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# LNG as a basic or transitional fuel in shipping

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# Abstract

This paper provides a comprehensive exploration of Liquefied Natural Gas (LNG) as a maritime fuel, addressing its technical, environmental, economic, and industry adoption aspects. The study reviews LNG's historical context, current status, and trends, emphasizing its potential to meet stringent emission standards. Technical considerations encompass LNG storage, handling, engine technologies, and safety. Environmental impacts, regulatory frameworks, and economic viability are analyzed, including case studies illustrating industry adoption. The paper scrutinizes LNG's role as a basic or transitional fuel, concluding that it serves as a transitional solution. Despite offering environmental benefits, challenges like methane slip and evolving regulatory targets position LNG as a temporary measure in the industry's shift toward zero-carbon fuels. The analysis contributes valuable insights for all the involved parties navigating the evolving landscape of sustainable shipping fuel alternatives, recognizing LNG's pivotal but temporary role in fostering environmentally conscious practices within the maritime sector.



Keywords: LNG, green fuel, transition to zero-carbon fuels, environmental factors, economic factors, maritime industry.

# Contents

# List of Abbreviations

LNG - Liquefied Natural Gas

IMO- the International Maritime Organization

HFO - Heavy Fuel Oil

CSR - Corporate Social Responsibility

CNG - compressed natural gas

MDO - marine diesel oil

ECA - Emission Control Areas

EEDI - The Energy Efficiency Design Index

SOx – sulfur oxide

NOx - nitrogen oxides

$CO_2$ – carbon dioxide

$CH_4$ – methane

ECA - Emission Control Areas

# Introduction

The document's goal is to investigate LNG's function as a fundamental or intermediate fuel. The report highlights LNG's potential to satisfy stringent emission limits by examining the historical background, present circumstances, and tendencies of the gas. Safety, engine technology, administration, and LNG storage are among the technical factors to take into account. Analysis is done on the effects on the environment, legal frameworks, and economic sustainability. Case studies showing industry adoption are also included. Despite providing environmental benefits, challenges such as methane leakage and evolving regulatory targets put LNG as a temporary measure in the industry's transition to zero-carbon fuels, concluding that it serves as a transitional solution.

Due to the necessity of minimizing environmental impact and adhering to stringent regulations, the maritime industry is currently undergoing significant changes. Accordingly, choosing fuel for transportation seems to be a key determinant that affects both operational effectiveness and ecological sustainability. Of all the options available, liquefied natural gas (LNG) has proven to be the most alluring since it can meet strict pollution regulations and be used as both a primary and an interim fuel for ships. The shipping sector has always played a major role in global trade; according to recent statistics, 80–90% of all transportation-related transactions take place at sea (Schnurr & Walker, 2019). This implies that a major actor in the world economy that primarily relies on fossil fuels—most notably bunkers and marine diesel—is inevitably going to have an effect on both the environment and the economy. The need for environmentally friendly alternatives is even more pressing now that the use of conventional fuels has resulted in problems with air pollution and CO2 emissions. LNG is a more environmentally friendly fuel option than other traditional fuels due to its high methane component. Growing global emissions are putting pressure on the maritime industry to decarbonize. Changes toward more ecologically friendly options are mandated by new laws from international regulatory bodies such as the International Maritime Organization (IMO) (Sharples 2019). The kind of fuel used in this setting becomes crucial to the industry's sustainability. Because of its low carbon content and ability to cut harmful emissions, especially "sulfur cap" emissions, LNG becomes a significant role in this battle (Halff et al. 2019).

It is not by coincidence that LNG is now used as a marine fuel. It is the outcome of numerous variables that have been at play for a while. LNG has become considerably more popular due to the growing worldwide need for cleaner energy, technological advancements in LNG infrastructure, and more environmental consciousness.

Additionally, until a new, more sustainable fuel is switched to, LNG can be utilized as a baseline or a bridge fuel (Englert et al. 2021). In order to accomplish the following goals, we will investigate the intricate world of LNG as a fundamental or transitional fuel in the maritime industry in this study: Examine the current state of affairs and trends surrounding the use of LNG; examine the technical aspects of its use on ships; look into the regulatory framework and environmental effects of its operations; evaluate the economic aspects of adoption; talk about industry practices using cases; and, finally, offer suggestions for future opportunities and challenges in the maritime industry.

LNG investigation starts with the paper's structure, which covers its overview and historical perspective in shipping before delving deeply into a thorough examination of its merits, disadvantages, and current state. Technical factors including handling, storage, adjustments to engine technology, infrastructure needs, and safety considerations are thoroughly investigated. The next one examines how LNG shipping affects the environment and the regulatory framework, covering topics such as the advantages to the environment, reducing greenhouse gas emissions and air pollution, and international initiatives and standards. The economic aspects of LNG adoption, including as cost analysis, investment implications, and shipping firms' financial viability, are covered in the next chapter. Case studies (like the Carnival Company's initiative) and examples of industry adoption are provided to demonstrate the concepts discussed so that lessons can be gained from successful implementation situations. The final section of the article discusses the industry's prospects for the future and looks at possible growth patterns, technological advancements, and other ways to overcome the problems that the usage of LNG fuel in the maritime industry is now facing. Finally, this report concludes with suggestions for additional research. This analysis aims to further the conversation about sustainable energy solutions for the maritime sector by giving stakeholders important information for strategic decision-making in the constantly changing field of shipping fuel substitutes.

