital role. Organizations such as the Society for Gas as a Marine Fuel (SGMF) and the SEA\LNG coalition are actively promoting the safe, efficient, and sustainable use of LNG in shipping. These groups work on establishing best practices, safety standards, technical guidelines, and training programs to facilitate LNG adoption.

Shipping companies have responded positively to these initiatives. Major operators like CMA CGM, MSC, MOL, NYK Line, and Shell have either launched or ordered LNG-fueled vessels. CMA CGM, for example, launched a fleet of LNG-powered container ships, including the world's largest LNG-fueled vessel, the CMA CGM Jacques Saadé. These vessels are equipped with dual-fuel engines that can operate on both LNG and marine diesel, providing flexibility and resilience. The development of LNG bunkering infrastructure has been critical to supporting its adoption. As of now, LNG bunkering is available in over 30 major ports worldwide, with ongoing expansion. LNG can be supplied via trucks, bunkering barges, or dedicated terminals, offering various scalable options for different ship sizes and types. Despite its many benefits, the use of LNG is not without challenges. Concerns about methane slip (the unburned methane released during combustion), high capital investment for retrofitting ships or building new LNG vessels, and limited bunkering infrastructure in some regions remain barriers. However, technological advancements in engine design, containment systems, and methane capture are helping to address these issues. Many stakeholders still view LNG as a transition fuel a cleaner option that bridges the gap between conventional fossil fuels and the eventual use of zero-emission alternatives. In conclusion, the initiative to use LNG as a marine fuel represents a major shift in the shipping industry's approach to fuel and emissions. Driven by international regulations, national incentives, technological innovation, and environmental responsibility, LNG is playing a critical role in decarbonizing maritime transport. While it may not be the final solution, it is a significant step forward in achieving a greener and more sustainable shipping sector.

3.5 India Initiatives to Use LNG as a Marine Fuel

India, being one of the largest maritime nations in the world with a vast coastline and busy port infrastructure, has recognized the critical importance of shifting to cleaner fuels to meet international environmental standards and improve air quality in coastal and port areas. In recent years, the Indian government has taken several comprehensive initiatives to introduce and promote the use of Liquefied Natural Gas (LNG) as a marine fuel, aligning itself with global trends toward sustainable and low-emission shipping. One of the primary drivers of this initiative is India's commitment to the International Maritime Organization's (IMO) regulations, especially the IMO 2020 Sulfur Cap, which limits sulfur content in marine fuels to 0.5% globally and 0.1% in Emission Control Areas (ECAs). Although India does not yet have designated ECAs, the government is proactively preparing its maritime sector to comply with future environmental regulations. The Ministry of Ports, Shipping and Waterways (MoPSW) has been at the forefront of this transformation, launching the Maritime India Vision 2030, a long-term strategic plan to modernize the Indian maritime sector. A core component of this vision is to develop green ports and green shipping corridors, in which LNG is identified as a crucial transition fuel due to its lower emissions profile.

To support the widespread adoption of LNG, the Indian government is developing LNG bunkering infrastructure at key ports. Ports including Kandla (Deendayal Port), Mumbai, Kochi, Chennai, Haldia, and Ennore have been selected for the development of LNG storage and refueling facilities. One of the most advanced among them is the Kochi LNG terminal, operated by Petronet LNG Limited, which is already operational and capable of supplying LNG as marine fuel. The Ennore LNG terminal in Tamil Nadu, developed by Indian Oil Corporation Limited (IOCL), is also being equipped for bunkering operations. The goal is to create a network of LNG-enabled ports along India's coastline to provide easy access to clean fuel for coastal and international shipping lines. Furthermore, the government has introduced policy and fiscal support to make LNG adoption more attractive. For instance, the Petroleum and Natural Gas Regulatory Board (PNGRB) has simplified the licensing process for LNG retail outlets, and LNG is taxed at a lower GST rate (5%) compared to conventional marine fuels like diesel, improving its cost competitiveness. The Sagarmala Programme, which aims to enhance port-led development, includes specific provisions for the adoption of green technologies and alternative fuels. Under Sagarmala, financial assistance is provided for setting up LNG infrastructure and retrofitting vessels to operate on LNG.

In the inland waterways sector, the Inland Waterways Authority of India (IWAI) is working on introducing LNG-fueled vessels for cargo and passenger movement, particularly on National Waterway-1 (the Ganga River). The deployment of LNG-powered barges and ferries is expected to reduce air pollution in riverine cities, lower fuel costs, and improve the overall efficiency of inland water transport. Public-private partnerships have also emerged in this space, with several Indian shipbuilders and shipping companies exploring dual-fuel engine technology that allows vessels to run on both LNG and conventional fuels. India is also engaging in international collaborations to facilitate its LNG transition. Organizations like the International Maritime Organization (IMO) and The Energy and Resources Institute (TERI) have supported Indian efforts through studies, policy frameworks, capacity-building workshops, and pilot projects. India is actively participating in global forums such as IMO's GreenVoyage2050 and IMO-Norway Zero-Carbon Partnership, where it shares knowledge and receives technical assistance for the decarbonization of its shipping industry.

One of the most forward-looking proposals is the establishment of green shipping corridors, which are low- or zero-emission maritime routes between major ports. India is in discussions with neighboring countries like Bangladesh, Sri Lanka, and the UAE to develop LNG-fueled or hybrid marine transport networks that would reduce emissions across regional trade routes. These green corridors aim to use LNG as a transitional fuel before switching to zero-carbon options like hydrogen or ammonia in the future.

Despite these positive developments, India still faces challenges in fully realizing its LNG marine fuel potential. The high capital cost of LNG-powered vessels, limited bunkering infrastructure in many ports, and the lack of trained personnel in LNG handling and safety are areas that need further development. However, the government is addressing these gaps through investments in training centers, international partnerships, and funding support to make LNG adoption viable and scalable. India's initiatives to promote LNG as a marine fuel represent a bold step toward maritime sustainability and energy security. Through strategic infrastructure development, policy incentives, private sector participation, and international collaboration, India is positioning itself as a regional leader in green shipping. LNG is seen not only as an environmentally responsible alternative to heavy fuel oil but also as a stepping stone toward a cleaner, more efficient, and future-ready maritime economy.

Indian ports have taken significant steps to support the transition toward cleaner marine fuels, especially Liquefied Natural Gas (LNG), in line with the country's broader strategy for green shipping and environmental sustainability. Under the guidance of the Ministry of Ports, Shipping and Waterways (MoPSW), various major ports across India have launched initiatives to develop LNG infrastructure for bunkering, storage, and vessel support services. These efforts are part of the Maritime India Vision 2030, which emphasizes the creation of sustainable ports with low emissions and advanced energy management systems. The Sagarmala Programme, which promotes port-led economic development, also supports LNG infrastructure as a key component of India's green shipping ecosystem.

One of the key port initiatives is the establishment of LNG bunkering facilities at select major ports including Kochi, Ennore (Kamarajar Port), Mumbai, Kandla (Deendayal Port), Haldia, and Paradip. The Kochi LNG terminal, operated by Petronet LNG Ltd, has become a pioneer by offering both import and bunkering services, with vessels already utilizing LNG fuel for coastal operations. The Ennore LNG terminal near Chennai, developed by Indian Oil Corporation Ltd (IOCL), has been designated as a strategic point for LNG distribution along the eastern coast. Ports like Mumbai and Kandla have identified dedicated zones for the setup of LNG storage and bunkering stations, and discussions are ongoing with private investors to build the necessary infrastructure. In addition to physical infrastructure, Indian ports are implementing Green Port Guidelines, which include provisions to incentivize the use of LNG. Some ports offer rebates on port charges for LNG-fueled vessels, provide priority berthing to ships using cleaner fuels, and invest in dual-fuel-compatible equipment for port operations. Moreover, ports are upgrading their shore facilities to support cold ironing (shore power) and LNG-powered harbor crafts, tugs, and pilot boats.

