

ISTANBUL TECHNICAL UNIVERSITY ★ GRADUATE SCHOOL

**ENVIRONMENTAL AND ECONOMIC ANALYSIS OF A CRUISE SHIP
USING LNG–MGO AS ALTERNATIVE FUELS**



M.Sc. THESIS

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Department of Maritime Transportation Engineering

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FEBRUARY 2026

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İSTANBUL TEKNİK ÜNİVERSİTESİ ★ LİSANSÜSTÜ EĞİTİM ENSTİTÜSÜ

**ALTERNATİF YAKIT OLARAK
LNG-MGO KULLANAN BİR KRUVAZİYER GEMİSİNİN
ÇEVRESEL VE EKONOMİK AÇIDAN İNCELENMESİ**

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Date of Submission : 29 December 2025

Date of Defense : 11 February 2026





To my family,



FOREWORD

I would like to express my sincere gratitude to my advisor, Dr. Burak ZİNCİR, whose insights, constructive criticism, and valuable recommendations greatly contributed to the completion of this thesis. I also extend my heartfelt thanks to my family for their unwavering moral support.

February 2026

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ABBREVIATIONS

ABS	: American Bureau of Shipping
CH₄	: Methane
CH₃OH	: Methanol
CII	: Carbon Intensity Indicator
CO	: Carbon Monoxide
CO₂	: Carbon Dioxide
DNV	: Det Norske Veritas
ECA	: Emission Control Area
ECAs	: Emission Control Areas
EEDI	: Energy Efficiency Design Index
EEXI	: Energy Efficiency Existing Ship Index
EGCS	: Exhaust Gas Cleaning System
EGR	: Exhaust Gas Recirculation
EU	: European Union
GHG	: Greenhouse Gas
H₂	: Hydrogen
HFO	: Heavy Fuel Oil
IMO	: International Maritime Organization
LNG	: Liquefied Natural Gas
LPG	: Liquefied Petroleum Gas
MDO	: Marine Diesel Oil
MGO	: Marine Gas Oil
NH₃	: Ammonia
NO_x	: Nitrogen Oxides
OCC	: Onboard Carbon Capture
PAHs	: Polycyclic Aromatic Hydrocarbons
PM	: Particulate Matter
SCR	: Selective Catalytic Reduction

SEEMP : Ship Energy Efficiency Management Plan

SO_x : Sulfur Oxides

VOCs : Volatile Organic Compounds

WHO : World Health Organization



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ENVIRONMENTAL AND ECONOMIC ANALYSIS OF A CRUISE SHIP USING LNG–MGO AS ALTERNATIVE FUELS

SUMMARY

As global rules to reduce greenhouse gas (GHG) emissions become stricter, the shipping industry, responsible for approximately 3% of global emissions, faces increasing regulatory pressure. The International Maritime Organization (IMO) aims to reduce CO₂ emissions by 40% by 2030 and achieve net-zero emissions by 2050, encouraging shipowners to consider alternative fuels such as LNG, hydrogen, ammonia, methanol, and biodiesel. Among these, LNG is currently the most widely used due to its technological maturity and lower SO_x, NO_x, and particulate emissions.

This study examines the operational, environmental, and economic performance of a cruise vessel with dual-fuel engines operating on LNG and MGO over a typical 7-day itinerary. The average weekly consumption amounts to 150 tons of MGO and 570 tons of LNG. While LNG usage on the engine can reduce CO₂ emissions by up to 27% and NO_x by 79% according to engine exhaust emission data, frequent shifts back to MGO significantly reduce overall benefits. A well-to-wake analysis shows that, including upstream emissions, LNG achieves only a 23.0% reduction in CO₂ emissions relative to MGO. When engine operating durations in MGO and LNG modes are included in the calculation, the CO₂ emission reduction decreases to 19.1%. The use of LNG reduces the CII index by 13.1%. Based on actual consumption data, CO_{2e} emission reduction of 1.0% observed with the usage of LNG as an alternative fuel. Methane slip issue in LNG use increases the GFI value, narrowing the gap between LNG and MGO.

