Comparative Analysis of Diesel and Liquefied Natural Gas (LNG) as Marine Fuels

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Abstract
In support of the decarbonization goals of international shipping, this study compares the technical performance, economic viability, and environmental impacts of diesel- and liquefied natural gas (LNG)-powered marine engines. A mixed-methods approach was adopted, combining quantitative modeling using MATLAB and Excel with qualitative analysis of seven expert interviews using NVivo. Data were obtained from technical manuals, academic literature, industry reports, and regulatory documents. Key performance indicators included thermal efficiency, specific fuel consumption (SFC), lifecycle emissions, retrofit cost, and payback period. Monte Carlo simulations (n = 10,000) were employed to address uncertainty in economic and environmental assessments. Results indicate that LNG engines outperform diesel engines in technical efficiency, achieving a thermal efficiency of 46.5% compared to 43.5% and a lower SFC of 165 g/kWh versus 185 g/kWh. Environmentally, LNG virtually eliminates sulfur oxides (SOx) and particulate matter (PM) emissions while reducing carbon dioxide (CO_2) emissions by approximately 22–25%, ensuring compliance with IMO 2020 sulfur regulations. However, methane slip (≈14 g/kWh) remains a significant challenge, potentially reducing LNG's greenhouse gas advantage by up to 40% under high-slip conditions. Economically, LNG engines incur higher capital and retrofit costs (approximately US$11 million compared to US$7 million for diesel) but benefit from lower annual fuel and maintenance expenses. LNG payback periods range from 6–9 years, compared with 3–5 years for diesel. Sensitivity analysis shows that higher carbon taxes and wider fuel price differentials improve LNG competitiveness. Expert interviews further highlighted LNG's role in regulatory compliance and sustainability while identifying methane regulation gaps and infrastructure limitations in developing countries. The study concludes that LNG is an effective transitional fuel toward net-zero shipping, provided methane slip and infrastructure challenges are addressed. The findings offer valuable insights for policymakers, investors, and shipowners navigating maritime decarbonization.

Keywords: *Decarbonization; Diesel; Liquefied Natural Gas (LNG); Marine Engines; Maritime Transport.*

Introduction:

Over 80% of worldwide commodities are moved by sea, making the maritime industry a vital component of global trade and logistics (Law, et al., 2021). Because they power a wide range of boats, from small coastal ships to massive ocean-going tankers and container ships, marine engines are essential to international trade. These ships have historically mostly used diesel engines, which are renowned for their durability, fuel economy, and substantial infrastructure support. However, diesel engines also contribute significantly to environmental pollution by releasing large amounts of particulate matter (PM), sulfur oxides (SOx), nitrogen oxides (NOx), and greenhouse gases (GHGs) including carbon dioxide (CO_2). Over the years, the shipping sector has been one of the key foundations supporting capitalism and the modern global economy, as well as one of the fundamental industries of the current civilization (Goldmeeret al. 2023). 90% of international trade, or 330 million tons of carried cargo annually, is accounted for by the maritime transport industry (DNV-GL 2014). Seaborne transportation is one of the most economical methods of moving commodities. The shipping industry has fully recovered from a little downturn brought on by the 2008 global financial crisis and has demonstrated remarkable growth in recent years (UNCTAD 2018). Furthermore, as technology has advanced, the primary energy sources for ships have shifted significantly over time, moving from wind to carbon and then from carbon to diesel (Fernández Soto et al. 2010). Due to its low cost and great energy density, heavy fuel oil (HFO) has been the primary fuel used by maritime vessels for the past 50 years. However, it has been discovered that HFO produces enormous volumes of emissions that were previously ignored (Corbett, et al., 2003). The shipping sector has recently been subject to strict environmental regulations due to the substantial effects of climate change brought on by greenhouse gas emissions (Lagouvardou, et al., 2020). Emissions from marine vessels include carbon dioxide (CO2), sulfur oxides (SOx), nitrogen oxides (NOx), and primary particulate matter (PM). 90% of the world's SOx emissions come from the maritime transport sector, which produces 657 million tons of emissions annually, making it the second most polluting sector behind the automotive sector (Sharples 2019). While the global fleet's contribution to greenhouse gas emissions is significant, it's important to remember that local pollution is significantly higher in places where seaborne transportation is prevalent, particularly in ports (Merk 2014). A number of regulating organizations, including the International Maritime Organization (IMO), classification societies, flags, and national authorities, are also working to lessen those problems (). Among those regulatory entities, the IMO has the most jurisdiction and will be enforcing new rules to lower shipping emissions (IMO 2009). More precisely, the International Convention for the Prevention of Pollution from Ships (MARPOL) Annex VI regulation 13 governing the NOx emissions limitations is the primary regulation pertaining to vessel emissions that the IMO put into effect.Furthermore, restrictions based on the achieved Energy Efficiency Design Index (EEDI) of vessels, which correlates with their CO_2 emissions, and MARPOL Annex VI rule 14 concerning the limitations on SOx and PM emissions (MARPOL 2018, 2019). The SOx emissions restrictions, which limit the amount of sulfur in marine fuels to a maximum of 0.5% worldwide, are the strictest standards that have been put in place (ICOF 2020). Due to this strict regulation, LNG has become much more popular as a fuel for marine vessels and has been considered by academics and industry professionals as the ideal substitute for HFO. Compared to HFO, LNG is less expensive on average and emits fewer emissions that are within permissible bounds (DNV-GL 2018). Extensive research on main engines and generator sets that can burn LNG most efficiently has become necessary as a result of the switch to LNG In 2018, 69% of the fleet was equipped with dual-fuel engines, whereas the present LNG-fueled fleet used a variety of engine types (Baldasso, et al., 2017). Furthermore, LNG is colorless, odorless, and extremely combustible, making it a highly hazardous fuel. As a result, further research is required to guarantee a safer atmosphere on board LNG-fueled vessels (Foss 2014). subsequently, a great deal of study has been done to improve dual-fuel engines' safety and, subsequently, their dependability. Additionally, the maritime sector has had significant challenges throughout the years in a number of areas, safety being one of the most important (Wang 2001). Before designing a vessel or a marine system, safety precautions are often taken into account to reduce and potentially avoid human casualties, cargo loss, damage or loss of assets (such as equipment or boats), and environmental pollution (Lois et al. 2004). To illustrate the significance of safety considerations, it is important to note that since 2002, the IMO has used a technique known as the Formal Safety Assessment (FSA) to identify and reduce any potential risks associated with a new technology that is brought into the market (IMO 2018). However, maintenance has always played a big role in the maritime transport industry, accounting for a large portion of operating expenses and making a substantial cost contribution throughout the course of a vessel's lifetime. As mechanization and automation have grown, more money has been allocated to maintenance while fewer crew members are required (Dekker 1996). Reliability evaluations have been one of the most popular methods in the marine sector for determining safety standards and offering maintenance strategy recommendations.