Ports are also working closely with public and private stakeholders, such as GAIL India, Shell, Adani Group, and Indian Register of Shipping (IRS), to ensure that safety, operational protocols, and training for LNG handling are in place. Workshops and training programs for port officials and crew are being conducted to develop expertise in LNG bunkering procedures, emergency response, and maintenance of cryogenic systems. Several ports are also participating in international collaboration programs to develop best practices for green port operations. Indian ports have joined hands with global partners through initiatives like the IMO’s GloLitter Partnerships Project and the GreenVoyage2050 initiative to explore low-carbon solutions including LNG. These partnerships aim to position Indian ports as clean, efficient, and globally competitive. Indian ports are actively embracing the LNG revolution by investing in critical infrastructure, policy support, stakeholder engagement, and international cooperation. These initiatives are transforming Indian ports into future-ready, sustainable hubs that support India’s clean energy and maritime decarbonization goals.

Kochi Port

Kochi Port, located in the southern state of Kerala, is one of the most advanced Indian ports in terms of adopting Liquefied Natural Gas (LNG) as a marine fuel. It has taken a leadership role in India’s green shipping movement by becoming the country’s first port to offer LNG bunkering services. This initiative is primarily driven through the Kochi LNG terminal, developed and operated by Petronet LNG Limited (PLL) at Puthuvypeen. Commissioned in 2013, this terminal has a capacity of 5 million tonnes per annum (MTPA) and serves as a key hub for both domestic LNG distribution and marine fuel supply. The terminal is strategically located close to the international shipping route and has direct access to port facilities, making it ideal for LNG bunkering operations. Kochi Port’s LNG bunkering services were officially launched in 2021, when it carried out India’s first LNG bunkering operation for an international coastal vessel, setting a national milestone. This was followed by regular bunkering for ships operating along the coastal shipping route between Kochi and Gujarat. The port offers truck-to-ship LNG bunkering and is working towards expanding into pipeline-based ship-to-ship bunkering, which will enable faster and more efficient fuel delivery. The LNG supplied from Kochi is not only used by vessels, but also by LNG powered inland water transport systems, including ferries and small cargo ships operating in Kerala's backwaters.

Figure 4(kochi port lng setup 2015) https://www.gminsights.com/industry-analysis/very-low-sulphur-fuel-oil-market

In alignment with the Maritime India Vision 2030 and the Green Port Guidelines, Kochi Port is actively working to reduce its carbon footprint and promote the use of alternative fuels. The Cochin Port Authority has partnered with key public and private sector companies such as Indian Oil Corporation (IOCL), BPCL, and Shell to promote LNG infrastructure, safety training, and awareness campaigns. The port has also taken steps to equip its staff with LNG handling skills, safety protocols, and operational training to support the long-term use of LNG. Moreover, the Kochi Port's initiative has inspired other Indian ports to follow suit. Its success in LNG bunkering has highlighted the commercial viability of LNG as a marine fuel in India and demonstrated the port's capability to support low-emission shipping. With strong government backing, strategic location, robust infrastructure, and early mover advantage, Kochi is playing a pioneering role in transforming India's maritime energy landscape, and is set to become a major LNG bunkering hub in South Asia.

Ennore Port

Ennore Port, also known as Kamarajar Port, located near Chennai in the southern state of Tamil Nadu, is a key player in India's transition to sustainable and cleaner maritime fuels. As part of the Indian government's push for green shipping, Ennore Port is one of the leading ports in the country to implement LNG bunkering infrastructure. The port is working to establish itself as a critical node for LNG distribution along the eastern coast of India. The initiative is driven by the port's strategic location, which facilitates efficient connectivity to both domestic and international shipping routes. In 2020, the port signed a Memorandum of Understanding (MoU) with Indian Oil Corporation Ltd (IOCL) and Shiv Vani Oil & Gas to develop LNG bunkering facilities, marking a significant step toward the growth of LNG-fueled shipping in India. Ennore Port's LNG bunkering facility is expected to be one of the most advanced on the eastern seaboard. The port has invested in infrastructure such as LNG storage tanks, supply pipelines, and truck-to-ship bunkering facilities to ensure smooth and safe delivery of LNG to vessels. This facility is poised to serve the growing number of LNG-powered vessels operating along India's coast and the Bay of Bengal. By offering LNG as a cleaner alternative to conventional marine fuels, Ennore Port aligns with the IMO's 2020 sulfur cap regulations, which limit sulfur content in marine fuels to 0.5%, as well as India's broader maritime environmental goals.

Further, the port has been collaborating with industry stakeholders, including GAIL India and Shell, to enhance its LNG bunkering capabilities and infrastructure development. Ennore Port is also integrating safety measures, including specialized training for port workers, ensuring compliance with international standards for LNG handling. It is positioning itself as a critical enabler of low-emission shipping along the eastern coast of India. The facility is expected to support not only coastal shipping but also international vessels, enhancing India's position in the global maritime industry by promoting LNG as a cleaner fuel. This initiative is part of a larger vision to create a green shipping corridor on the east coast of India, which would allow for the seamless use of LNG in maritime transportation. The development of the LNG infrastructure at Ennore Port complements the Sagarmala Programme and India's Maritime India Vision 2030, which aim to reduce carbon emissions in the maritime sector, improve air quality, and transition towards more energy-efficient shipping practices. Through these steps, Ennore Port is not only supporting the growth of LNG as a marine fuel but also contributing to India’s broader commitment to sustainable development and energy transition.

Mumbai Port

Mumbai Port, one of India’s most prominent and busiest ports, located on the western coast of India, has taken significant strides toward embracing Liquefied Natural Gas (LNG) as a marine fuel to support the country's transition to a cleaner and more sustainable shipping industry. As part of India’s national efforts to reduce emissions from the maritime sector, Mumbai Port has been actively involved in the development of LNG bunkering infrastructure. Recognizing the importance of LNG in helping vessels meet the IMO 2020 sulfur cap regulations, which limit sulfur content in marine fuels to 0.5%, Mumbai Port is positioning itself as a key player in India’s green shipping movement. Mumbai Port is collaborating with several key stakeholders, including Indian Oil Corporation Ltd (IOCL), GAIL India, and private sector players like Shell to develop LNG bunkering terminals and infrastructure within the port. The aim is to provide LNG refueling facilities for both domestic and international vessels, especially as more shipping companies are moving toward LNG-powered ships to comply with global emission reduction targets. The Mumbai Port Trust (MPT) has initiated the process of establishing a LNG bunkering facility, including LNG storage tanks, a pipeline network, and specialized bunkering vessels, to ensure the safe and efficient transfer of LNG fuel to vessels calling at the port.

This initiative is further bolstered by Mumbai Port's alignment with the Sagarmala Programme and Maritime India Vision 2030, which emphasize the importance of developing sustainable and low-carbon energy solutions for India’s ports. Mumbai Port has also been working closely with India’s Ministry of Ports, Shipping, and Waterways (MoPSW) to ensure that LNG bunkering services are available to vessels in a timely and cost-effective manner. Mumbai, being one of the largest international shipping hubs in India, is well-positioned to become a major LNG bunkering center for both coastal shipping and global shipping routes. The port's commitment to LNG is also complemented by its focus on adopting other green technologies, including shore-to-ship power for reducing emissions from vessels at berth and reducing the overall environmental impact of port operations. Mumbai Port is also investing in training and safety programs to ensure that its personnel are well-equipped to handle LNG safely, by international standards for LNG handling and bunkering. Mumbai’s LNG initiative is part of a broader vision to turn India's major ports into green and sustainable maritime hubs. The development of LNG bunkering infrastructure is expected to contribute significantly to reducing sulfur oxide (SOx), nitrogen oxide (NOx), and particulate matter (PM) emissions from ships calling at the port, thereby improving air quality in Mumbai and the surrounding coastal region. By embracing LNG as a clean marine fuel, Mumbai Port is not only advancing India's environmental goals but also enhancing its competitiveness as a regional maritime leader, facilitating cleaner, more energy-efficient shipping operations.