# 1. LNG in Shipping: Overview

The maritime industry must adjust to new demands as a result of environmental imperatives to find cleaner and more sustainable fuel options for all forms of maritime transportation. Since liquefied natural gas has an environmentally beneficial operating profile, it appears to be seen as a solution in this regard. This chapter explores the composition, historical evolution, and present status of LNG as a maritime fuel, delving deeply into the realm of LNG in shipping. We'll look at how LNG is better for the environment than conventional fuels. To set the scene for the discussion surrounding this specific fuel type in shipping, issues pertaining to infrastructure development, technological improvements, and the continuing debate surrounding its lifecycle greenhouse gas emissions will also be covered. To set the stage the chapter will start with the basics.

## 1.1 What is LNG?

Transparent and colorless, LNG is produced by heating natural gas to a very low temperature of about -162°C (-260°F). The gas's volume is greatly decreased during this cryogenic procedure, making it more suitable for storage and transit. Methane, which comes from natural gas reserves, is the primary ingredient in LNG. Through the process of liquefaction, contaminants and other hydrocarbons are eliminated, producing a high-purity natural gas that may be burned in engines.

LNG emits significantly less sulfur oxides (SOx), nitrogen oxides (NOx), and particulate matter than traditional bunker fuels derived from oil, such as heavy fuel oil (HFO) (Fun-sang Cepeda et al. 2019). Practically speaking, LNG has a 30% lower carbon content per unit of energy than traditional bunker fuels because it is mostly composed of methane. According to Schnurr and Walker (2019), LNG emits 25% less carbon dioxide (CO2) into the environment when burned for energy than conventional bunker fuels like HFO and MDO, but it emits more methane (CH4). However, LNG is seen as a greener and more ecologically friendly fuel substitute that helps to lower greenhouse gas emissions and solves climate change-related issues (Butarbutar & Gurning, 2022). Within an industry that accounts for approximately 33% of air pollutants associated to "trade-related emissions" (Schnurr & Walker, 2019), liquefied natural gas (LNG) presents a significant opportunity to mitigate its adverse environmental effects.

## 1.2 Historical Perspective of LNG in Shipping

The use of LNG in shipping dates back to the middle of the 20th century. In 1959, "The Methane Pioneer," the first LNG carrier, set out on a historic voyage to deliver LNG from the United States to the United Kingdom. With this, LNG was formally presented as a practical fuel for long-distance travel. Technological developments have brought down costs throughout time, making it more economically viable and, as a result, having a larger range of applications in the sector.

LNG came under increasing attention in the early 21st century due to worries about conventional energy sources, environmental issues, and the expanding liquidity of the global gas market. The sector looked for cleaner options as a result of strict environmental rules, especially those imposed by the International Maritime Organization (IMO), which is pushing for emission reductions. The world's efforts to switch to clean, low-carbon energy have changed the dynamics of the market, bringing with them innovations in infrastructure, handling, and production. It is noteworthy that this increase has concentrated in some areas, like Northern Europe and Asia, where market penetration has been fueled by government subsidies and strict environmental rules (Aczel, 2022).

Furthermore, recent geopolitical events have brought attention to the necessity of moving toward shorter-term, more flexible contracts that reflect evolving energy markets and the ever-increasing need for all parties involved to adjust appropriately (Botão et al., 2023). As a result, an increasing number of business representatives include LNG in their fleet. LNG usage has been limited to some fleet segments, such as Chinese waterways and Scandinavian ferry lines, because of the early development of the distribution infrastructure. Certain boats, such as cruise ships and Aframax tankers in the North Sea–Rotterdam trade, are exclusively powered by LNG and are only used on particular routes. LNG bunkering increased significantly after nine 22,000-TEU ships fuelled by LNG were purchased by the large container carrier CMA CGM. The deal prompted a surge of interest in LNG bunkering from other shipping companies (Halff et al. 2019) including Hyundai Merchant Marine, Hapag Lloyd from Germany, Carnival Cruise vessels, etc.

## 1.3 Current Status and Trends

Due to a number of considerations, such as economic ones like oil prices, LNG's potential as a more promising fuel has historically been widely accepted (Adekoya et al., 2024). Nevertheless, it appears that the maritime industry's thoughts for the future of its use are impeded by the stringent environmental restrictions. In instance, the overall lifecycle greenhouse gas benefits of using LNG remain unclear, despite its obvious advantages over conventional fuels in terms of lowering emissions of SOx, NOx, and particulate matter as well as lower CO2 emissions during combustion. Because LNG is liquefied methane, a powerful greenhouse gas, this uncertainty stems from the nature of LNG itself (Song 2021). The potential release of unburnt methane into the atmosphere, the so-called methane leakage/methane slip, poses a challenge to the theoretical GHG benefits of LNG (Herdzik 2018).

The aforementioned feature of LNG appears to be forming a unique trend of its own, limiting its widespread adoption globally. The shipping industry is under stress due to the unanswered question about LNG's greenhouse gas performance. Although there is agreement on the short-term advantages of better air quality, there is ongoing debate on LNG's role in reducing greenhouse gas emissions over the long run. Because of this, different industry leaders have different opinions about how LNG may help decarbonize shipping, which reflects the complexity of ongoing discussions in the marine industry (Song, 2021). There are ongoing discussions on the viability and efficiency of using LNG as a decarbonization solution, despite the fact that several shipping lines, like CMA CGM, have demonstrated action by deploying the largest LNG-powered container ship in the world. Therefore, as one of their pro-environmental measures, the key participant in the maritime industry chooses to use a different type of methanol fuel, also known as "green fuel," according to the Maersk sustainability report for 2023 (Maersk 2023). Limiting the use of fossil fuels, including LNG, is essential to achieving the IMO's climate targets, as evidenced by the fact that the organization's Initial GHG Strategy aims to reduce GHG emissions from the international maritime fleet by at least 50% by 2050 and phase them out as quickly as possible within the century (Englert,2021).