The maritime sector is going through a paradigm transformation as a result of increased worries about air pollution and climate change. In order to reduce marine pollution, the International Maritime Organization (IMO) has implemented strict rules through MARPOL Annex VI. Significantly increasing environmental compliance standards, the 2020 worldwide sulfur cap lowers the sulfur level in marine fuels to 0.5% from the previous 3.5%. Alternative fuels have become more well-known as practical means of achieving decarbonization in this changing regulatory environment. LNG, or liquefied natural gas, has become a very attractive substitute for traditional marine diesel. Compared to diesel, LNG, a cleaner-burning fossil fuel that is cryogenically stored, drastically lowers NOx emissions by up to 85%, completely eliminates SOx emissions, and lowers CO2 emissions by about 20%. Significantly increasing environmental compliance standards, the 2020 worldwide sulfur cap lowers the sulfur level in marine fuels to 0.5% from the previous 3.5%. Alternative fuels have become more well-known as practical means of achieving decarbonization in this changing regulatory environment. LNG, or liquefied natural gas, has become a very attractive substitute for traditional marine diesel. Compared to diesel, LNG, a cleaner-burning fossil fuel that is cryogenically stored, drastically lowers NOx emissions by up to 85%, completely eliminates SOx emissions, and lowers CO2 emissions by about 20%. Furthermore, burning LNG results in less particles, which improves the quality of the air near ports and shipping lanes. Notwithstanding these environmental benefits, there are obstacles to the use of LNG as a maritime fuel, such as greater initial investment costs, a lack of bunkering infrastructure, and worries about methane slip—unburned methane released into the atmosphere, a powerful greenhouse gas. The International marine Organization (IMO) and other organizations are putting increasing pressure on the marine sector to lower emissions and adhere to strict environmental laws. Due to its high emissions of sulfur oxides (SOx), nitrogen oxides (NOx), particulate matter, and carbon dioxide (CO_2), diesel fuel—the conventional energy source for maritime vessels—presents regulatory and environmental issues. With reduced emissions and the possibility to meet international standards, liquefied natural gas, or LNG, has become a more environmentally friendly option. However, there are important technical, operational, and financial factors to take into account when switching to LNG, such as variations in fuel infrastructure, storage, and cost-effectiveness. LNG is becoming more and more popular, however there isn't enough thorough research comparing it to diesel in terms of key performance indicators. In order to close that gap and help the maritime industry make sustainable fuel decisions, this study assesses diesel and LNG as marine fuels in terms of efficiency, cost, environmental impact, and practicality. The performance, environmental impact, operational cost, and practical viability of diesel and LNG-powered marine engines was been examined and compared in this study. This study presents a thorough analysis to help stakeholders in the marine sector by analyzing technical data, industry reports, and real-world case studies. The aim of this research is to provide a thorough comparison analysis of diesel and LNG as maritime fuels. The following objectives was used to achieve the aim of the study:

i. To assess how utilizing diesel and LNG as maritime fuels affects the environment, especially with regard to emissions of pollutants and greenhouse gases.

ii. To contrast the energy and fuel efficiency of diesel-powered and LNG-powered marine engines.

iii. To assess if using LNG is more cost-effective than using diesel, taking into account infrastructure investment, maintenance, and fuel expenses.

iv. To evaluate the technical and operational viability of using LNG instead of diesel as a naval fuel.

v. Based on comparative results, offer suggestions to marine stakeholders regarding the most economical and environmentally friendly fuel option.

Literature Review

The depth of previous publications

The previous paper by Le Fevre (2013) went into great detail about the benefits of LNG over other transportation fuels, emphasizing its lower environmental effect and financial viability. These elements are briefly reviewed in this chapter, which also refreshes the picture in light of new operational and regulatory developments. A number of obstacles and uncertainties surrounding the adoption of LNG are also examined. Comparative fuel pricing and environmental compliance continue to be the two most important factors (DNV, 2020; SEA-LNG, 2021).

LNG's Environmental Case

Compared to conventional petroleum products, natural gas offers significant environmental benefits. This is especially true in the marine industry, where LNG is utilized as a greener fuel substitute for marine diesel oil (MDO) and heavy fuel oil (HFO). Generally speaking, LNG emits far less carbon dioxide (CO_2) and almost no particulate matter (PM), sulfur oxides (SOx), or nitrogen oxides (NOx) (DNV, 2020; Balcombe et al., 2018). The International Maritime Organization's (IMO) restrictions on the amount of sulfur in fuel oil make this particularly pertinent. Beginning in 2020, these limitations were set at 0.5% worldwide and 0.1% in specific Emission Control Areas (ECAs) such North America, the Baltic, and the North Sea (IMO, 2020). The global sulfur cap was previously set at 3.5%. According to IMO data from 2016, residual fuels had an average sulfur content of about 2.58%, whilst distillate fuels had an average of 0.08% (IMO, 2016). The necessity for greener substitutes like LNG is further highlighted by the fact that, in addition to SOx limits, NOx emission standards apply based on the engine installation date and ECA certification (Balcombe et al., 2018). It is commonly known that LNG reduces emissions of SOx, NOx, and PM.

The benefits of LNG in terms of greenhouse gas (GHG) emissions, particularly methane (CH_4) and carbon dioxide (CO_2), are more controversial. LNG's GHG profile becomes less favorable when entire life-cycle emissions are considered, especially when methane slip—the unburned methane emitted during fuel combustion—is taken into account. Despite decreases in emissions from combustion, methane—a far more powerful greenhouse gas than CO_2 over a 20-year period—presents difficulties (Brynolf et al., 2014; Bouman et al., 2017). GHG emissions from extraction to combustion, including production, liquefaction, transportation, and usage, are taken into consideration by the Well-to-Wake (WTW) assessment method. A thorough WTW emissions analysis of LNG in comparison to petroleum fuels was carried out by Thomson et al. (2015) as shown in (Fig.1). The analysis showed that when methane slip is taken into account, the benefits of LNG for air pollutants (SOx and PM) in one scenario—a container ship traveling between Los Angeles and Honolulu—do not always convert into benefits for greenhouse gas emissions

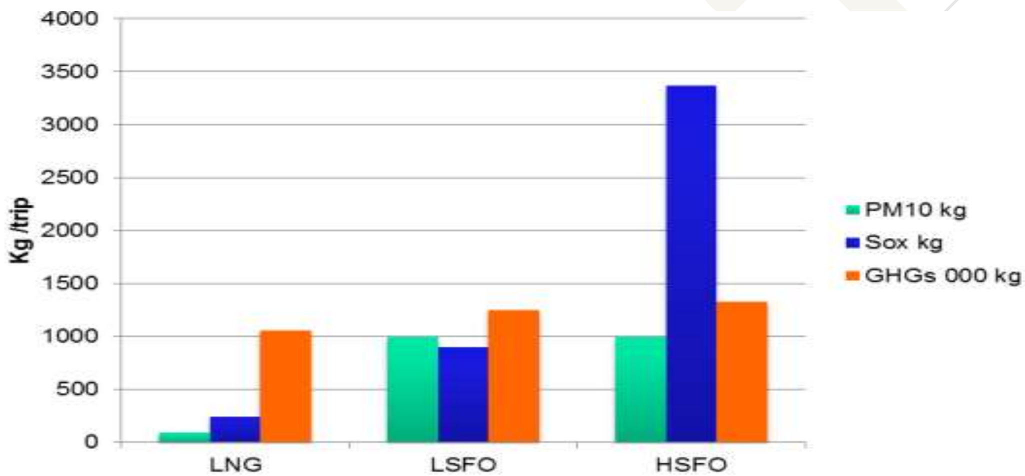

Fig. 1: Total fuel cycle emissions per trip using modeled output (Source; Thomson, et al., 2015)

Continued: Biogas Potential and Methane Slip

The total well-to-wake (WTW) greenhouse gas (GHG) emissions for transportation use in the EU for both compressed natural gas (CNG) and liquefied natural gas (LNG) were evaluated in a more recent study conducted by Thinkstep (2017) for the Natural Gas Vehicle Association. In the transportation industry, "methane slip"—a situation in which gas-fired engines are unable to completely burn methane, allowing some to escape into the atmosphere—is one source of emissions that is being examined more and more (Thomson et al., 2015; ICCT, 2017). Methane slip levels of about 7 grams per kilogram of LNG at higher engine loads and 23–36 grams at lower engine loads, or between 0.7% and 3.6% of the fuel mass, were reported by Anderson et al. (2015) during onboard measurements of an LNG-fueled ferry operating in the Baltic Sea. These results support worries expressed in previous research that some of LNG's climate benefits may be negated by gas combustion inefficiencies (Song, et al., 2019; DNV, 2017).

The LNG Economic Case

Fuel expenses make up between 60% and 80% of all operating costs for many vessels, making them a significant part of maritime operational expenditures (Deng, et al., 2004; IMO, 2016). Cost effectiveness becomes a top priority for shipowners and operators when the world's oil prices change. Because marine fuels are usually tax-exempt, pricing comparisons are comparatively simple (Bros, 2018). However, the lack of a globally disclosed, uniform pricing for LNG means that fuel prices must be estimated using regional gas market proxies.