Kandla Port

Kandla port, officially known as Deendayal Port Authority (DPA), located in the state of Gujarat, is at the forefront of India's transition to sustainable maritime fuels. Strategically situated within the Rotterdam-Singapore Green Shipping Corridor, DPA is actively developing infrastructure to become a zero-emission fuel bunkering hub. . DPA is investing in the establishment of LNG bunkering facilities to cater to the growing demand for cleaner marine fuels. The port is focusing on building the necessary infrastructure to support LNG bunkering operations, aligning with India's commitment to reducing carbon emissions in the maritime sector.

In addition to LNG, DPA is exploring the production of green hydrogen and green ammonia as alternative marine fuels. The port is targeting a production capacity of 7 million tons per annum (MTPA) of green ammonia, MTPA of green hydrogen, positioning DPA has joined the Methanol Institute, reflecting its commitment to advancing green fuel bunkering. The port is also collaborating with international partners to establish best practices and standards for LNG bunkering operations, ensuring alignment with global maritime fuel trends. To ensure the safe handling of LNG, DPA has developed Standard Operating Procedures (SOPs) for LNG bunkering. The port is also investing in training programs for personnel to handle LNG safely, following international standards for LNG bunkering operations.

3.6 Data Analysis for the Market for LNG Fuel.

The Fuel Cost Comparison

Fuel Type	**Approximate Price (2024)**	**Energy Content (MJ/kg)**	**$/GJ (Energy-Adjusted Cost)**
HFO	$450/ton	~40	~$11.25

Fuel Type	Approximate Price (2024)	Energy Content (MJ/kg)	$/GJ (Energy-Adjusted Cost)
MGO	$750/ton	~42.7	~$17.57
LNG	$900/ton	~50	~$18

LNG is cleaner, but **currently more expensive per unit of energy** than HFO

3.7 Operational & Maintenance Costs

LNG:

- Lower engine wear due to cleaner combustion.
- Longer engine life and reduced oil consumption.
- Requires cryogenic handling and more training.
- O&M savings up to 20–30% compared to HFO.

HFO:

- Higher maintenance due to soot, sulfur, and sludge.
- Requires scrubbers to meet IMO sulfur limits.

MGO:

- Cleaner than HFO, but still causes wear.
- No need for scrubbers, but more expensive fuel.

3.8 Capital Expenditures:

Item	LNG	HFO/MGO
Engine (Dual-fuel/LNG)	+20–30% higher	Standard
Fuel Tank (LNG cryogenic)	4–6 times larger & costlier	Compact
Retrofit Cost (Existing Ship)	$10–20 million	Minimal or none

LNG vessels have a higher initial cost due to tank and engine technology.

3.9 Environmental Compliance & Regulatory Cost:

 LNG meets **IMO 2020** sulfur cap and **IMO 2030** GHG targets better than HFO/MGO.

 Reduces:

- **SOx by ~100%**
- **NOx by ~85%**
- **CO_2 by ~20%**

 Avoids costs for:

- Scrubbers
- Emission penalties or carbon pricing

3.10 Fuel Infrastructure & Availability

- **LNG bunkering** is limited but growing at major ports (Rotterdam, Singapore, etc.).
- Lack of global infrastructure adds **logistical and opportunity costs**.

Total Cost of Ownership (TCO):

Component	LNG Vessel	HFO Vessel	MGO Vessel
CapEx	High	Low	Medium
Fuel Cost	Medium/High	Low	High
Maintenance	Low	High	Medium
Emission Penalties	Low	High	Medium
Infrastructure	Limited	Established	Established

3.11 Conclusion of LNG Fule

- **Economically feasible in the long run**, especially for:
  - **New builds**
  - **High-utilization vessels** (e.g., container ships, ferries)
  - Routes with LNG availability
- **Less attractive for retrofits** unless regulatory pressure or fuel prices shift.

- **Environmental compliance and potential carbon taxes** could tip the balance in LNG’s favor.

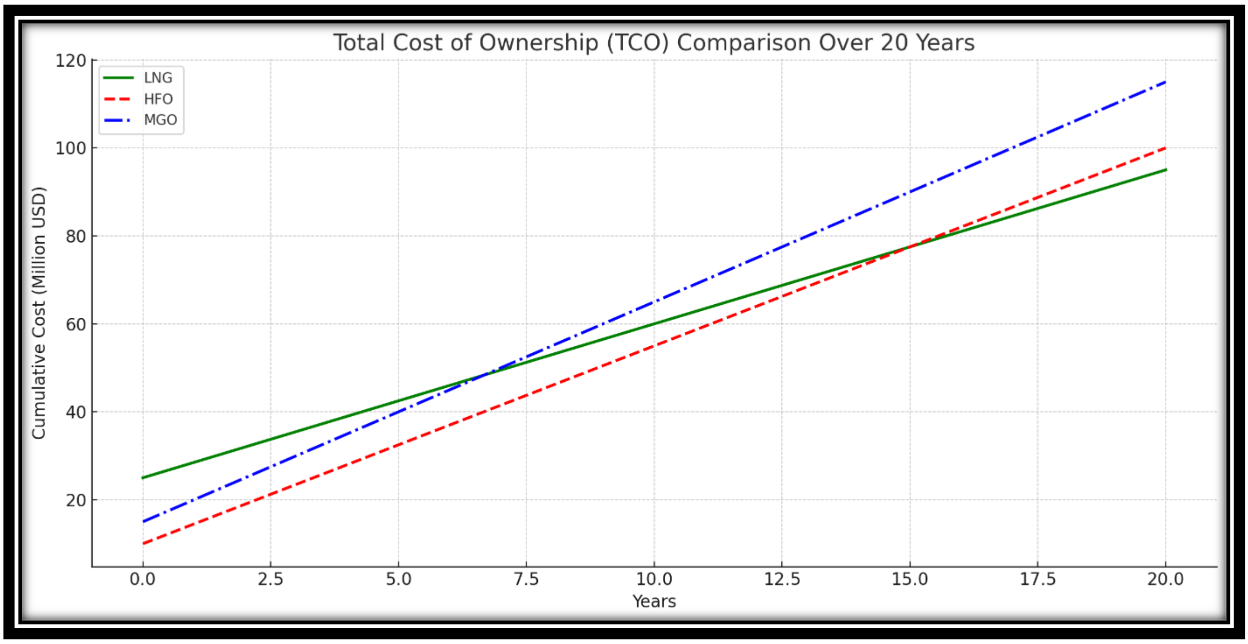

Figure 9 sources https://www.researchgate.net/figure/Cost-breakdown-for-all-vessel-types_fig3_344282178

 LNG **(green)** has a higher initial cost but becomes competitive after around 8–12 years due to lower OPEX.

 HFO **(red)** is cheapest upfront, but long-term costs rise faster due to higher maintenance and compliance expenses.

 MGO **(blue)** is consistently the most expensive over time due to high fuel costs despite moderate CapEx.

CHAPTER 4
(Analytics)

4.0 Marine Transportation and Energy Use

Current Energy Use of vessel

Bunker: Bunker fuel is the colloquial term for fuel oil used by marine vessels. Bunker fuels A, B, and C are respectively downgrading quality-classifications of fuel oil, characterized by their boiling points, carbon-chain lengths, and viscosities, all of which contribute to their value (in other words, Bunker A is more valuable than Bunker C) (see Fig. 2 for a breakdown of fuel mix types for various marine vessel types, and Figs. 3 and 4 for CO2 emissions from various marine vessel types). Currently, most of the global shipping fleet, relies on diesel Bunker C fuel oil which contributes significant amounts of GHG, sulfur, and other emissions that contribute negatively to climate change and negative environmental and human health impacts. In Fig. 2, HFO, MDO/MGO, and LSHFO are considered Bunker fuels, which highlights a significant proportion of the merchant fleet is powered by this fuel type.