The construction of the infrastructure necessary for the fuel's use is another trend resulting from the adoption of LNG fuel. Bunkering facilities and storage capacity play a crucial role in facilitating the LNG's wider adoption in the marine sector. Ships can restock on LNG if sufficient bunkering facilities are available at strategic ports along their route. It goes without saying that without one, the integration of the aforementioned fuel cannot proceed. In response to this necessity, extensive effort is being done to advance the issue's development in terms of both the actual planning and building of the premises as well as the compilation of the pertinent rules (Aneziris et al. 2020). For instance, it is anticipated that LNG would rank among the most widely utilized fuel types in the Russian Arctic region for the next 20 years (Klimentyev et al. 2017). and thus researchers put quite an emphasis on the issue, providing a comprehensive plan for the infrastructure provision in the far northern (Arctic) of the Russian region, catering to ship-to-ship bunkering methods. The construction the infrastructure projects (e.g. Yamal LNG project, Arctic LNG2, Pechora LNG), specialized carriers and consideration of innovative technologies further emphasize the prospects and opportunities for LNG bunkering in the Arctic regions of Russia (Klimenyev et al. 2017). Similarly, among others, also the USA is actively working on energizing its maritime sector through the development of LNG infrastructure and the relevant policy frameworks (Sadler & Onge, 2023).

Furthermore, when it comes to the field of technological advancement, it is crucial to bring up the engine construction and alterations that are on everyone's mind. Because dual-fuel engines may run on both conventional fuels and LNG, depending on operating requirements, environmental laws, or fuel supply, they appear to be taking the lead in this industry. This adaptability offers a transitional strategy that enables ships to comply with current laws while being ready for stricter environmental rules in the future. Ships powered by LNG are increasingly being used in specialized markets and short-haul shipping. Dual-fuel engine technology has become increasingly important as the maritime industry continues to move toward cleaner fuels (Boretti 2020).

Drawing the line, it should be noted that although LNG burns demonstrably cleaner than conventional choices, its lifecycle greenhouse gas impact remains unclear. Due to its complexity, the industry is divided in how to adopt it; some see LNG as a transitional fuel, while others are looking into other options. Expanding LNG adoption is being made possible by technology breakthroughs and infrastructure development, especially with regard to dual-fuel engines. In the end, LNG's potential to significantly reduce greenhouse gas emissions and to support the environmental aims of the shipping sector will determine how far it can go in the industry.

## 2. Technical Aspects of LNG Utilization

The use of LNG by the maritime sector requires a thorough comprehension of its technical characteristics. This chapter explores the complexities of using LNG, including engine technology, infrastructural requirements, storage and handling of LNG aboard ships, and critical safety considerations. The chapter will examine the technical features of the fuel's operation in order to delve deeper into the question of its actual sustainability. LNG has a high energy density and burns cleanly, yet there are still concerns about its lifecycle emissions. These factors are thought to be crucial in the discussion of LNG adoption by the maritime sector in light of its greener operational objectives going forward.

LNG is the most power-efficient fuel type, outperforming other fuels like oil, natural gas, coal, and paraffin oil, with a high heating value of 45.26 MJ/kilo. Furthermore, LNG demonstrates a high degree of combustion efficiency, as evidenced by the fuel burning entirely without any residues or air emissions (Pospíšil et al. 2019; Danilov et al. 2019). This is ascribed to decreased convection and radiation losses, as well as the absence of chemical and mechanical incompleteness of combustion. LNG is renowned for having a low proportion of harmful materials in its combustion byproducts, which reduces its environmental effect. LNG has far less harmful emissions than liquid or solid fossil fuels because it burns without producing any ash, carbon, or sulfur compounds. This characteristic contributes to the increased durability of combustion units (Algayyim et al. 2024).

LNG use has clear environmental benefits over heavy fuel oil use, even thugh its CO2 emissions are still far from the targeted zero-carbon line. This has previously been mentioned above. When considering the power production from fuel burning, the change yields a noteworthy reduction of 29.2% in CO2 emissions. Furthermore, switching from marine gas oil to LNG results in a noteworthy 24.5% decrease in CO2 emissions when considering power output (Sharples 2019). This indicates that there is a good chance that LNG will replace other fuels in the maritime industry that are less harmful to the environment and more sustainable. As the sector works to comply with strict environmental standards and support international efforts to mitigate climate change, the adoption of LNG emerges as a promising solution, offering a substantial reduction in carbon emissions and paving the way for a greener future in marine transportation.

## 2.1 LNG Storage and Handling on Ships

Specialized tanks made to resist extremely low temperatures are used to store LNG on ships. The materials used to build these cryogenic tanks are usually able to withstand the necessary temperature of about -162 Co. Membrane tanks and spherical tanks are the two primary types of LNG storage systems on ships, and each has pros and downsides. LNG must be transported via a number of routes, including loading tankers, shipping by sea, railcars, cryogenic tank cars, unloading into LNG terminals that have been regasified, and distribution to end users. Re-gasification at the buyer's end entails a series of steps that include processing equipment for evaporating gases, odorization units, gas-regulation stations, evaporative systems, port facilities, and odorization units (Danilov et al. 2019).