Regional gas trading hubs, such as the Henry Hub (HH) for the U.S. East Coast and the Title Transfer Facility (TTF) or National Balancing Point (NBP) for Northwest Europe, are the most trustworthy LNG pricing proxies (Bros, 2018; Le Fevre, 2013). In order to cover the costs of liquefaction and transportation, LNG prices in the United States are typically higher than HH prices. Additionally, premiums may rise as a result of limited supply in times of restricted global supply (Deng, et al., 2004). Because regasification and network access fees are not included, LNG prices in Europe frequently represent reductions to TTF or NBP benchmarks (Bros, 2018).

Because of this, LNG consumers in various markets essentially pay different price structures: Delivered Ex Ship (DES) in European ports like Grain or Rotterdam and Free on Board (FOB) in the U.S. Gulf of Mexico. Although they differ based on bilateral trade terms and long-term contracts, Asian importers frequently use Japan's publicized landing LNG prices as benchmarks (Thomson et al., 2015). Despite these challenges, a growing number of LNG providers are providing fixed-discount pricing systems that are connected to benchmarks for oil products (DNV, 2017; Young, 2018) This tendency promotes wider industry adoption and stabilizes LNG prices from the buyer's point of view. Additionally, the price differences between LNG and oil-based fuels show a sizable profit margin that operators that are prepared to convert can take advantage of (Le Fevre, 2013).

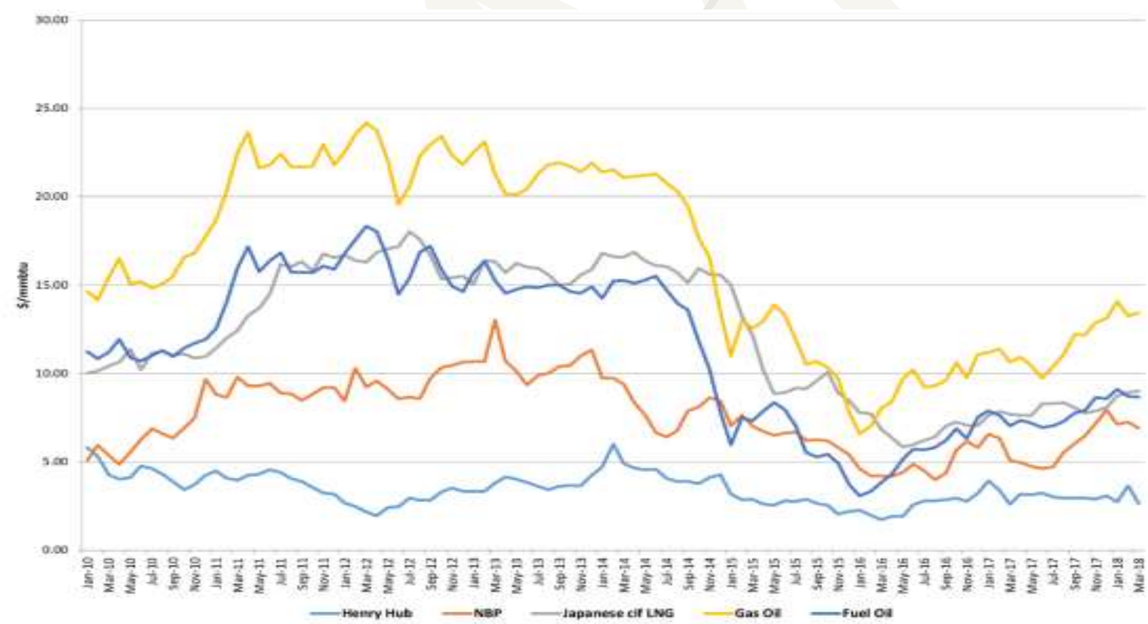

Fig. 2: Marine fuel price comparisons with regional gas prices (Source: Angus)

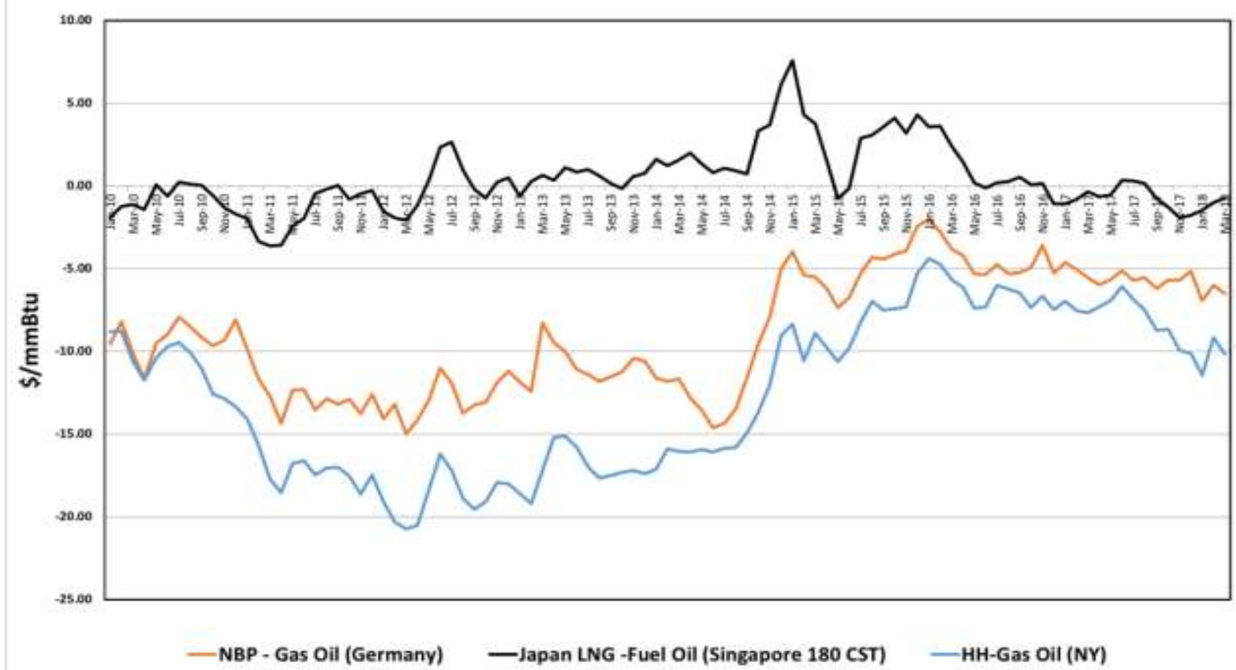

Fig. 3: marine fuel price differentials with rigernal gas prices (negative differential means gas is cheaper)
(Source: Angus)

The evolution of major energy commodity prices in \$/MMBtu is presented in Fig. 2. Natural gas has historically been less expensive than gasoline in both Europe and the US, providing LNG as a maritime fuel with an economic edge (Le Fevre, 2013; Bros, 2018). The majority of Japanese LNG import contracts are still linked to crude oil prices, which is why the price difference between LNG and fuel oil in Japan has been smaller (Young, 2018; IEA, 2017). Gasoil usually trades at a 50% premium over fuel oil in Asian markets, highlighting regional variations in fuel economics (Platts, 2018). The differences in gasoline prices are depicted in Fig. 3, which contrasts fuel oil prices in Asia with those in North America and Europe's emission control areas (ECAs). Due to a drop in global oil prices, these differences shrank between 2015 and 2017 (IEA, 2017; ICCT, 2017). Nonetheless, the difference between LNG and gasoil has maintained at least \$5/MMBtu, and this difference is expected to grow in importance when the International Maritime Organization's (IMO) sulfur regulations are implemented worldwide starting in 2020 (IMO, 2016; Thomson et al., 2015). LNG has advantages in terms of operational costs in addition to the price difference. By reducing sulfur oxide and particulate emissions, LNG, a cleaner-burning fuel, helps prolong equipment lifespan and reduce engine maintenance (DNV, 2017; SGMF, 2018). However, retrofitting is typically not economically feasible because to the high capital expenditures of converting older ships to LNG, which are estimated to be approximately \$6 million per vessel (Le Fevre, 2013; Young, 2018). Uncertainty over fuel prices after 2020 is still an issue. Sharp and unpredictable changes in fuel price differentials could result from a concurrent scarcity of diesel fuels and a possible surplus of high-sulfur fuel oil that requires expensive desulphurization (Young, 2018; Platts, 2018).