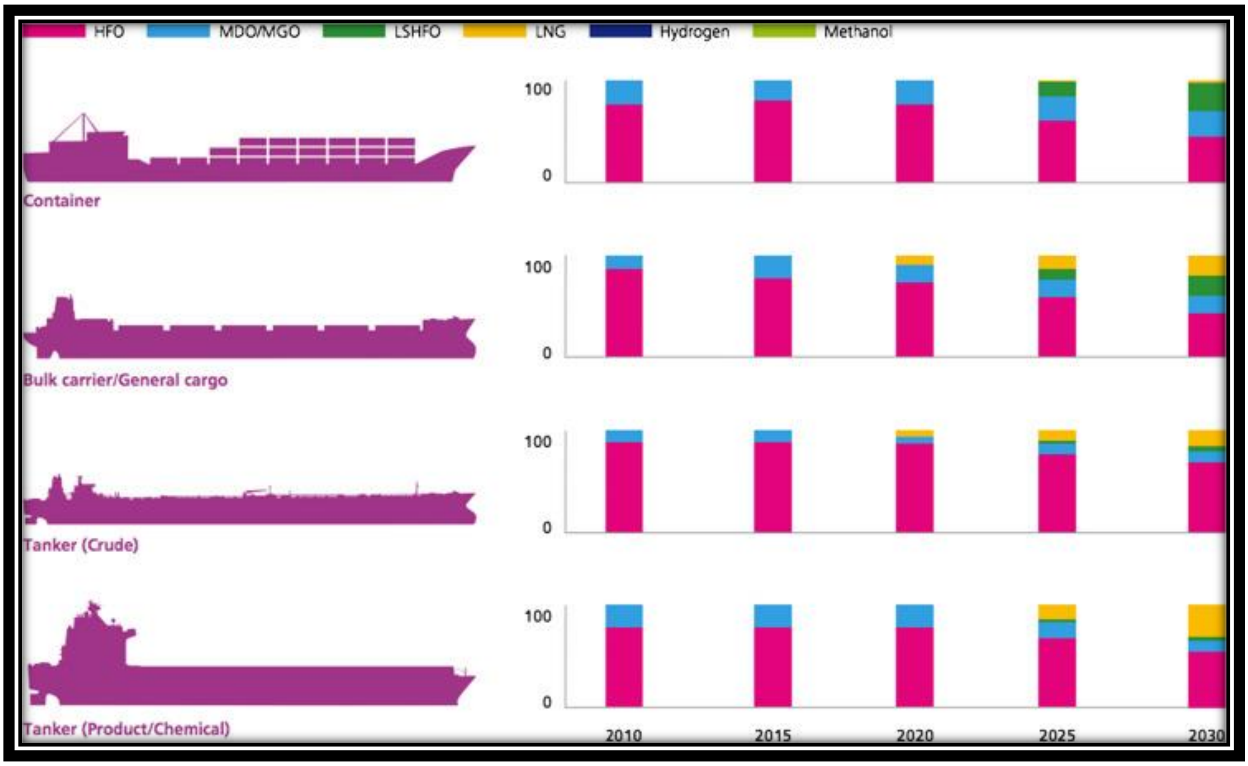

Figure 10 (about energy use by vessel) sources: https://www.mdpi.com/1996-1073/15/21/7910

Fuel mix for various vessel types. HFO = Heavy Fuel Oil; MDO/MGO = Marine Diesel/Gas Oil; LSHFO = Low Sulfur Heavy Fuel Oil; LNG = Liquefied Natural Gas.

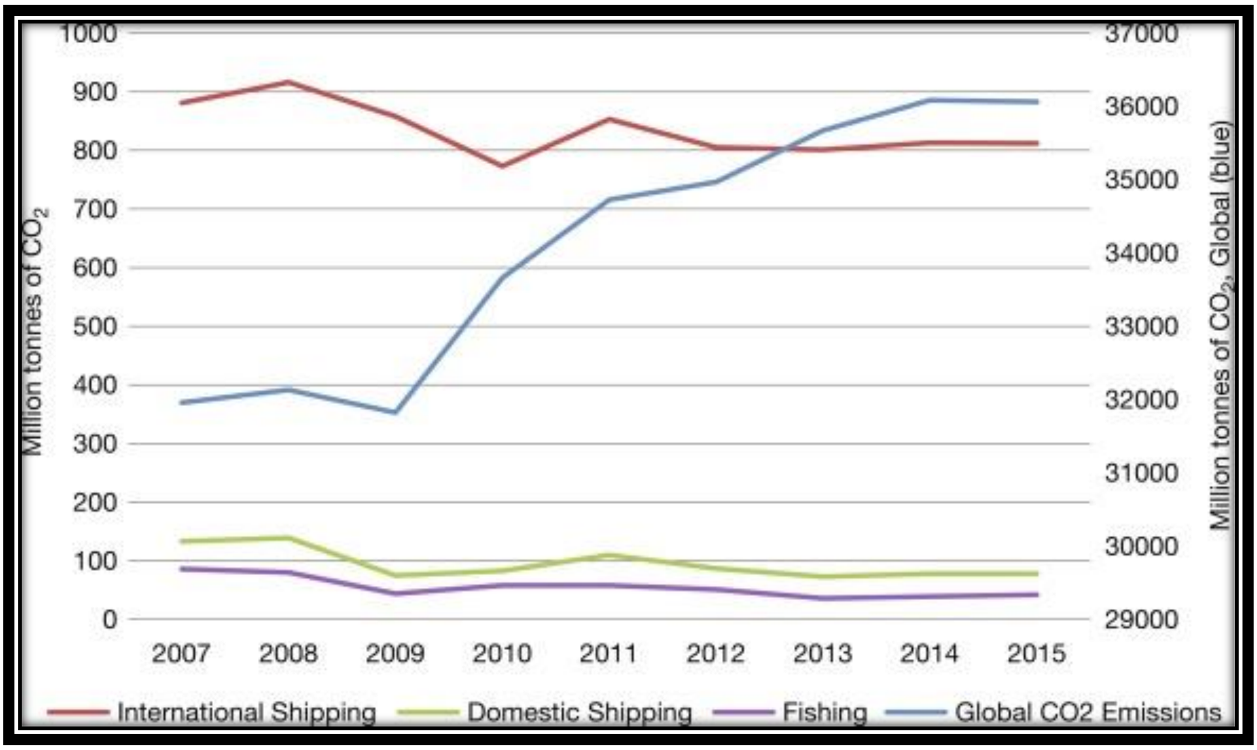

Figure 11 (about co2 emissions) sources: https://mmtrading.sg/2023/04/03/carbon-emission-from-ships/

Data from Olmer, N., Comer, B., Roy, B., Mao, X., Rutherford, D. (2017). Greenhouse gas emissions from global shipping, 2013–2015. The International Council on Clean Transportation (ICCT), Washington.

CO2 emissions from different sources of marine transportation.