LNG can be stored and transported more effectively since it has a higher energy density in its liquid state than in its gaseous condition. This feature is especially helpful to the marine sector since it allows vessels to transport a greater quantity of energy in a comparatively smaller area, increasing the fuel's overall energy density. For long-distance shipping, where it's critical to maximize energy storage while minimizing occupied space, this efficiency is critical. Furthermore, LNG's higher energy density helps to lessen logistical difficulties and makes it a feasible solution to meet the energy needs of marine boats (Englert et al. 2021).

Shipboard LNG handling necessitates careful adherence to safety measures. Because LNG has distinctive characteristics, such as its extremely low temperature and potential volatility, loading and unloading activities must adhere to certain policies, procedures, and equipment (Aneziris et al. 2020) in order to prevent spills and leaks. The implementation of specialized transfer systems, emergency response trained staff, and cryogenic hoses are all examples of comprehensive safety measures. LNG is moved from offshore storage tanks to the ship's containment system during the loading phase, and the opposite occurs during the unloading process. Severe spills, leaks, and other events that can jeopardize the integrity of the LNG containment system are guarded against by strong safety measures. These safety protocols are not only essential for protecting personnel and assets but also align with international regulations and industry best practices, fostering a secure and sustainable LNG shipping environment (Surinov 2023).

Furthermore, vapor control systems are used to regulate the release of boil-off gas, guaranteeing environmental protection and reducing hazards. Vapor control systems are used to efficiently handle this unavoidable gas leak. These systems have two main goals: first, they control and confine the dispersion of potentially combustible gases, which ensures safety within the LNG facility; second, they reduce the environmental impact of the gas discharge into the atmosphere. Vapor management systems use a variety of technologies, like re-liquefaction units (Tan et al., 2018), to minimize losses and maximize the use of LNG by recondensing the boil-off gas back into a liquid condition (Barelli et al., 2022).

## 2.2 Engine Technologies and Modifications

LNG is used as a greener fuel substitute in the maritime sector. There are several ways to make the switch to LNG propulsion, such as dedicated LNG, dual-fuel, and engine retrofitting. Engines specifically made to run on LNG are being developed and used. These specialized LNG engines, which mark a technological advance in the marine sector, are frequently seen in newly constructed ships that are intended to run primarily on LNG. These engines are made to effectively utilize the special qualities of natural gas. High-pressure direct injection is one example of an advanced technology that is essential to combustion process optimization. High-pressure direct injection systems improve the air- LNG mixing, which encourages more complete combustion and raises engine efficiency. This technology allows for precise control over the injection timing and fuel-air mixture, contributing to reduced emissions of pollutants such as nitrogen oxides. Implementating such sophisticated engine technologies reflects the industry's commitment to sustainability and compliance with stringent environmental regulations (Boretti 2020 b).

Dual-fuel engines are still another popular strategy. LNG and conventional liquid fuels like diesel or heavy fuel oil can both power these engines. Because of their adaptability, ships can change their fuels according on availability, price, and legal requirements. High-pressure direct injection is a common feature of dual-fuel engines that allows for the burning of both liquid and LNG fuels. Dual-fuel engines are a popular option since they provide fuel selection flexibility. LNG is injected into the combustion chamber of these engines, where it mixes with air prior to ignition (Boretti 2020 b, Boretti 2020 a).

It is possible to convert some ships with traditional diesel engines to accept LNG. Retrofitting entails changing current engines to make them dual-fuel capable, meaning they can run on LNG and diesel. This approach is a transitional strategy for vessels with older propulsion systems. Retrofitting existing ships for LNG utilization involves modifications to accommodate LNG storage tanks and the installation of LNG bunkering systems. Engine retrofitting is also necessary to enable the combustion of LNG.

The age of the ship, its operational profile, and the accessibility of LNG infrastructure at ports all influence the approach that is chosen. For instance, LNG is the best option for traveling long distances because, in comparison to compressed natural gas (CNG), cryogenic storage permits a higher energy density (Boretti 2020, a). LNG gives ships a longer range, which is advantageous because they frequently travel great distances without stopping frequently to refuel. The development of LNG engines specifically for new build boats and retrofitting options for fleets already in operation is becoming more and more important as the maritime sector continues to shift toward cleaner fuels.

## 2.3 Safety Considerations

The use of LNG raises intrinsic safety issues, mainly related to flammability, explosion risks, cryogenic qualities, and abrupt phase changes. First and foremost, flammability is a major safety factor for LNG. Because methane is the main ingredient in LNG and is highly flammable, LNG may pose a fire risk in the event of an accident. Careful handling and preventive measures are necessary since inadvertent leaks have the potential to create clouds of combustible gas. Explosion risks result from the particular ratios at which vaporized LNG combines with air to generate explosive combinations. Explosion risks can be increased by unintentional releases, poor ventilation, or the existence of ignition sources, which can generate explosive atmospheres. Understanding these conditions is crucial for mitigating potential risks during various operational phases (Iannacconea et al. 2018).

Furthermore, the cryogenic characteristics of LNG add even another level of safety risk. LNG has cryogenic risks since it must be transported and stored at very low temperatures. Accidental contact with LNG or its fumes might cause frostbite, cryogenic burns, or embrittlement-related equipment damage. To overcome these obstacles, equipment insulation and appropriate safety procedures are essential. There are extra dangers associated with rapid phase changes from liquid to gas during a release. During bunkering or transfer operations, accidental spills, leaks, or releases may cause fast vaporization and consequent overpressure scenarios. In order to avoid mishaps and guarantee the safe handling of LNG throughout its supply chain, managing these transitions is essential (Forte & Ruff 2017).