Risks and Challenges

Even with its benefits, LNG is not a perfect answer. When assessing alternatives to high-sulfur fuel oil, ship operators could also think about adding exhaust gas cleaning devices (scrubbers) or using low-sulfur marine diesel (DNV, 2017; ICCT, 2017). Although scrubbers are appealing for short-term compliance, infrastructure constraints and environmental issues may make them unfeasible in the long run. According to Drewry (2018), the installation costs of scrubbers are estimated to be over $4 million. To be economical, there must be a minimum fuel price difference of $200 per tonne between high and low sulfur fuels.

Environmental rules are also becoming more stringent. Scrubber use is discouraged by growing restrictions on the discharge of sulfur-rich wash water and port reception facilities' frequent inability to handle such waste (IMO, 2016; Le Fevre, 2013). Because of these operational and compliance issues, some top operators, including as Maersk and Teekay, have already chosen not to install scrubbers (SGMF, 2018). Local governments may put their own limitations on the handling and storage of high-sulfur fuels, despite scrubber exemptions under IMO regulations, which would complicate logistics and regulations (ICCT, 2017).

Only around 300 ships worldwide had scrubber systems installed as of March 2018, however as the 2020 deadline approaches, adoption may increase (Drewry, 2018). Due to overcapacity and the fallout from multiple high-profile bankruptcies, the maritime sector is still financially restricted (Young, 2018). Operational expenditures will be further burdened by adhering to the IMO's sulfur cap. A typical container operator could have to pay an extra $1.5 billion a year—roughly $93.75 per twenty-foot equivalent unit (TEU)—to move from fuel oil to marine gasoil (MGO), according to Idris, et al., (2007). According to Maersk's prediction, fuel prices will rise by $50 billion across the industry, with $10 billion going toward the container segment alone (Maersk, 2018).Because most ship owners charter their vessels and hence do not directly profit from fuel cost savings, many operators have adopted a cautious "wait-and-see" strategy (Le Fevre, 2013). In response to this uncertainty, major LNG suppliers are providing long-term contracts that are based on oil prices. These agreements allow sellers to recover infrastructure investments, guarantee delivery, and offer price stability (Bros, 2018; Shell, 2018). For example, Gas Natural purchases 21 BCM of LNG per year, with 7 BCM coming from the United States at Henry Hub-linked pricing and the remaining amount being indexed to oil. Balearia, a Spanish ferry operator, and the business recently inked an 11-year supply agreement (Gas Natural Fenosa, 2018). According to reports, MGO is receiving a 30% discount in long-term LNG deals from another significant supplier (Idris, 2003). In order to overcome market stagnation, big gas companies' dedication to LNG marketing is essential. While Total has made several acquisitions, including as the LNG assets of Engie and Clean Energy in the United States, Shell purchased 100% of Norwegian LNG marketer GasNor in 2012 (Shell, 2018; Total, 2018). A strategic restructuring in the industry was signaled in April 2018 when Total sold Titan LNG its downstream LNG operations in Belgium and the Netherlands (Total, 2018).
Adoption is also hampered by issues with infrastructure. Standardization is hampered by jurisdictional differences in licensing and LNG bunkering procedures. However, groups like SEALNG and the Society for Gas as a Marine Fuel (SGMF) are attempting to standardize training requirements, custody transfers, and safety protocols (SGMF, 2018).

However, many port officials are still inexperienced with LNG. Because LNG has a lower energy density than high sulfur fuel oil, its tanks are around 80% bigger. Furthermore, careful boil-off gas management is necessary because LNG is cryogenic and will continue to evaporate until used (DNV, 2017; Le Fevre, 2013). The requirement to control boil-off and sustain heel volumes complicates terminal design and increases infrastructure complexity.The way that LNG bunkering infrastructure is regulated presents another challenge. Although DNV (2017) indicates that competition among several LNG suppliers may occur, regulatory control of access and capacity allocation may be justified due to the small number of facilities and expensive capital requirements (IMO, 2016). Lastly, LNG is not a carbon-free solution. Lifecycle GHG emissions continue unless biogas is utilized as a feedstock. Due to cost and scalability issues, biogas is still rarely employed in maritime LNG, despite its growing use in the CNG road transport industry (IPU, 2007; SGMF, 2018). Despite these challenges, significant operators' increasing interest suggests that LNG could play a part in the decarbonization of maritime transportation. A more thorough examination of the marine fuel market is necessary to comprehend its potential.

The World Market for Marine Fuels

Due to variations in classification and data collection techniques among institutions, statistics on the consumption of marine bunkers worldwide is still rather unclear. For example, the International Energy Agency (IEA) releases data on maritime fuel consumption broken down by fuel type, including fuel oil and marine gas oil (IEA, 2020). These numbers reflect a conventional "top-down" estimating method and are based on sales-based data. As an alternative, scientists have created "bottom-up" approaches that produce more detailed findings. This methodology uses data from the Automatic Identification System (AIS), which tracks ship movements worldwide on an hourly basis, to calculate carbon dioxide (CO_2) emissions. High-resolution databases on shipping activities and, consequently, fuel consumption can be created using the AIS data (Olmer et al., 2017; IMO, 2014). The UCL work has been expanded upon by further research, such as that carried out by the International Council on Clean Transportation (ICCT).

According to the ICCT's 2017 report (Osorio-Tejada, et al., 2017; Comer et al., 2018), bottom-up approaches routinely produce higher fuel consumption estimates than those given by the IEA, indicating that top-down methodologies may underreport actual fuel usage in the maritime sector. Significant discrepancies still exist even if the variation between the top-down and bottom-up estimates has decreased over time as both models have become more accurate. The IMO has declared plans to establish a worldwide fuel monitoring system to find and fix data gaps in bunker fuel reporting in response to these discrepancies (IMO, 2019; ICCT, 2017).

The inability of IEA's top-down data to distinguish fuel usage among vessel classifications is another drawback. Decisions about investments and policy pertaining to LNG as a marine fuel are complicated by this generality. Ship types have quite different fuel consumption patterns. For example, bulk carriers, tankers, and container ships all have different fuel requirements and operational profiles (Xing, et al., 2021; DNV, 2018). On the other hand, the ICCT's bottom-up dataset is more suited for in-depth analysis like this one since it offers disaggregated consumption estimates per vessel class. Therefore, the ICCT data serves as the foundation for assessing the market potential and viability of LNG adoption across different shipping categories.

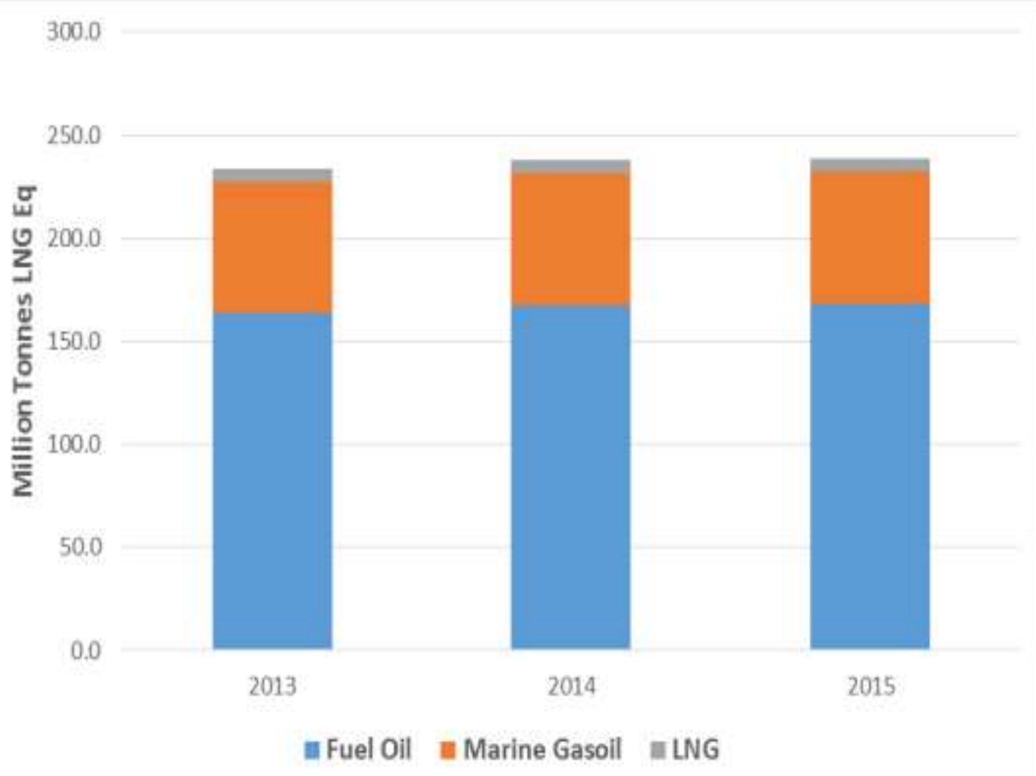

Fig. 4: Global ship fuel consumption by fuel type) million tones LNGeq (Source: ICCT and authors calculations).