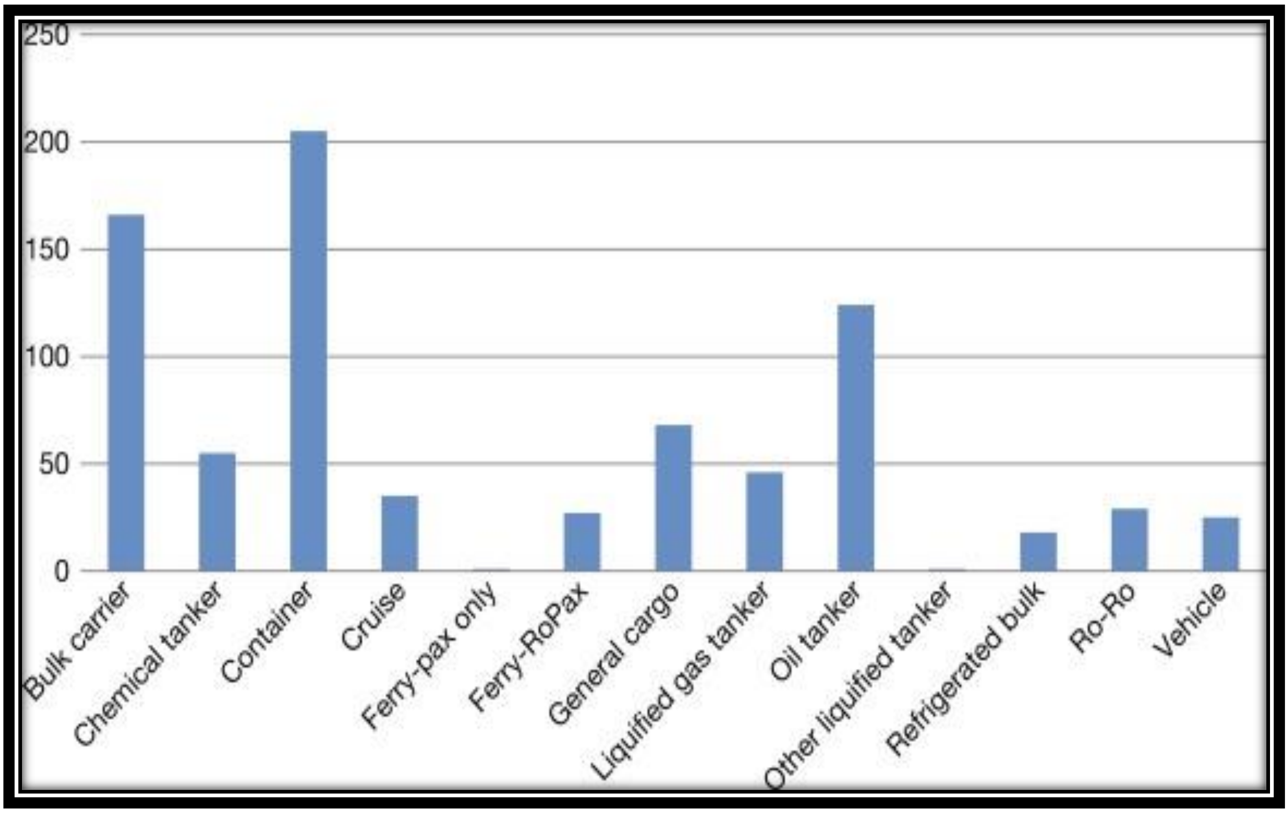

Figure 12 (about c02 emissions in marine transportation), Sources: https://mmtrading.sg/2023/04/03/carbon-emission-from-ships/

4.1 Emission Reductions – Quantitative Comparison:

Pollutant	**LNG vs HFO**	**LNG vs MGO**	**Explanation**
CO_2 (Carbon Dioxide)	20–25%	15–20%	Cleaner combustion and higher hydrogen-to-carbon ratio
SO_x (Sulfur Oxides)	100%	100%	LNG is sulfur-free
NO_x (Nitrogen Oxides)	85–90%	80%	Lower combustion temps reduce NO_x formation
PM (Particulate Matter)	95–100%	90%	No soot, minimal ash formation in combustion

Detailed Breakdown:

A) CO_2 Reduction

- LNG has a higher **hydrogen-to-carbon ratio** than HFO/MGO.
- Typical CO_2 emissions per GJ:
    - **LNG**: ~56.1 kg/GJ
    - **HFO**: ~77.4 kg/GJ
    - **MGO**: ~74.1 kg/GJ
- LNG offers **~20% CO_2 reduction**, though **methane slip** can reduce this benefit if not properly managed.

B) SO_x Elimination

- HFO contains 2–3.5% sulfur; LNG contains **no sulfur**.
- LNG completely eliminates SO_x, avoiding acid rain and respiratory health impacts.

C) NO_x Reduction

- LNG engines (especially Otto-cycle/lean burn) operate at **lower combustion temperatures**, reducing NO_x formation.
- **Tier III NO_x compliance** is possible without SCR (Selective Catalytic Reduction).

D) Particulate Matter Reduction

- Virtually **no PM emissions** from LNG combustion.
- HFO/MGO emit soot, ash, and ultrafine particles affecting air quality and health.

Real-World Impact Example:

One large container ship (e.g., 14,000 TEU) using LNG instead of HFO over 1 year:

Pollutant	Annual Reduction Estimate
CO_2	20,000–25,000 tons
SO_x	500–1,000 tons
NO_x	1,200–1,800 tons

Pollutant	Annual Reduction Estimate
PM	150–200 tons

4.2 LNG adoption yields major environmental benefits,

especially for reducing **SO_x, NO_x, and PM emissions** to near zero.

CO_2 emissions are also significantly reduced, making LNG one of the cleanest transitional fuels for maritime transport.

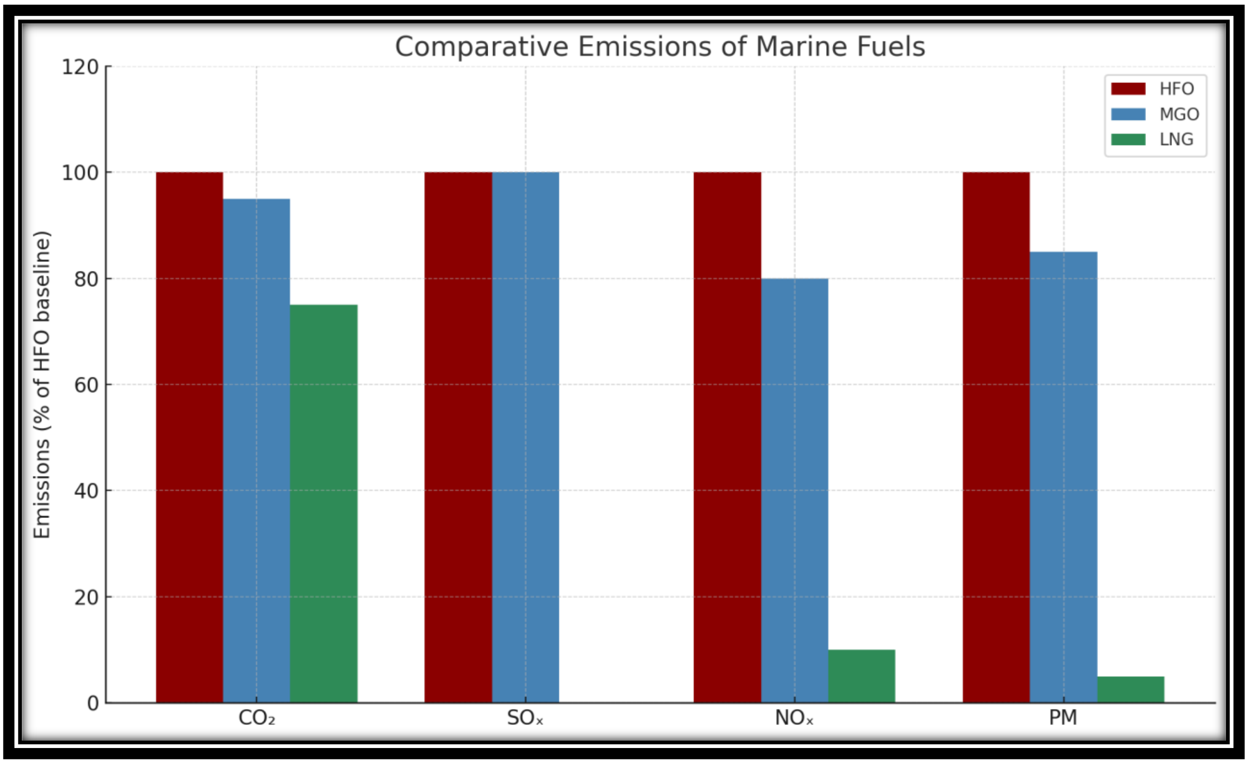

Figure 13 (about comparative emissions of marine fuels) Source: https://www.zerocarbonshipping.com/publications/determining-the-impact-and-role-of-onboard-vessel-emission-reduction

LNG dramatically reduces SO_x (~100%), PM (~95%), and NO_x (~90%), with a ~25% drop in CO_2.