Furthermore, storage, transportation, and the crucial issue of collision and grounding safety need to be taken into consideration. The integrity of LNG storage tanks becomes crucial in the unfortunate event of a collision or grounding problem. LNG storage tanks' sturdy structural design is essential for preventing possible catastrophes. Strict safety precautions are built into these tanks to withstand outside impacts and stop spills. The intention is to minimize the danger of environmental effect by keeping LNG contained even in unfavorable circumstances. The main goal of collision and grounding safety procedures is to prevent spills. LNG storage tanks are made durable and able to bear the stresses applied during such occurrences thanks to advanced engineering.This resilience is coupled with state-of-the-art safety features that activate in response to external pressures, further fortifying the containment structure. Understanding the technical aspects of LNG utilization in shipping is imperative for stakeholders across the maritime industry (Rötzer, 2019).

An interdisciplinary strategy is needed to mitigate these safety problems. First and foremost, appropriate protocols and training are essential to guarantee that staff members have the abilities to handle LNG and respond to emergencies (Forte & Ruff 2017). Another important tool is a comprehensive risk assessment, which helps to systematically identify possible dangers and facilitates the implementation of mitigation solutions. Safe LNG activities are based on following national and international safety norms and laws. To effectively manage and mitigate events, it is essential to have a robust emergency response strategy that includes regular drills (Forte 2017). Moreover, the safety of LNG storage, transfer, and propulsion systems is improved by the integration of cutting-edge technology and engineering safeguards (Park et al. 2018). Finally, space constraints pose a safety issue at all stages of LNG handling, and thus particular care should be taken in respect to mitigating any escalation of the potential disaster (e.g. caused by ignition) through the development of proper risk management programs (Forte & Ruff 2017) Together, these mitigation measures form a comprehensive strategy, promoting the secure and sustainable integration of LNG in maritime operations.

The evidence studied leads to the conclusion that using LNG has distinct obstacles because safe operations of ships necessitate major technological integrations (such as specialized tanks, cryogenic handling, and engine modifications). Furthermore, there are serious safety problems with the gasoline. These hazards could be reduced by emergency preparations, risk assessments, training, and laws, but their proper execution may be hampered by their high costs. Nevertheless, LNG has the potential to open the door for a greener nautical future as safety regulations tighten and technology develops.

# 3. Environmental Impacts and Regulatory Framework

The utilization of LNG as a marine fuel carries noteworthy ecological consequences and demands a strong regulatory structure to facilitate its sustainable assimilation into the shipping sector. This chapter examines the environmental effects of LNG, including the improvements in air quality brought about by lower emissions of SOx, NOx, and particulate matter. As was already said, there are still worries about its widespread adoption due to lifecycle greenhouse gas emissions. The chapter thus attempts to address the question of whether the fuel has the ability to stand as a viable shipping energy solution in an evolving regulatory framework, led by the IMO's decarbonization targets, by assessing all the relevant to the issue aspect.

## 3.1 Environmental Benefits of LNG

Balcombe et al. (2022) have noted that one of LNG's main environmental benefits is its ability to improve air quality. The combustion of LNG results in reduced levels of sulfur oxides (SOx), nitrogen oxides (NOx), and particulate matter as compared to conventional marine fuels like heavy fuel oil (HFO) and marine diesel oil (MDO) (Iannaccone et al., 2020).This promotes healthier ecosystems and communities by lowering air pollution in port areas and along shipping routes. 2020; Sharma et al. Nevertheless, due to methanol emissions, LNG is still a long way from being a zero-carbon fuel (Balcombe et al., 2022).What is more, many studies (Pavlenko et al., 2020, Iannaccone et al., 2020, Parfomak et al. 2019) raise concerns about the actual reduction in GHG emissions on a life-cycle basis. In particular, Pavlenko et al. (2020) indicate that, compared to MGO, LNG provides 15% less GHG emissions over a 100-year time frame, but this holds only for some engine types, in particular to high-pressure dual-fuel engines, which are identified as effective in reducing well-to-wake GHG emissions, especially for large low-speed engines (Sharafian et al., 2019). Similarly, the role of the engine type is highlighted by Balcombe et al. (2022), which means that not all vessels using LNG are falling under the low-emission category.

## 3.2. Regulatory frameworks

The IMO's (Initial Maritime Organization) strategy on reducing greenhouse gas emissions from ships has increased the examination of liquefied natural gas's greenhouse gas performance during its lifecycle. The IMO's climate targets, which call for a 50% decrease in GHG emissions from the global maritime fleet by 2050, cast doubt on LNG's ability to help the industry decarbonize. There is disagreement at the moment over LNG's future importance due to unclear short-term drivers and insufficient regulatory incentives (Englert et al., 2021). Specifically, as evidenced by Baresic et al. (2018), cost may not be an advantageous factor for LNG when compared to conventional fuels. Maritime policymakers, unable to directly influence prices, rely on regulations governing greenhouse gas emissions, air pollutants, and energy efficiency to ensure LNG's competitiveness (Wang & Wright, 2021).

LNG adoption is significantly influenced by air pollution regulations, such as global sulfur caps and emission control areas (ECAs). Using LNG is thought to be an efficient approach for ships to satisfy the carbon emission restrictions specified by the Energy Efficiency Design Index (EEDI) guideline. According to Zakaria and Rahman (2017), LNG is seen as having an emissions benefit because the EEDI rule only takes into consideration emissions during ship operation and does not account for emissions over the course of the LNG lifecycle. However, because of its GHG emission problems, LNG acceptance is highly impacted by how strict possible regulations are. While existing regulations provide some incentive for LNG adoption, they are unlikely to cause a worldwide consensus on the long-term adoption of LNG because the goal of a 50% reduction in GHG emissions by 2050 could discourage major investments in LNG infrastructure (Englert et al. 2021). Thus, without other factors at play (e.g. substantial growth in LNG demand as a bunker fuel), significant investments in LNG infrastructure are improbable and thus its role as a basic fuel is not stable.