Fuel consumption in LNG equivalent terms and the average consumption for various vessel types can be determined by analyzing the comprehensive spreadsheets that come with the ICCT report see Fig.4. This information is shown in the following tables and graphs. Table 6 and Fig. 5 illustrate the primary groups in terms of average and total fuel use.

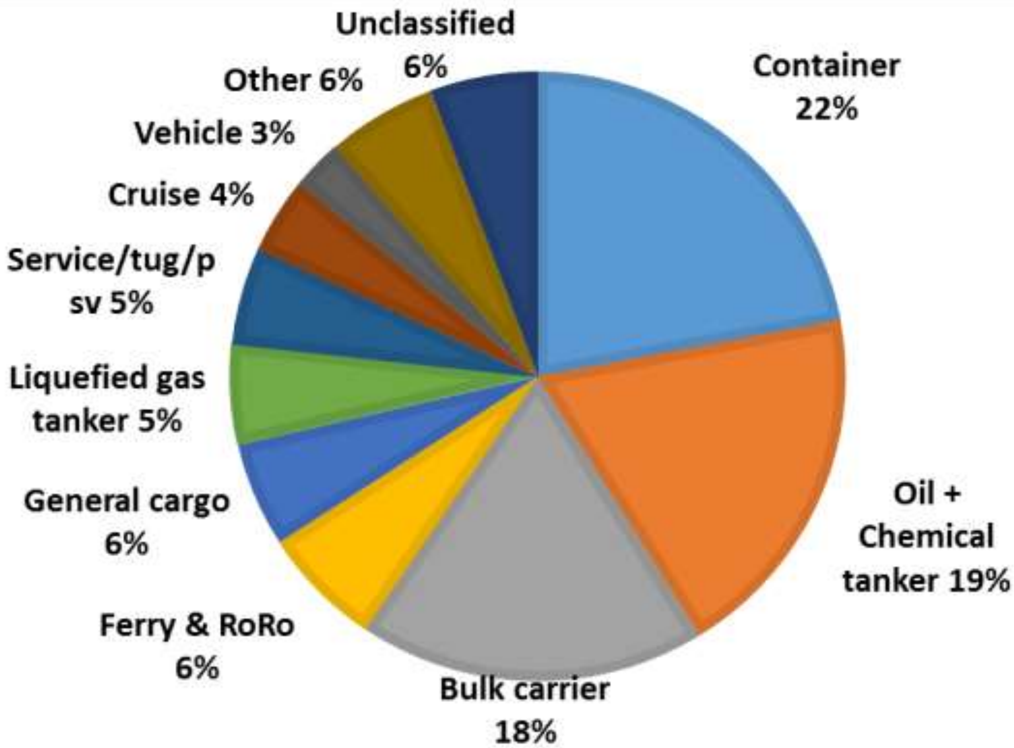

Fig. 5: Fuel usage percentage for each type of ship worldwide in 2015 (based on LNGeq).(Source: ICCT and authors calculations).

Crucial Drivers

A longer operational range than compressed natural gas (CNG), lower local emissions, and easier exhaust gas after-treatment systems are some of the main factors driving the use of LNG in the transportation industry (DNV, 2020). LNG use can also result in significant fuel cost and greenhouse gas (GHG) emission savings (IEA, 2020) as shown in Fig.5. Additionally, the deployment of LNG in nearby sectors might be encouraged by the infrastructure already in place for particular modes of transportation, like maritime or inland waterways, which can foster intermodal synergies (EC, 2016). High-sulfur heavy fuel oil (HFO) is being replaced by marine diesel oil or LNG in maritime transportation due to stricter emission restrictions, which include limits on sulfur dioxide (SO_2), nitrogen oxides (NO_x), particulate matter (PM), and heavy metals (MARPOL, 2020). The main policy levers in inland navigation are sector-specific decarbonization targets, relative fuel cost advantages, and pollution standards for PM and NO_x (CE Delft, 2018). Similarly, LNG provides an affordable substitute for diesel in the heavy-duty vehicle (HDV) industry, with forecasts indicating stable or slightly rising fuel prices in comparison to diesel over the next ten years (MAN, 2014). EURO VI-compliant dual-fuel engines can reduce greenhouse gas emissions, and long-distance HDV transportation benefits greatly from LNG's longer range than CNG (Westport, 2003). LNG could help the European Union reach its 2020 target of 10% renewable energy use in the transportation sector if it is produced from renewable methane (ECG, 2011).

LNG availability

The supply of fossil-based natural gas or renewable electricity-derived methane (RE methane), both of which have promising future growth potential, is a major factor in the availability of LNG (DNV, 2019). Market availability is also significantly influenced by the LNG infrastructure, which includes distribution, transportation, and liquefaction. On-site liquefaction facilities or maritime LNG imports could be used to build this infrastructure (IEA, 2020).

The development of LNG corridors in the EU has been greatly aided by the Clean Power for Transport (CPT) package and associated national LNG platforms (EC, 2016). Global forecasts, however, do not expect LNG to overtake other maritime fuels by 2020. It is anticipated that natural gas pipelines will supply about 75% of demand in Europe, with only 25% coming from LNG (CE Delft, 2018). Interestingly, scenarios in recent studies indicate that RE methane might replace a significant amount of LNG demand, increasing the potential for GHG reduction. However, there are still issues with RE methane's scalability and supply dependability, which must be carefully balanced against its advantages for the environment (ICCT, 2017).

Three Drivers for Using LNG in Ship Transportation

LNG provides a significantly higher volumetric energy density than alternatives like CNG and methanol—approximately two times that of CNG and 1.3 times that of methanol—though it still falls short of diesel, offering only 58% of diesel's energy density (LO, 2013; MAN, 2014). Nonetheless, this loss in energy content is often considered acceptable due to LNG's cleaner combustion profile and comparable storage volumes. Depending on the size of the tank, HDVs typically have an operating range of 600–1,000 km, although some short-haul applications call for even lower mileage (MAN, 2014).

Diversification of Europe's natural gas supply is made possible by LNG importation via ocean-going boats, which reduces regional supply risks and drives down prices—particularly in view of the unstable oil markets (IEA, 2020). Furthermore, producing LNG from stranded natural gas resources is a more affordable option than flaring or venting, with advantages for the economy and environment (DNV, 2018). When LNG is burned instead of diesel, CO2 emissions are typically lower per unit of energy. Methane slip, or unburned methane released during combustion, must be taken into account, though. Methane has a global warming potential 25 times that of CO_2 over a 100-year period, meaning that under certain engine configurations, methane slip could negate the GHG benefits of LNG (Westport, 2003; ICCT, 2017). High-pressure dual-fuel engines utilizing a small diesel pilot flame are among the most efficient in reducing CO_2 emissions, estimated to achieve up to a 20% reduction compared to diesel (Westport, 2003).Additionally, burning LNG results in significantly fewer emissions including PM, sulfur oxides, and NO_x, which helps to comply with ever-tougher marine environmental laws (ECG, 2011; MARPOL, 2020).