To further improve LNG's decarbonization potential, additional mitigation pathways were explored. IMO emission measuring methods, including CII, GHG intensity, and GFI were calculated for this example vessel. Cost-benefit and SWOT analyses were conducted to assess LNG's effects on the vessel. Although LNG is an alternative fuel with a 20.1% advantage when consumption data and maintenance costs are included, it provides a 14.6% cost advantage. Operating the engines in LNG mode offers advantages in both fuel costs and carbon-emission reductions. Engines do not operate continuously in LNG mode. It was observed that the engines operate in MGO mode for 12.1% of the total operation time. Operational constraints and unexpected malfunctions lead to increased engine running hours in MGO mode.

Operation in MGO mode diminishes the effectiveness of emission reductions, increases fuel expenditures due to higher fuel prices, and results in elevated vessel emission indices and associated carbon tax liabilities. Consequently, the payback period of the LNG system investment has been extended by more than 12.1%. In conclusion, LNG represents a practical short-term transition fuel for meeting IMO decarbonization goals, but long-term compliance will likely require engines capable of using zero-carbon fuels or integration of onboard carbon capture systems.



ALTERNATİF YAKIT OLARAK LNG-MGO KULLANAN BİR KRUVAZİYER GEMİSİNİN ÇEVRESEL VE EKONOMİK AÇIDAN İNCELEMESİ

ÖZET

Yüzyılın ilk çeyreğinde, küresel nüfus artışı, sanayileşme ve değişen tüketim alışkanlıkları, enerji talebinde benzeri görülmemiş bir artışa neden olmuştur. Bu durum, fosil yakıtların yoğun kullanımını beraberinde getirerek atmosferdeki sera gazı konsantrasyonlarını kritik seviyelere taşımış ve küresel ısınma ile iklim değişikliğini dünyanın en önemli gündem maddesi haline getirmiştir. Küresel ticaretin omurgasını oluşturan ve dünya ticaret hacminin yaklaşık %90'ını taşıyan denizcilik sektörü, bu ekolojik krizde önemli bir paya sahiptir. Mevcut veriler ışığında, küresel insan kaynaklı sera gazı emisyonlarının yaklaşık %3'ü uluslararası denizcilik faaliyetlerinden kaynaklanmaktadır. Geleneksel gemi yakıtları olan HFO ve MGO kullanımı, sadece CO_2 değil, aynı zamanda asit yağmurlarına neden olan SO_x , solunum yolu hastalıklarını tetikleyen NO_x ve kanserojen etkiye sahip PM gibi zararlı kirleticilerin de atmosfere salınmasına yol açmaktadır. Bu çevresel tehditler karşısında, IMO ve Avrupa Birliği gibi düzenleyici otoriteler, denizcilik sektörünün karbonsuzlaşması için hedefler ve bağlayıcı regülasyonlar ortaya koymuştur. IMO'nun 2023 yılında revize ettiği Sera Gazı Stratejisi, 2008 yılı referans değerlerine kıyasla, gemi taşımacılığındaki karbon yoğunluğunun 2030 yılına kadar en az %40 oranında azaltılmasını ve 2050 yılı civarında net sıfır emisyona ulaşılmasını hedeflemektedir. Bu hedeflere ulaşmak amacıyla, EEDI, EEXI ve CII gibi mekanizmalar zorunlu hale getirilmiştir. Ayrıca Avrupa Birliği'nin FuelEU Maritime düzenlemesi ve Emisyon Ticaret Sistemi gibi bölgesel girişimler, fosil yakıt kullanımını finansal yaptırımlarla baskılayarak alternatif enerji kaynaklarına geçişi hızlandırmayı amaçlamaktadır. Denizcilik endüstrisi, geleneksel fosil yakıtların yerini alabilecek temiz enerji kaynaklarına yönelmiştir. LNG, metanol, amonyak, hidrojen ve biyoyakıtlar gibi alternatif yakıtlar, sektörün geleceği için potansiyel adaylar olarak değerlendirilmektedir. Bu seçenekler arasında LNG, teknolojik olgunluğu, küresel tedarik zincirinin varlığı ve düşük emisyon profili ile geçiş yakıtı olarak öne çıkmaktadır. Ancak LNG'nin fosil kökenli bir yakıt olması ve yanma sürecinde gerçekleşebilen metan kaçağı problemi, onun uzun vadeli sürdürülebilirliği konusunda soru işaretleri yaratmaktadır.