In summary, it can be said that the use of LNG presents difficult legal and environmental issues. Although it provides cleaner air, its lifecycle greenhouse gas impact is still up for debate. This implies that LNG's long-term survival is far from a guarantee, even as the IMO presses the industry to lessen its carbon burden on the environment. The capacity of LNG to significantly reduce emissions is critical to the maritime industry's future, particularly as laws tighten and alternative fuels become more prevalent.

# 4. Economic Considerations

In continuation of the discussion of the viability of LNG as a basic fuel, it is important to address its economic implications. This chapter explores the economic considerations for shipping companies contemplating the switch. Fuel costs, a major operational expense, drive the search for cost-competitive alternatives. By addressing the economic considerations of LNG adoption, the chapter aims to determine whether the fuel offers all that it needs for the maritime industry to operate in an environmentally friendly but also economically beneficial way.

Liquefied natural gas must be economically competitive to be widely used as a bunker fuel in maritime transportation, especially when compared to traditional bunker fuels made from oil. Fuel expenses drive businesses to look at alternative energy sources because they account for 50–70% of operating expenditures (Serra & Fancello, 2020). A historical barrier to the use of LNG has been the inadequate price difference between LNG and heavy fuel oil. The outcome may not be ideal when the expense of installing aboard equipment and geographical restrictions are taken into account (Englert et al. 2021). LNG's economic feasibility necessitates a minimum price margin that is constantly lower than that of HFO, which is determined by various factors such as equipment costs, shipyard specifications, payback periods, and vessel design. It is difficult to generalize about the extent of this price difference because of the many variables involved (such as the ship's size and operational requirements, which are dependent on the distance traveled, the weight of the cargo, the engine type, etc.). For instance, Xu et al. (2020) state that ship size and ideal routes are two of the most important variables supporting the LNG adoption's economic viability in Arctic navigation. However, even in the presence of ideal conditions, particular situations (climate, for example) might produce distinct economic outcomes, underscoring the flexible nature of LNG's economic advantages across diverse geographical areas (Xu et al., 2020).

Additionally, such factors as infrastructure availability and cost of technical considerations should be taken into account. In this respect, the integration of dual-fuel engines introduces a beneficial dimension of fuel flexibility for liner shipping. This factor becomes crucial in scenarios with limited LNG bunkering facilities. The ability to switch between fuels as prices fluctuate enhances resilience and reduces the need for excessive space dedicated to LNG storage. Such flexibility is a strategic advantage, providing economic adaptability in the face of changing fuel market dynamics (Tan et al., 2020).

Because of the geopolitical dynamics and variations in the global oil and gas market, it is challenging to predict prices, particularly when comparing natural gas and crude oil (Pulhan et al. 2020). A layer of uncertainty is added to the issue by regional variations in natural gas pricing systems. For instance, China's embrace of environmentally friendly energy solutions is a driving force behind LNG integration, whereas India's potential as a major LNG consumer is constrained by infrastructural issues and securing regulatory backing for consumption (Losz et al. 2019). When alternative zero-carbon bunker fuels such as hydrogen or ammonia are taken into account for possible future usage, the difficulty increases (Englert et al. 2021).

Due to the numerous dynamically changing contingent factors related to installation and operation costs, as well as regional regulatory differences, the analysis of pertinent literature revealed the prevalence of negative economic evaluations of LNG adoption for the far-reaching future. These uncertainties make it more difficult for the maritime sector to get a clear business signal for significant LNG investment. The complex nature of economic factors is highlighted by historical data and geographical differences in the natural gas/crude oil price disparity (Wang et al., 2021). As a result, it is doubtful that the industry will see a high-certainty signal for major LNG uptake in the long run. However, it would be incorrect to ignore the fact that there are several factors that support the use of LNG. Besides its widely recognized environmental benefits (compared to conventional fossil fuels), has several other advantages, including LNG-based fuel systems exhibit better sustainability performance compared to conventional marine fuel technologies (Iannaccone et al. 2020). The emphasis on environmental benefits, combined with the economic aspect of LNG adoption, speaks in favor of a broader push for greener alternatives in the maritime industry.

Having analyzed all the above information, it could be concluded that the economic viability of LNG remains complex. Price fluctuations, infrastructure availability, and future alternative fuels create uncertainty. While the economic evidence from the practice suggests challenges, LNG's environmental benefits and potential for sustainability improvements remain attractive. As effective industry operation requires careful consideration of all the aspects of fuel integration, the balance between economic and environmental factors seems to continue to pose a considerable challenge for the time being.

# 5. Case Studies and Industry Adoption

The shipping sector is being forced to adopt environmental sustainability and look into new avenues for achieving it by the impending environmental concerns. Among these is the use of cleaner fuels. This chapter looks at real-world case studies to show how the industry is being shaped by the adoption of Liquefied Natural Gas in accordance with new environmental standards and ideals. The chapter explores the experiences of many businesses that included LNG-powered ships in their fleet. The chapter attempts to give a realistic picture of the situation by discussing the benefits and drawbacks of the specific fuel integration as they have been encountered by these companies. The chapter will present the case study in its dynamic development, showing not only the current state of the issue but also mentioning the challenges of the early period of LNG adoptions by major representatives of the industry. Such an approach will give a more comprehensive picture of all the complexities involved.