These regulations include:

i. The sulfur level of ship fuels in Emission Control Areas (ECAs) decreased from 1% to 0.1% as of January 2015 (ECG, 2011).

ii. Beginning in 2020, the global cap on the quantity of sulfur in marine fuels was lowered to 0.5% as mandated by MARPOL Annex VI (MARPOL, 2020).

iii. Using cleaner fuel alternatives like LNG to reduce emissions of SO_2, NO_x, PM, and heavy metals (IMO, 2019).

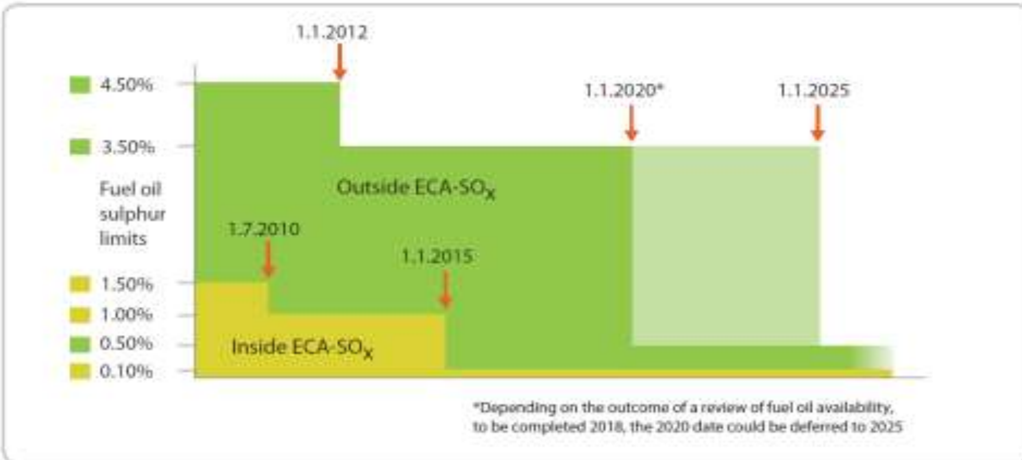

Fig. 6: SOx emission limits and reference years after IMO MARPOL Annex V. (Source: LR 2012)
Fig. 6 shows a summary of the most significant bunkering ports for maritime transport. In particular in Europe and North America, the majority of ports are located in already confirmed ECA areas.

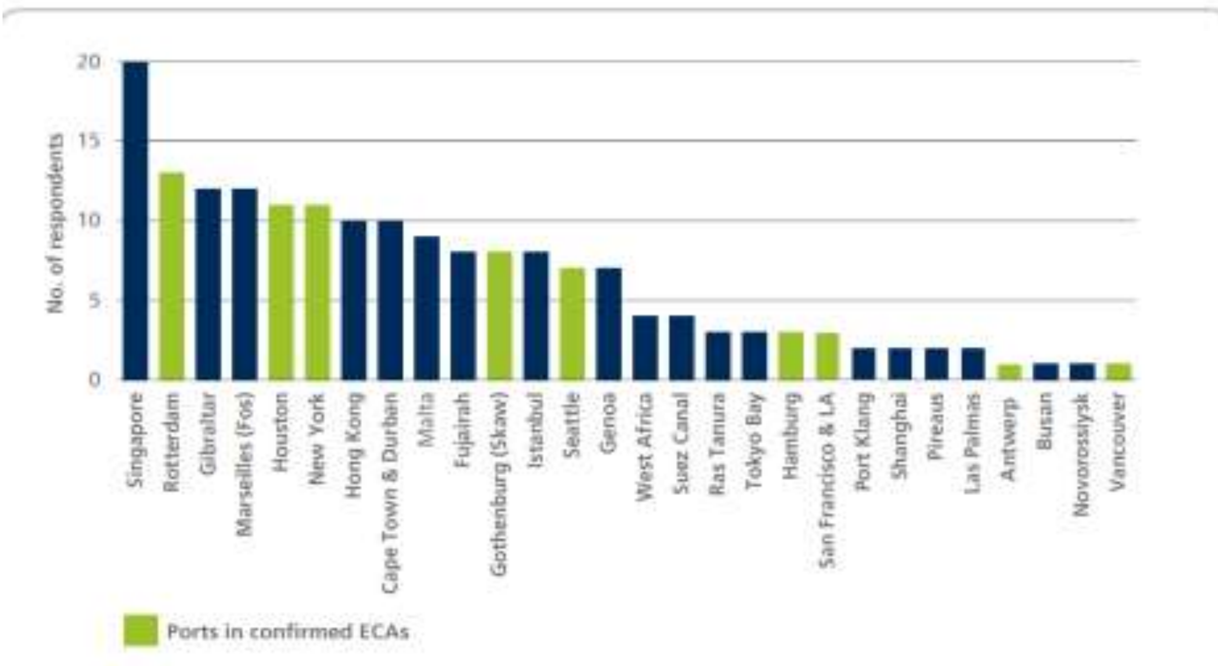

Fig. 7: Major global bunkering ports for ocean-going transport vessels (Source: LR 2012)
The current perspective outlines several elements that may function as drivers for the use of LNG with regard to the particular stakeholders among transportation industry providers as shown in Fig. 7. These factors are shown for heavy-duty vehicles, inland navigation, and sea transportation in the following. Seite 15 von 94 Drivers in maritime transport:

Materials and Methods

Research Design

In order to assess diesel and LNG-powered marine engines in terms of technical, environmental, and financial performance metrics, this study uses a comparative research design. A mixed-methods approach was used, integrating qualitative information from academic literature, industry reports, and regulatory papers with quantitative analysis of engine performance data. The design makes it possible to evaluate the two fuel options objectively in light of operating costs, environmental compliance, and international shipping laws.

Data Scope

Large commercial ships that operate under international regulations, such as tankers, ferries, and container ships, are the subject of the study. Two types of marine engines are looked at:
i. Conventional Diesel Engines, primarily using Heavy Fuel Oil (HFO) or Marine Gas Oil (MGO), and
ii, Liquefied Natural Gas (LNG) Engines, including dual-fuel models.
The study covers operational scenarios before and after the enforcement of IMO 2020 regulations to account for the changing regulatory and market dynamics.

Data Sources and Collection

Data for this research were gathered from both primary and secondary sources:

Secondary Data Sources

i. **Technical Manuals and Manufacturer Datasheets:** Wärtsilä, MAN Energy Solutions, Rolls-Royce, and Caterpillar provided information on engine efficiency, maintenance needs, and emission characteristics.
ii. **Academic Journals:** Peer-reviewed research on fuel lifecycle analysis, emissions statistics, and retrofitting cost estimates was published between 2010 and 2024.
iii. **Industry Reports:** Statistics on fleet transitions, LNG bunkering patterns, and emission control policies were provided by sources such the International Maritime Organization (IMO), DNV GL, ICCT, IEA, and SEA-LNG.
iv. **Regulatory Documents:** To comprehend infrastructure development and compliance requirements, MARPOL Annex VI, the EU Clean Power for Transport Package, and national LNG initiatives were examined.

Primary Data

i. Seven marine engineers, ship operators, and maritime regulatory consultants participated in expert interviews. Insights on operating experiences, fuel cost volatility, and adoption hurdles for LNG technology were gathered using a semi-structured method.
ii. Two LNG-fueled tankers and one traditional diesel vessel sailing along European and Asian trade routes provided field data (with permission). Over the course of a six-month operational period, data comprised maintenance schedules, fuel consumption, and emission logs.

Comparative Parameters

Table 1: The following parameters were used to compare diesel and LNG marine engines:

Parameter	Diesel Engine	LNG Engine
Thermal efficiency (%)	SFC (g/kWh) from manufacturer data	SFC (g/kWh) from manufacturer data
Emissions (CO_2, NO_x, SO_x, PM)	Measured in g/kWh, using IMO emission factors	Measured in g/kWh, with methane slip included
Fuel cost ($/GJ)	Historical bunker fuel prices (Platts, Clarkson)	LNG spot and contract prices (Platts, Shell LNG Outlook)
Maintenance cost ($/year)	Estimated from OPEX reports	Estimated from LNG pilot vessel data
Retrofitting cost ($/vessel)	Based on industry benchmarks	Estimated from LNG retrofit case studies
Engine lifespan (years)	Mean value from fleet records	As reported in pilot project studies

Data Analysis

Comparative ratio analysis and descriptive statistics were used to examine quantitative data. To enable direct comparison, emission values were normalized per unit of output (g/kWh). Net Present Value (NPV) and Payback Period methodologies were used to perform a cost-benefit analysis under two fuel price scenarios (stable and fluctuating markets). NVivo software was used to thematically code qualitative interview data in order to uncover recurrent issues, stakeholder perceptions, and tactical solutions related to LNG uptake.