MGO performs better than HFO on NO_x and PM, but still emits SO_x and more CO_2 than LNG.

4.3 Infrastructure Development Impact on Cost-Benefit Ratio:

Initial Challenges (High Cost, Low Availability)

Factor	Impact on LNG Cost	Resulting Effect on CBR
Limited bunkering ports	↑ Fuel logistics cost	↓ CBR (less efficient routes)
Cryogenic storage needs	↑ CapEx for port/ship	↓ CBR (more upfront investment)

Mature Infrastructure (OPEX Benefits, Better Bunkering)

Factor	Impact	Resulting Effect on CBR
Global LNG bunkering	↓ Fuel uncertainty & cost	↑ CBR (higher availability)
Economies of scale	↓ Infrastructure/unit cost	↑ CBR (long-term savings)
Supply chain development	Stable pricing	↑ CBR (better predictability)

LNG becomes more viable and economically competitive as infrastructure improves globally, especially on established shipping corridors (e.g., Asia–Europe, US–Asia).

4.4 Regulatory Policy Impact on LNG Ship CBR:

Current Policies

- **IMO 2020**: Limits sulfur content in fuel, favors LNG over HFO.
- **NOx Tier III regulations**: LNG engines are inherently compliant, avoiding costly retrofits.

Fuel Type	Scrubber Cost	Emission Fine Risk	Regulatory Burden
LNG	$0	Low	Low
HFO	$2–5M/ship	High	High
MGO	$0	Medium	Medium

Future/Proposed Regulations

- IMO GHG Strategy 2030/2050
- EU ETS & Carbon Taxes

- Will penalize CO_2-intensive fuels like HFO and MGO
- LNG has ~20–25% lower CO_2 per energy unit

Regulatory-Driven CBR Impact

Scenario	**LNG Impact**	**HFO Impact**
Carbon Tax ($100/ton CO_2)	↑ Cost modestly	↑↑↑ Cost sharply
Emission credits or subsidies	↓ Effective cost	None
Methane slip regulation (future)	Potential ↑ maintenance	N/A

4.5 Quantitative Example: CBR Under Two Scenarios

Scenario	**LNG Ship (CBR)**	**HFO Ship (CBR)**
Base Case (2024)	1.1	1.3
Improved Infra + Carbon Tax	**1.5**	**0.9**
Strict IMO 2030 Compliance	**1.6**	**0.8**

- CBR > 1 = Economically beneficial
- **Regulation & infra shifts make LNG more favorable over time**

Infrastructure development and regulatory support significantly increase the cost-benefit ratio of LNG ships, especially in the long term. While LNG starts with high CapEx, maturing bunkering networks and tightening emissions regulations gradually tilt the balance in its favor.

CHAPTER 5
(Findings and Conclusion)

5.1 Findings and Conclusion:

The study undertaken provides a holistic evaluation of Liquefied Natural Gas (LNG) as a marine fuel, examining its economic feasibility, environmental advantages, regulatory compliance potential, and infrastructural limitations in comparison to traditional fuels such as Heavy Fuel Oil (HFO) and Marine Gas Oil (MGO). The findings clearly demonstrate that LNG presents itself as a viable transitional fuel that aligns well with the International Maritime Organization's (IMO) increasingly stringent environmental regulations, such as the IMO 2020 sulfur cap and the future IMO 2030 and 2050 decarbonization targets. LNG significantly reduces emissions: sulfur oxides by nearly 100%, nitrogen oxides by approximately 85%, and carbon dioxide by 20-25%, thereby offering clear environmental advantages. Economically, LNG adoption shows promise in long-term cost savings—particularly in terms of reduced maintenance costs, lower emissions penalties, and potentially favorable carbon taxation regimes—although high initial capital expenditures for LNG engine retrofitting and cryogenic fuel tanks remain substantial entry barriers. The research indicates that for new builds or high-utilization vessels such as container ships and ferries operating on established LNG routes, the Total Cost of Ownership (TCO) of LNG-powered vessels becomes competitive after 8–12 years of operation. However, for older vessels, retrofitting proves economically less attractive unless offset by regulatory incentives or drastic shifts in fuel pricing. Infrastructure development, although expanding globally, is still uneven and remains a critical limitation in ensuring seamless LNG availability. Nonetheless, initiatives in India—such as those at Kochi, Ennore, and Mumbai ports—along with global port investments, signal a positive trajectory toward LNG readiness. In summary, while LNG is not a zero-emission solution and faces challenges like methane slip and limited bunkering support, the overall cost-benefit analysis reveals that LNG is a strong transitional fuel for the maritime sector. Its adoption supports the industry's path to decarbonization and provides economic resilience in an era of regulatory transformation and environmental accountability. The findings of this study strongly recommend strategic investment in LNG infrastructure, policy support for early adopters, and continued innovation in engine technologies to minimize methane emissions. As the maritime industry moves toward cleaner operations, LNG stands as a crucial bridge fuel in the sustainable evolution of global shipping.Marine fuel regulations are critical in ensuring that shipping operations are conducted in a manner that is environmentally sustainable and safe.

The International Maritime Organization (IMO) is the primary global body responsible for setting these standards. Under its MARPOL Annex VI, the IMO regulates air pollution from ships by setting limits on emissions such as sulfur oxides (SOx), nitrogen oxides (NOx), and particulate matter. One of the most significant regulations is the IMO 2020 Sulfur Cap, which came into effect on January 1, 2020. This regulation limits the sulfur content in marine fuels to 0.50% m/m globally, reduced from the previous 3.50%. Within Emission Control Areas (ECAs), such as the North American coast, the Baltic Sea, and the North Sea, a stricter limit of 0.10% m/m applies. To comply, ships may use low-sulfur fuel oils (LSFO), install scrubbers (exhaust gas cleaning systems), or switch to alternative fuels like LNG (Liquefied Natural Gas) and methanol Economic Feasibility.

This study titled "Cost-Benefit Analysis of Using LNG as a Fuel for Vessels" has presented a detailed and critical evaluation of Liquefied Natural Gas (LNG) as an alternative marine fuel in the context of rising environmental concerns, stricter regulatory frameworks, and the global push for sustainable shipping. Through an integrated analysis encompassing economic, environmental, operational, and regulatory dimensions, the findings reveal that LNG offers a promising, albeit transitional, solution for reducing emissions and achieving cost-effective compliance with international maritime standards.

From an environmental standpoint, LNG significantly reduces harmful emissions when compared to conventional marine fuels such as Heavy Fuel Oil (HFO) and Marine Gas Oil (MGO). Specifically, LNG reduces sulfur oxide (SOx) emissions by almost 100%, nitrogen oxide (NOx) emissions by up to 85%, and carbon dioxide (CO2) emissions by approximately 20-25%. These reductions not only contribute to meeting the International Maritime Organization's (IMO) 2020 sulfur cap but also align well with the IMO 2030 and 2050 greenhouse gas (GHG) reduction targets. Moreover, LNG combustion produces negligible particulate matter, leading to improved air quality, especially in port cities and emission control areas (ECAs). These environmental advantages position LNG as a viable intermediate fuel as the industry transitions toward zero-emission alternatives such as hydrogen, ammonia, and biofuels.