Bu tez çalışması, teorik tartışmaların ötesine geçerek, çift yakıtlı motorlara sahip modern bir kruvaziyer gemisinin gerçek operasyonel verilerini analiz etmekte; LNG ve MGO kullanımının çevresel, operasyonel ve ekonomik performansını karşılaştırmalı olarak inceleyerek literatüre kazandırmayı amaçlamaktadır. Bu çalışmada, vaka analizi yöntemi benimsenmiş ve Doğu ile Batı Karayipler rotasında düzenli seferler gerçekleştiren, 183.000 Gross Ton büyüklüğünde, 300 metre uzunluğunda ve 8 metre drafta sahip bir kruvaziyer gemisi incelenmiştir. Toplam 8.000 kişilik yolcu ve mürettebat taşıma kapasitesine sahip olan bu gemi, enerji

ihtiyacını karşılamak üzere dört adet 4 zamanlı, çift yakıtlı jeneratör ile donatılmıştır. Bu motorlar hem LNG hem de MGO ile çalışabilme esnekliğine sahiptir. Araştırma verileri, geminin gerçek operasyonel koşulları altında toplanmıştır. 7 Günlük 20 seferin verileri analiz edilmiştir. Bu veri seti; yakıt tüketim miktarlarını, motor yük profillerini, egzoz gazı emisyon ölçümlerini, motorların çalışma saatlerini, operasyonel arıza ve yakıt değişimine sebep olan güvenlik sebepli yakıt değişimi kayıtlarını kapsamaktadır. Çalışmanın metodolojisi üç ana eksen üzerine kurulmuştur. Operasyonel analiz kısmında motorların gaz modu ve dizel modu çalışma sürelerinin dağılımı incelenmiş, LNG sistemindeki teknik aksaklıkların, sensör arızalarının ve güvenlik prosedürlerinin yakıt tercihinin olan zorunlu etkileri nicel verilerle ortaya konmuştur. Çevresel etki analizi kısmında geminin emisyon performansı hem tanktan pervaneye hem de yakıtın üretim ve lojistiğini kapsayan kuyudan pervaneye yaklaşımları ile hesaplanmıştır. NO_x , SO_x , PM ve CO_2 emisyonlarındaki değişimler analiz edilmiş; geminin CII ve GFI indeks değerleri hesaplanarak uluslararası standartlara uyumu değerlendirilmiştir. Yakıt maliyetleri, sistemin bakım ve onarım giderleri, ilk yatırım maliyetleri ve işletme giderleri karşılaştırılmış; LNG yatırımının geri dönüş süresi üzerinde operasyonel faktörlerin etkisi hesaplanmıştır. Ayrıca, LNG kullanımının stratejik boyutunu değerlendirmek amacıyla güçlü ve zayıf yönleri ile fırsat ve tehditlerini içeren kapsamlı bir SWOT analizi yapılmıştır.

Analiz edilen geminin tipik bir 7 günlük seferinde, otel tüketimi ve itki sistemi dahil olmak üzere enerji ihtiyacını karşılamak için ortalama 150 ton MGO ve 570 ton LNG tüketildiği tespit edilmiştir. Teorik olarak geminin tamamen LNG ile çalışması hedeflense de gerçek operasyonel veriler motorların kesintisiz olarak gaz modunda çalışmadığını göstermektedir. Toplam 46.995 saatlik motor çalışma süresi incelendiğinde, motorların %12,1 oranında 5.717 saat MGO modunda çalıştığı belirlenmiştir. Bu zorunlu dizel kullanımının temel nedenleri arasında; entegre silindir basınç izleme sensörlerinin aşırı hassasiyeti, ani yük değişimlerinde veya sensör hatalarında motorun güvenlik protokolü gereği otomatik olarak dizel moduna geçmesi diğer bir ifade ile trip olmasıdır. LNG ikmalindeki lojistik kısıtlamalar ve bakım süreçleri yer almaktadır. Özellikle sefer başına jeneratörlerin ortalama 10 ila 16 kez "istemsiz yakıt geçişi" yaşadığı ve her bir geçiş sonrası gaz moduna güvenli dönüşün yaklaşık 45 dakika sürdüğü saptanmıştır. Bu operasyonel kesintiler, LNG'nin potansiyel çevresel ve ekonomik faydalarının pratikte tam olarak elde edilememesine neden olan en önemli faktördür.