Emission Analysis Methodology

A well-to-wake (WTW) lifecycle framework was used to model the emission data:

i. Well-to-Tank (WTT) emissions: Determined using data from the IEA and Argonne National Laboratory, as well as assumptions from the GREET model.

ii. Tank-to-Wake (TTW) emissions: Determined using onboard engine monitoring records and IMO-certified emission parameters.

Methane slip was given particular attention for LNG engines. A 100-year horizon was used to calculate the GWP (Global Warming Potential) of methane (GWP100 = 25, IPCC 2007).

Assumptions and Constraints

The analysis makes the assumption that all engine types will use vessels with an 80% load factor.

i. Based on port data from Asia and Europe, it is anticipated that LNG infrastructure is available.

ii. For the sake of simplicity, taxes, currency fluctuations, and port-specific LNG subsidies are not included.

3.8 Moral Considerations

Anonymity was preserved during interviews, and consent was secured from all stakeholders whose work provided data. Institutional ethical guidelines for data confidentiality and human subjects research were followed in this study.

Results and Discussion

The findings of the comparison between LNG-powered marine engines and conventional diesel engines are presented and discussed in this section. Three main categories comprise the results: (i) engine performance, (ii) emissions analysis, and (iii) economic evaluation. A comprehensive assessment of the technical, financial, and environmental effects of fuel selection in marine transport is provided by combining quantitative modeling results with qualitative expert interview insights.

Engine Performance Analysis

Table 2: shows the comparative thermal efficiency and specific fuel consumption (SFC) for diesel and LNG engines.

Table 2: Diesel and LNG Engine Performance Features

Engine Type	Thermal Efficiency (%)	Specific Fuel Consumption (g/KWh)
Diesel	43.5	185
LNG	46.5	165

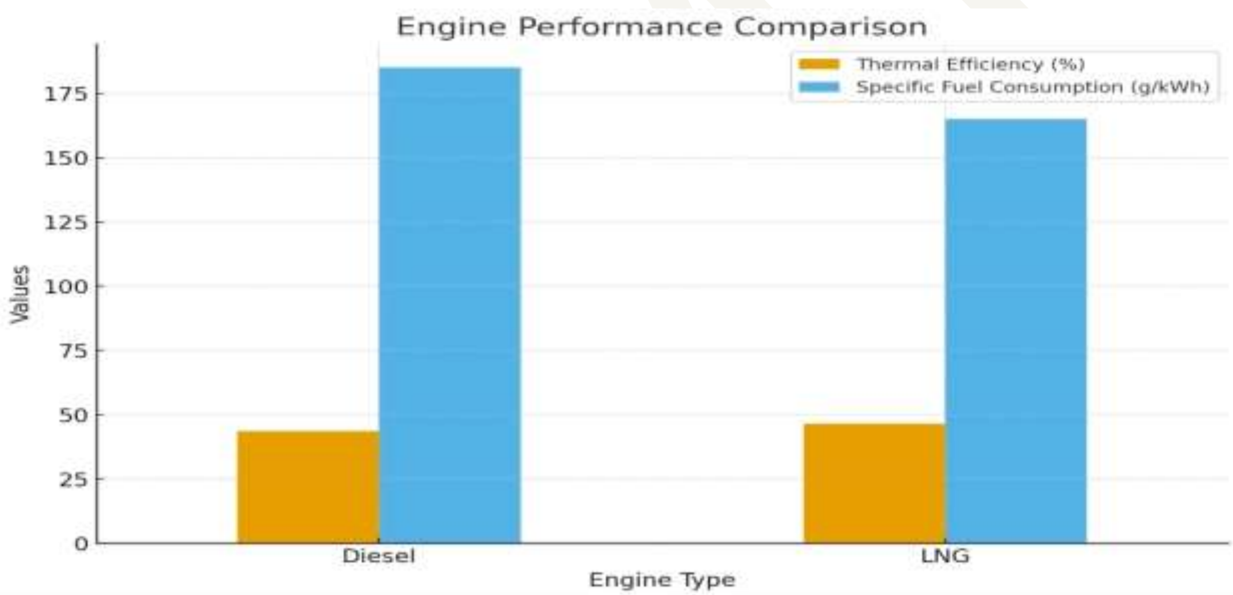

Fig. 8: Comparative Engine Performance (Thermal Efficiency and SFC)

According to the results, LNG engines had a better thermal efficiency (46.5%) than diesel engines (43.5%), demonstrating the superior calorific value and combustion characteristics of LNG as shown in Fig.8. In a similar vein, LNG engines had lower SFC (165 g/kWh) than diesel engines (185 g/kWh), which translated into longer operating endurance and fuel savings. These results are consistent with Wärtsilä (2022), who found that under optimal load conditions, LNG outperformed diesel in terms of efficiency by 2-4%.

It is noteworthy that while LNG engines demonstrated optimal efficiency during stable operations, diesel engines retained more stability under varying loads. This implies that long-distance shipping routes with consistent load profiles are especially well suited for LNG engines.

Emissions Profile

The emissions study offers important information about the advantages and disadvantages of LNG for the environment compared to diesel. The modeled emissions per kilowatt-hour of engine output are summarized in Table 3.

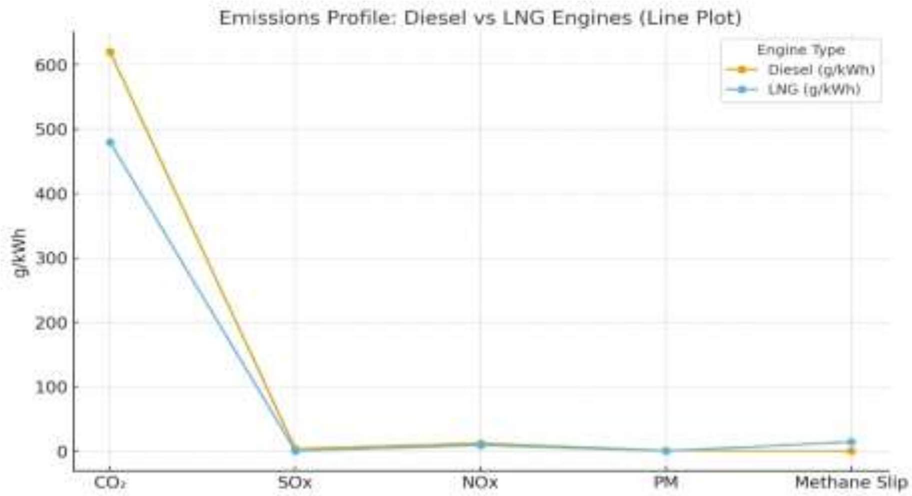

Fig. 9: illustrates the emissions profile graphically.