Economically, LNG adoption involves high initial capital expenditures, including the cost of retrofitting existing vessels or constructing new LNG-powered ships, as well as investing in cryogenic storage systems and specialized engines. Retrofitting costs alone can range from $10 to $20 million per vessel. Despite these substantial upfront costs, LNG proves to be economically viable over the long term, especially for new builds and vessels operating on fixed, high-utilization routes with established LNG infrastructure. The study's cost-benefit analysis indicates that LNG-fueled ships experience lower operational and maintenance costs due to cleaner combustion, reduced engine wear, and extended machinery life. Additionally, LNG reduces exposure to future carbon taxes and emission penalties, providing a financial hedge in a regulatory environment that increasingly penalizes high-emission fuels.

In terms of infrastructure and operational readiness, LNG bunkering facilities are expanding but remain concentrated in certain regions, such as Europe, Asia-Pacific, and North America. The availability of LNG at major ports is gradually improving, supported by government policies, public-private investments, and international collaborations. In India, ports like Kochi, Ennore, and Mumbai have initiated LNG bunkering operations, with plans for further expansion under the Maritime India Vision 2030 and the Sagarmala Programme. However, global infrastructure development is still uneven, which poses logistical and strategic challenges for shipowners considering LNG adoption. Furthermore, operational risks related to methane slip, which is the unintended release of unburned methane, need to be mitigated through technological innovation and improved engine design.

The findings of this research suggest that LNG is most economically and operationally beneficial for newly built vessels and high-frequency routes where LNG infrastructure is already available or under rapid development. For older ships, the high retrofitting costs and limited refueling options can offset the long-term benefits, unless supported by regulatory incentives or fuel subsidies. The Total Cost of Ownership (TCO) model demonstrates that while LNG vessels require higher capital investments, they offer lower lifecycle costs over an 8-12 year period due to reduced fuel expenses, maintenance savings, and regulatory compliance advantages. This positions LNG as a competitive marine fuel solution in the medium term.

Ultimately, LNG serves as a practical and strategic bridge fuel, facilitating the maritime industry's gradual shift toward cleaner energy sources. While not without its limitations, such as price volatility and methane emissions, LNG currently offers a balanced mix of environmental compliance and long-term cost efficiency. To enhance its feasibility, policy makers and industry stakeholders must focus on accelerating LNG infrastructure development, standardizing global bunkering protocols, and incentivizing innovation in dual-fuel engine technology. These coordinated efforts will ensure that LNG continues to play a pivotal role in maritime decarbonization strategies, even as the industry prepares for the adoption of zero-carbon fuels in the decades ahead.

In conclusion, the cost-benefit analysis of LNG as a marine fuel confirms its potential to meet regulatory mandates, reduce environmental impact, and offer financial sustainability over the long term. The adoption of LNG should be pursued strategically, with a focus on new vessel construction, infrastructure investment, and international collaboration. As the global shipping industry navigates the path to a greener future, LNG remains a critical transitional tool in achieving a sustainable and resilient maritime ecosystem.

- LNG presents **higher upfront capital costs** due to the need for dual-fuel engines and cryogenic storage.
- However, LNG can result in **20–30% savings in operational and maintenance costs** over the vessel's lifetime.
- **Total Cost of Ownership (TCO)** becomes competitive after **8–12 years**, especially for new builds or high-utilization ships (e.g., container ships on established routes).

Environmental Benefits

- LNG significantly outperforms traditional marine fuels (HFO and MGO) in emission reduction:
  - **SO_x**: ~100% reduction
  - **NO_x**: ~85–90% reduction
  - **CO_2**: ~20–25% reduction
  - **Particulate Matter**: ~95–100% reduction
- LNG aligns well with **IMO 2020, 2030, and 2050** decarbonization targets.
- **Methane slip** is a concern, but it can be mitigated with advanced engine technologies.

Infrastructure & Operational Viability:

- LNG bunkering infrastructure is expanding globally but still limited. Ports like Kochi, Ennore, Mumbai, and Kandla are actively investing in LNG infrastructure in India.
- Bunkering availability and cryogenic handling requirements add operational complexity.

- As infrastructure matures and economies of scale improve, LNG becomes increasingly viable.

Regulatory & Policy Impact

- LNG avoids **scrubber installation costs** and reduces exposure to **carbon pricing** and **emission fines**.
- Under regulatory pressure (IMO/EU ETS), LNG's **cost-benefit ratio (CBR)** improves substantially:
  - **CBR > 1** under carbon tax and strict emission regimes.
  - LNG becomes the **economically and environmentally preferred** choice.

Long-term outlook

- LNG is seen as a **transitional fuel** toward zero-emission solutions like hydrogen and ammonia.
- It offers a **balanced trade-off** between current environmental compliance and long-term economic efficiency.
- Widespread LNG adoption depends on **fuel price stability, infrastructure investment, and policy incentives**.

LNG is not the cheapest upfront, **but it emerges as a** cost-effective, regulatory-compliant, and environmentally sustainable fuel **over time. It is best suited for** new builds**, ships operating on** high-frequency routes**, and operators aiming for** early compliance with future decarbonization mandates**.**

Category	**Key Findings**
Economic Feasibility	High upfront cost, but lower O&M; Break-even in 8–12 years for high-utilization ships.
Environmental Benefits	Reduces SO_x (~100%), NO_x (~85–90%), CO_2 (~20–25%), and PM (~95–100%).
Infrastructure & Operational Viability	Limited but growing LNG bunkering; complexity in handling mitigated by training and investment.

Category	Key Findings
Regulatory & Policy Impact	Avoids scrubber cost and penalties; favorable under IMO/EU regulations and carbon pricing.
Long-Term Outlook	Transitional fuel; balances near-term compliance with long-term economic and sustainability goals.

Liquefied Natural Gas (LNG) stands as a practical and forward-looking alternative to traditional marine fuels in today's evolving regulatory and environmental landscape. While challenges such as high capital costs and limited infrastructure remain, the long-term benefits—including substantial emission reductions, operational savings, and alignment with IMO targets—make LNG a compelling choice for sustainable shipping. As the industry continues its transition toward cleaner energy solutions, LNG emerges not as the final destination, but as a critical stepping stone toward a greener and more resilient maritime future.

5.2 Findings

1. **Environmental Benefits**
   LNG significantly reduces harmful emissions compared to conventional marine fuels such as Heavy Fuel Oil (HFO) and Marine Gas Oil (MGO). It nearly eliminates sulfur oxides (SOx), reduces nitrogen oxides (NOx) by up to 85%, and cuts carbon dioxide (CO_2) emissions by approximately 20–25%. These reductions make LNG highly effective in meeting the International Maritime Organization's (IMO) 2020 sulfur cap and align with the IMO's 2030 and 2050 decarbonization goals. Additionally, LNG combustion results in minimal particulate matter, contributing to better air quality in port areas and along shipping routes.
2. **Economic Feasibility and Cost Efficiency**
   Although the initial capital expenditure for LNG-powered ships is high—ranging from $10 to $20 million for retrofitting—the long-term operational savings are substantial. LNG engines require less maintenance due to cleaner combustion, leading to lower engine wear and longer machinery life. The Total Cost of Ownership (TCO) analysis shows that LNG-fueled vessels become cost-competitive after 8–12 years of operation. This is particularly true for new builds and high-utilization vessels operating on fixed routes.