Real-world case studies are the most effective way to demonstrate how LNG has been successfully adopted by the shipping industry as its main fuel source. An increasing focus on environmental sustainability and energy efficiency is characterizing a transitional era that the marine industry, a cornerstone of global trade, is going through. In this regard, the introduction of the CMA CGM JACQUES SAADE, the largest LNG-powered containership in the world, is a significant accomplishment and evidence of the dedication of CMA CGM, a top global shipping and logistics company, to leading the industry's energy shift. The world saw its first use of LNG as the main propulsion fuel for ultra-large containerships in 2017 when Rodolphe Saadé, the Chairman and CEO of CMA CGM, took the strategic choice to order nine 23,000-TEU containerships. This action demonstrated the company's unwavering dedication to environmental stewardship and established it as a leader in the energy transition within the industry. LNG has major environmental benefits as a clean energy source. It is estimated that the CMA CGM JACQUES SAADE's adoption of LNG will result in a 99% reduction in sulfur oxide and fine particle emissions, an 85% reduction in nitrogen oxide emissions, and a 20% reduction in carbon dioxide emissions. (SGA CMA, 2019). This aligns with global efforts to mitigate the environmental impact of the maritime sector and adhere to stringent emission standards (Englert at al. 2021).

Carnival Corporation, a significant participant in the cruise business, is another illustration of the incorporation of LNG-powered vessels. Their flagship vessels, the Mardi Gras and the AID Anova, serve as examples of how LNG technology has been successfully implemented. These boats demonstrate a dedication to sustainability and environmental preservation in addition to adhering to strict environmental standards. It is anticipated that by 2025, Carnival Corporation would increase the number of LNG-operated vessels in its fleet by up to 10 (Ahmed et al. 2022). Given the recent tragedy involving the Azura ship that disregarded European legislation's sulfur regulations (Samuel 2020), the established trend of implementing greener operational practices not only advances environmental goals but also improves the company's damaged reputation with consumers (Garay & Paloti, 2018).

On the other hand, Maersk Line, a leader in the shipping sector, encountered difficulties when LNG was first introduced. Maersk's experience demonstrates the challenges and complications faced by early adopters, from modifying existing vessels to managing the changing regulatory landscape (Halff 2017). Perhaps for this reason, Song (2021) reports that Maersk has questioned the shipping industry's significant investment in LNG as a marine fuel, pointing to hazards associated with methane slippage and minimal emission gains. Rather, it suggests lignin, methanol, biodiesel, and ammonia as fuels for net-zero emissions. Wartsila, on the other hand, is in favor of LNG propulsion and highlights its adaptability to future low-carbon fuel conversions as well as continuing initiatives to reduce methane slip. This reveals a significant industry divide on the role of LNG and underscores debates about the most effective pathways to achieve sustainable shipping (Adamopoulos 2021).

The aforementioned case studies provide insightful information about LNG's practical application as a maritime fuel. While organizations such as CMA CGM and Carnival Corporation highlight the advantages of LNG for regulatory compliance and the environment, Maersk Line's experience underscores the difficulties faced by early adopters. There is currently disagreement in the industry about LNG's long-term function. While some supporters, like Wartsila, highlight its adaptability for upcoming low-carbon conversions, others doubt its capacity to reduce emissions in comparison to alternative fuels. In light of this, it can be said that these case studies demonstrate how the maritime sector is continuously changing and seeking out greener alternatives.

# 6. Future Prospects and Challenges

The potential and difficulties of LNG as a primary or intermediate fuel are crucial as the maritime sector carries out its shift to more environmentally friendly operations. The possibilities and difficulties of LNG as a maritime fuel are examined in this chapter. The shift to sustainability necessitates knowledge of LNG's future growth potential, technological developments, and lingering obstacles. In order to achieve this, we will investigate the elements that propel the adoption of LNG, such as tighter environmental laws, social pressure for eco-friendly behavior, and its appropriateness as a stopgap.

## 6.1. Potential Growth and Expansion

First off, the need for cleaner fuel substitutes is rising due to the increased emphasis on decarbonization around the world and the strict rules imposed by international organizations. Furthermore, social pressures with ecological awareness play a significant role in wider LNG adoption in addition to institutional and regulatory pressures, market factors, and resource availability issues (Serra & Fancello, 2020). This is because LNG is a highly viable option that offers significant reductions in greenhouse gas emissions when compared to traditional fuels. Furthermore, LNG is a good option for a short- to medium-term fix since it efficiently supports the current engine and system technology, promoting legal compliance, practical experience, economy, and the availability of natural gas worldwide (Zakaria & Rahman, 2017).

Greener practices are adopted by shipping businesses as a result of social pressures fueled by environmental consciousness. Companies are driven to decrease pollution and enhance fuel economy by investor and customer demands for environmentally friendly activities. The public's pressure on sustainable shipping methods is aided by non-governmental organizations, citizen groups, and environmental organizations. Given the multitude of factors at play, the marine industry is forced to embrace greener methods, including the adoption of fuel. For instance, Kotrikla & Chortatsiani (2022) observe that travelers aboard cruise ships are becoming more environmentally conscious, aware of the industry's negative effects on the environment, and willing to take part in efforts to mitigate such effects. Similarly, Lee et al. (2020) looked into market sentiments in South Korea and reveal a significant willingness among the public to pay a premium for products imported via environmentally friendly LNG-fueled vessels. This underscores the potential economic gains and market preferences associated with LNG adoption (Lee et al., 2020). Thus, the voice of consumers/clients will also be included in the policy-making decisions, hopefully resulting in further promotion of greenery/viable solutions to the environmental conundrum of the maritime industry.