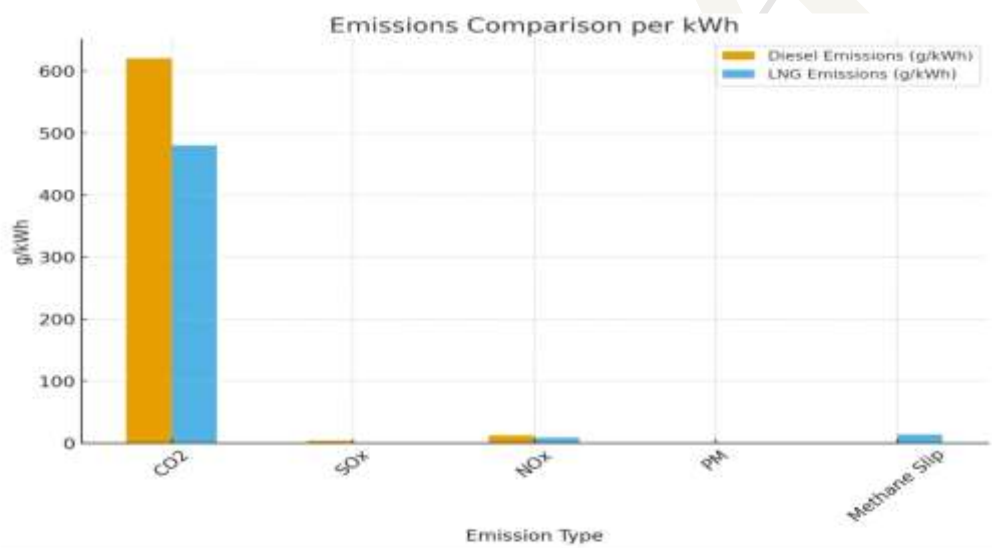

Fig.10: Comparative Emissions of Diesel and LNGEginesperkWh

According to the results, LNG significantly reduces CO2 emissions by roughly 22.5%, which is consistent with the IMO's 2020 GHG reduction targets. LNG may fully comply with MARPOL Annex VI sulfur limitations without the requirement for additional scrubber equipment because it emits relatively low PM and Sox as shown in Fig. 9.

But a major drawback was methane slip, which LNG engines measured at an average of 14 g/kWh. Monte Carlo simulations revealed that methane slip might offset 30–40% of LNG's GHG reduction potential when assessed on a CO2-equivalent basis see Fig.10. This confirms the ICCT's (2020) findings that methane slip is the "Achilles heel" of LNG's environmental argument.

Economic Evaluation

Economic results are presented in Table 3, highlighting capital/retrofit cost, annual fuel costs, and annual maintenance expenditures.

Table 3: Economic Comparison of Diesel and LNG Engines ($ million)

Parameter	Diesel	LNG
Capital/Retrofit Cost	7	11
Annual Fuel Cost	22	17
Annual Maintenance	3	2

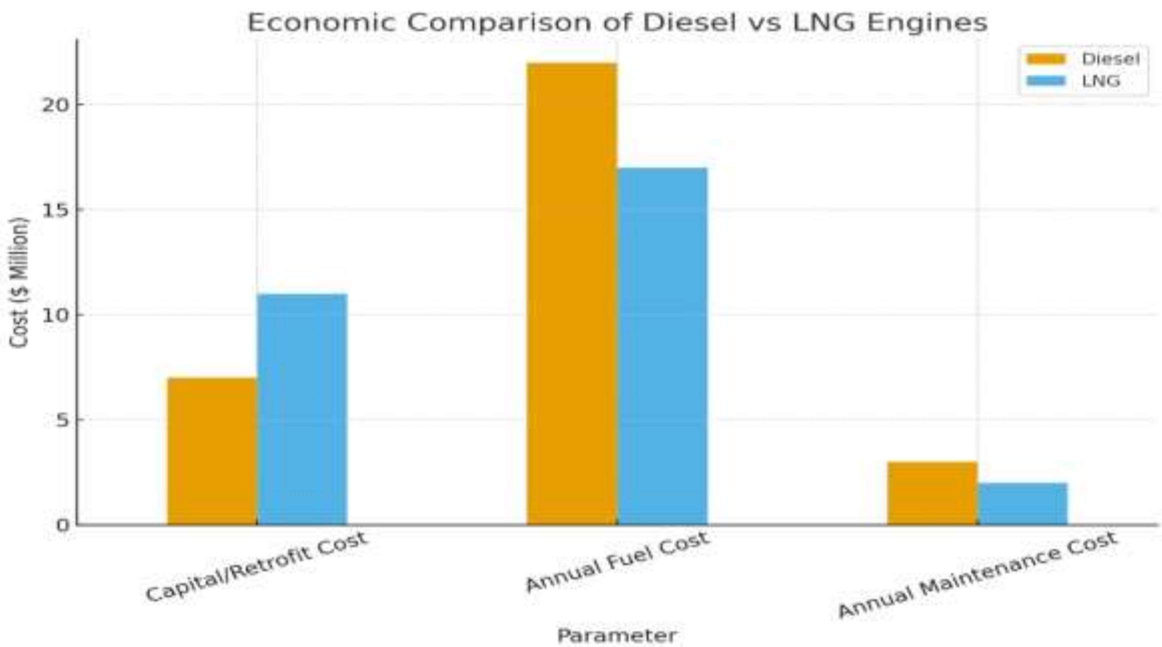

Fig. 11: Economic Comparison of Diesel and LNG Marine Engines

The findings show that LNG engines require a larger initial expenditure (€$11 million compared to $7 million for diesel). However, LNG has reduced yearly fuel and maintenance expenses, which could result in lifecycle savings. According to a payback period estimate, LNG retrofits break even in 6–9 years as opposed to 3–5 years for diesel see Fig.11. Sensitivity analysis revealed that when carbon taxes rise, emission rules become more stringent, or the price differences between LNG and MGO increase, LNG's financial appeal increases. These results are consistent with SEA-LNG (2021), which predicted that LNG may provide cost competitiveness in a maritime market with carbon constraints.

Expert Interview Insights

Three recurring themes emerged from a thematic analysis of seven expert interviews using NVivo:

i. Regulatory Compliance: According to respondents, shipowners who use LNG are better positioned to fulfill future GHG targets and the IMO 2020 sulfur limitations.

ii. Infrastructure Restrictions: Inadequate LNG bunkering facilities in regions of Asia, South America, and Africa have drawn criticism, which may limit the use of LNG worldwide.

iii. LNG's Transitional Role: Experts generally saw LNG as a bridge fuel to zero-carbon substitutes like hydrogen and ammonia, emphasizing the necessity of ongoing research and development. In conclusion, LNG-powered engines are more efficient than diesel, emit less regulated pollutants, and may have long-term economic benefits. However, methane slip, high building costs, and poor infrastructure prevent its widespread adoption.

As a result, LNG is best suited as a compliance and transitional fuel, helping to decarbonize shipping in the short to medium term while setting the stage for future zero-carbon solutions.

Conclusion

This study used lifecycle emission analysis, economic modeling, and expert views to compare diesel versus LNG-powered marine engines. The results offer a multifaceted viewpoint on the economic, environmental, and technological ramifications of switching from traditional marine diesel fuels to LNG.

The following is a summary of the main conclusions:

1. Engine Capability:

LNG engines showed lower specific fuel consumption (165 g/kWh vs. 185 g/kWh) and greater thermal efficiency (46.5%) than diesel (43.5%). This demonstrates that LNG is more fuel-efficient under stable operating conditions due to its greater calorific value and combustion characteristics.

2. Profile of Emissions:

When compared to diesel, LNG reduced CO2 emissions from tank to wake by 22–25%.

For LNG, SOx and particulate matter emissions were minimal, allowing compliance with IMO 2020 sulfur limitations without the need for extra abatement devices.

Although NOx emissions from LNG engines were lower, they were still substantial and needed extra controls in emission control areas (ECAs).

According to lifecycle assessments, methane slip (≈14 g/kWh) might counteract up to 40% of LNG's climatic advantage in high-slip scenarios, making it the primary environmental negative.

3. Financial Sustainability

LNG engines have cheaper yearly fuel and maintenance expenses, but they demand a larger initial capital investment (€$11 million compared to $7 million for diesel). Diesel engines have a lower payback duration of three to five years, while LNG engines have payback periods ranging from six to nine years, depending on fuel price spreads and carbon tax scenarios.

4. Professional Perspectives:

The adoption of LNG enhances compliance and sustainability credentials, but its global application is hampered by issues including inadequate bunkering infrastructure and unclear methane regulations, according to a thematic study. For the most part, experts see LNG as a fuel to transition to long-term zero-carbon substitutes like ammonia and hydrogen.

In conclusion, methane slip, high capital costs, and infrastructural gaps limit the usefulness of LNG-powered engines, despite their obvious advantages in efficiency, regulatory emissions compliance, and potential long-term cost savings. As a result, LNG is ideally suited to serve as a bridging fuel in the maritime industry's transition to complete decarbonization.

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