3. **Operational and Maintenance Advantages**

   LNG engines offer smoother and more efficient operations. Due to the cleaner nature of LNG combustion, ships powered by LNG experience fewer maintenance issues, reduced lubricant consumption, and improved engine performance. Crew training and handling protocols do become more complex due to cryogenic storage requirements, but the overall reduction in unexpected engine breakdowns offsets these challenges.

4. **Regulatory Compliance**

   LNG enables shipowners to meet current and anticipated environmental regulations without the need for expensive after-treatment systems like scrubbers. This simplifies compliance with IMO standards and helps avoid future penalties or costs associated with carbon taxation and emission credits. It positions LNG as a fuel that is not only regulatory-compliant but also future-proof to a reasonable extent.

5. **Infrastructure Development and Regional Readiness**

   The availability of LNG bunkering infrastructure is expanding but remains regionally limited. Countries in Europe, North America, and East Asia have made significant progress in LNG port readiness. In India, strategic initiatives under Maritime India Vision 2030 and Sagarmala Programme have led to the development of LNG facilities at key ports such as Kochi, Ennore, Mumbai, and Kandla. However, global inconsistency in LNG availability still poses a logistical barrier for wide-scale adoption.

6. **Methane Slip and Environmental Risks**

   One concern noted in the findings is methane slip—the unintended release of unburned methane, which is a more potent greenhouse gas than CO_2. While LNG has lower CO_2 emissions, the impact of methane slip can offset some of its environmental benefits. Technological improvements in dual-fuel engines are being developed to address this issue, but it remains a factor in the complete environmental assessment of LNG.

7. **Policy and Market Dynamics**

   Government incentives, port fee rebates, and carbon tax regulations are increasingly favoring LNG use. Policy frameworks in India and abroad are supporting LNG adoption through tax benefits, infrastructure grants, and green shipping corridors. Additionally, fluctuating global fuel prices influence the competitiveness of LNG versus traditional fuels, but future projections indicate LNG prices will stabilize due to diversified global supply.

5.3 Suggestions

1. **Accelerate LNG Infrastructure Development**
   Governments and private stakeholders should invest more aggressively in LNG bunkering facilities across major ports globally, especially in developing regions. Widespread infrastructure will reduce operational risk, improve fuel availability, and enhance the economic feasibility of LNG adoption.
2. **Incentivize LNG-Fueled Vessel Construction**
   Policy frameworks should promote the construction of new LNG-powered vessels through tax rebates, subsidies, or green financing mechanisms. Given that retrofitting is less economically viable, support for new builds will yield greater long-term benefits.
3. **Improve Engine Technology to Reduce Methane Slip**
   Research and development should focus on advanced dual-fuel engines and combustion systems that minimize methane slip. Reducing this drawback is essential to ensuring LNG's environmental superiority over conventional fuels.
4. **Promote Training and Safety Standards**
   To support safe and effective LNG operations, maritime institutions and regulatory bodies must provide specialized training programs for ship crews, port staff, and bunkering personnel. Standardizing global LNG safety and handling protocols is critical.
5. **Integrate Carbon Pricing into Financial Models**
   Policymakers should continue integrating carbon taxes or emissions trading schemes into fuel cost structures. This will naturally increase the competitiveness of low-emission fuels like LNG, making them more attractive without direct subsidies.
6. **Develop Green Shipping Corridors**
   Countries and ports should collaborate to establish "green shipping corridors" where vessels can rely on consistent LNG availability and benefit from coordinated incentives. These corridors can serve as test beds for broader LNG adoption and future zero-carbon fuels.
7. **Encourage Multinational Collaborations**
   Partnerships between shipping companies, port authorities, engine manufacturers, and international organizations (IMO and SGMF) can accelerate innovation, reduce cost burdens, and harmonize global LNG-related regulations and standards.

8. **Prepare for the Transition Beyond LNG**
   LNG should be viewed as a transitional fuel. Stakeholders must simultaneously begin investing in and piloting next-generation zero-emission fuels such as green ammonia, hydrogen, and bio-LNG, ensuring a smoother shift when these technologies mature

5.5 Final Conclusion

The transition to sustainable maritime fuel is not merely a regulatory requirement but an environmental and economic imperative—and this study confirms that Liquefied Natural Gas (LNG) stands out as a viable and pragmatic alternative to conventional marine fuels. While the path to LNG adoption presents clear challenges in terms of high capital costs, infrastructure gaps, and methane slip, the long-term operational savings, regulatory compliance advantages, and significant emission reductions make LNG a strong transitional fuel for the global shipping industry. It aligns effectively with IMO targets, supports public health by improving air quality, and offers financial resilience against rising carbon-related penalties. However, LNG is not the ultimate destination—it is a crucial bridge. Its success depends on coordinated efforts in infrastructure expansion, engine innovation, policy incentives, and international collaboration. By strategically embracing LNG today, the maritime industry can confidently navigate toward a cleaner, more efficient, and future-ready ecosystem tomorrow.

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List of Glossary of Terms

LNG (Liquefied Natural Gas)	Natural gas that has been cooled to -162°C to become liquid for ease of storage and transport.
Marine Fuel	Fuel used to power ships and vessels; includes HFO, MGO, VLSFO, and alternative fuels like LNG.
HFO (Heavy Fuel Oil)	A residual fuel oil used in marine engines; known for high emissions of sulfur and particulate matter.
MGO (Marine Gas Oil)	A distillate marine fuel with lower sulfur content than HFO, used to comply with emission regulations.
VLSFO (Very Low Sulfur Fuel Oil)	Marine fuel with sulfur content ≤0.5%, compliant with IMO 2020 regulations.
SOx (Sulfur Oxides)	Harmful emissions from burning sulfur-containing fuels; contributes to acid rain and air pollution.
NOx (Nitrogen Oxides)	Emissions resulting from combustion; harmful to health and environment.
Methane Slip	The release of unburned methane from LNG engines; a concern due to methane's high global warming potential.
Bunkering	The process of supplying fuel to ships; LNG bunkering refers to fueling ships with LNG.
Retrofit	Modifying existing ship engines and systems to operate on LNG instead of conventional fuels.
Capex (Capital Expenditure)	Initial costs involved in LNG adoption (e.g., retrofitting engines, installing LNG storage tanks).
Opex (Operational Expenditure)	Ongoing costs including fuel, maintenance, crew training, etc.
Payback Period	The time required to recoup the investment made in LNG adoption through operational savings.
Emission Control Areas (ECAs)	Designated sea areas with stricter emission limits for SOx, NOx, and particulate matter.
IMO (International Maritime Organization)	UN agency responsible for regulating shipping, including environmental standards like MARPOL.

Carbon Pricing	A cost applied to carbon emissions to encourage reduction in greenhouse gas output.
Total Cost of Ownership (TCO)	The overall cost of a vessel over its operational lifetime, including capex and opex.
Dual-Fuel Engine	An engine capable of operating on both LNG and conventional marine fuels.
Energy Efficiency Design Index (EEDI)	IMO measure to promote design improvements for more energy-efficient ships.
Greenhouse Gases (GHGs)	Gases like CO_2, CH_4 that trap heat in the atmosphere and contribute to climate change.
Port Infrastructure	Facilities at ports needed to support LNG bunkering, such as storage tanks, pipelines, and safety systems.
Small-Scale LNG	LNG distribution in smaller quantities, often used in niche markets or remote locations.
Life Cycle Assessment (LCA)	Evaluation of environmental impacts of LNG from production to consumption.

CAGR: Compound Annual Growth Rate
IMO: International Maritime Organization
BDI: Baltic Dry Index
SVAR: Structural Vector Autoregression
ARIMA: Autoregressive Integrated Moving Average
VECM: Vector Error Correction Model
Entropy Management: An environmental strategy to reduce energy waste in shipping systems
Hedging: Risk reduction technique used in freight rate forecasting