## 6.2 Technological Innovations fostering LNG fuel adoption

Technology advancements will have a significant impact on how LNG is used in transportation in the future. Future technological advancements are expected to improve LNG's overall viability as a naval fuel while also increasing its efficiency and safety. Future technical advancements, for instance, might concentrate on enhancing the environmental profile of LNG-powered ships even more (Danilov et al. 2019). To improve the overall effectiveness of LNG consumption in maritime transport, this might involve developments in propulsion systems, such as more ecologically friendly and efficient engines (Jang et al. 2021, Boretti 2020a, b) (Iannaccone, et al 2020).

The source highlights cutting-edge frameworks such as the ECSO (Efficient and Safe Cooperation Organization) to maximize traffic organization for LNG carriers in terms of safety. It is anticipated that this field will see improved safety practices, emergency response plans, and state-of-the-art monitoring and control systems in order to reduce possible dangers related to LNG storage and transportation (Klein et al. 2017).

Furthermore, improvements in containment technology and other storage system innovations may improve efficiency and safety. For example, the source discusses advancements in aluminum alloy membrane tank containers, which provide increased safety, extended operating times, and reduced weight. These containers have a positive effect on the economic efficiency of LNG transportation by increasing safety, extending operation times, and reducing weight. Adoption of such cutting-edge storage technologies enhances LNG transportation's safety and economic feasibility across a range of modalities, including maritime transportation. Future developments could improve these storage options even further, increasing their dependability and effectiveness for LNG applications in maritime environments (Mamedova & Gogolukhina 2020).

## 6.3. Challenges in LNG fuel adoptions

Even if the use of LNG has advanced significantly, there are still issues that must be resolved before it can be widely adopted. Technical challenges, which include high implementation costs and industrial resistance to change, need for sophisticated and economical solutions like gas analysis systems. High investment costs and cybersecurity concerns are obstacles to the LNG industry's adoption of Industry 4.0 technologies, which emphasize automation and data analytics. Additional hurdles include environmental concerns, scalability issues, and legal and economic barriers. The LNG sector faces challenges such as exorbitant development expenses, sluggish regulatory adjustment, and the requirement for greener and more sustainable technology to meet international environmental standards. The scalability of new technologies, especially in transportation and storage, presents a complex and costly challenge. Integrating LNG technologies with renewables demands careful planning for compatibility (Adekoya et al. 2024).

Now let's talk about how politics and regulation play a part in shaping LNG technology. As a reflection of the complex balance between policy, innovation, and investment, the 2020 sulfur emissions rule from the IMO spurs innovations but also creates uncertainties (Petrov et al., 2019). Green innovation is driven by environmental rules, but development may be hampered by unpredictable economic policies (Li et al., 2021). Given that policy and regulation are essential for fostering innovation, resolving issues, and guaranteeing the safe and sustainable expansion of the LNG sector, it is imperative that policy approaches be tailored to regional variations for effective implementation.

Consequently, despite the notable advancements, obstacles still need to be overcome before LNG can be widely adopted. Concerns about the environment, scalability, and economic, technical, and legal obstacles all pose significant obstacles to LNG's further use and integration into the maritime sector. The industry struggles with the demand for greener technology, high development costs, and slow regulatory adaptation. But despite these challenges, there have also been notable advancements. Technological developments in safety measures, propulsion systems, and storage solutions, for instance, offer potential alternatives. In the end, LNG's future depends on its capacity to overcome these obstacles and help create a better maritime environment. In order to promote innovation and guarantee the safe and sustainable expansion of the LNG industry, policy approaches that are customized for regional variations will be essential.

# Conclusion

Our analysis of the aforementioned data led us to the conclusion that liquefied natural gas integration in the maritime sector represents a major advancement toward ecologically friendly and sustainable practices. The use of LNG as a maritime fuel has significant positive effects on the environment. It reduces particulate matter, sulfur oxide, and nitrogen oxide emissions, improving air quality and efficiency overall. Nevertheless, when it comes to answering the question of whether LNG functions as a fundamental or transitional fuel in the maritime sector, the data points to LNG functioning as a transitional fuel. Even though it is significantly less harmful to the environment than conventional marine fuels, especially when it comes to lowering sulfur oxides, nitrogen oxides, and particulate matter, it is still unable to achieve the targeted zero-carbon emission levels.

The examined sources highlight the ongoing discussion within the sector over LNG's long-term potential, with issues voiced regarding its less-than-ideal emission gains and the potential for methane leak. An excellent illustration of this type of behavior is Maersk's doubt and support for the use of alternative fuels to help achieve the net-zero emissions target, such as biodiesel, methanol, and ammonia. LNG has been actively integrated as a contemporary option among greener alternatives, as demonstrated by the case studies of industry giants that have adopted it, such as CMA CGM and Carnival Corporation. Nonetheless, taking into account the examined regulatory frameworks, such as the IMO's 2050 greenhouse gas reduction targets, the industry's acknowledgement of the necessity to shift to zero-carbon bunker fuels emphasizes LNG's temporal applicability even more. Economic considerations and uncertainties surrounding LNG's price competitiveness and infrastructure investments also position it as a transitional solution awaiting more sustainable alternatives.

Therefore, it is possible to draw the conclusion that, even though LNG helps the environment and provides a concrete short-term option for the industry to transition, its status as a transitional fuel on the road toward a zero-carbon future in maritime transportation is indicated by the unresolved issues surrounding its greenhouse gas emissions and the evolving regulatory frameworks.

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