Çevresel analiz sonuçları, teorik beklentiler ile operasyonel gerçeklik arasındaki farkı çarpıcı bir şekilde ortaya koymaktadır. Motor üreticisinin test verilerine göre, LNG modunda çalışıldığında MGO ya kıyasla NO_x emisyonlarında %79, karbondioksit emisyonlarında ise %27'e varan azalmalar mümkündür. Ayrıca, LNG'nin kükürt içermemesi nedeniyle SO_x ve partikül madde emisyonları %90 oranında elimine edilmektedir. Ancak, geminin %12,1 oranındaki dizel kullanımı ve yakıtın tüm yaşam döngüsü hesaba katıldığında bu kazanımlar azalmaktadır. NO_x Emisyonları: Teorik olarak %79 olan NO_x azaltım oranı, motorların dizel modunda çalıştığı süreler denkleme eklendiğinde gerçek hayatta %69 seviyesine gerilemektedir. CO_2 Emisyonları incelemesinde sadece gemi üzerinden tanktan pervaneye referans değerleri dikkate alındığında, haftalık yakıt tüketim profiline göre %23,0 oranında bir CO_2 azaltımı hesaplanmıştır. Ancak, yakıtın çıkarılması, işlenmesi, sıvılaştırılması ve nakliyesini kapsayan kuyudan pervaneye analizi de yapıldığında, LNG tedarik zincirindeki enerji yoğun süreçler ve taşıma nedeniyle bu oran %19,1'e düşmektedir.

LNG alternatif yakıt kullanımıyla teorik olarak CO_{2e} emisyonlarında %1,2 azalma beklenmektedir. Ancak motorların güvenlik sebebiyle MGO moduna geçmesinden dolayı tüketilen MGO da hesaba dahil edildiğinde, CO_{2e} emisyonlarındaki düşüşün %1,0 olduğu bulunmuştur. LNG kullanımı sayesinde geminin CII skoru 5,57 olarak hesaplanmış ve IMO derecelendirme sisteminde A derecesi elde edilmiştir. Eğer gemi sadece MGO kullansaydı bu değer 7,26 olacak, ancak yine de A derecesinde kalacaktı. GFI değeri ise LNG kullanımıyla %11,8 oranında iyileştirilmiştir. Bu veriler, LNG'nin CO_2 emisyonlarını azaltmada etkili olduğunu, ancak metan kaçağı ve operasyonel kesintilerin CO_{2e} emisyonlarındaki etkiyi sınırladığını gözlemlenmiştir. Gemide bulunan 4 jeneratörün metan slip oranı motor üreticisi tarafından %2 olarak belirtilmiştir.

Ekonomik analiz kısmında, LNG'nin yakıt maliyetleri açısından sağladığı avantajı ve buna karşılık artan işletme giderlerini ortaya koymaktadır. LNG'nin birim enerji başına maliyeti, MGO'ya kıyasla %20,1 daha düşüktür. İncelenen geminin haftalık yakıt maliyeti, çift yakıtlı sistemle 541.761 dolar iken, sadece MGO kullanılması durumunda bu rakamın 647.952 dolar'a çıkacağı hesaplanmıştır. Bu fiyat farkı, gemi işletmesine yıllık bazda 5,51 milyon dolarlık bir teorik yakıt tasarrufu sağlayabilirken gerçek yakıt tüketimlerine göre %16,4 yakıt tasarrufu sağladığı görülmüştür. Ancak bu tasarruf, yüksek ilk yatırım maliyetleri ve artan bakım giderleri ile azaldığı gözlemlenmiştir. Yakıt avantajından fazlalık bakım giderleri çıkarıldığında, LNG kullanımı haftalık 14.6% maliyet düşürdüğü bulunmuştur. Çift yakıtlı motorların ve LNG sistemlerinin kurulum maliyeti, konvansiyonel sistemlere göre daha yüksektir. Daha da önemlisi, çift yakıtlı motorların bakım maliyetleri, tek yakıtlı dizel motorlara göre %38,5 daha fazladır. Bunun nedenleri arasında; gaz modunda çalışan motorlarda silindir gömleklerinde görülen aşınmalar, hassas sensörlerin sık arızalanması örneğin tek yakıtlı motorda 400 sensör varken çift yakıtlıda yaklaşık 800 sensör bulunması ve bu sensörlerin hassas olmasıdır. Yapılan maliyet-fayda analizi sonucunda, yakıt tasarrufu ile sağlanan gelirin bir kısmının artan bakım maliyetlerine harcandığı görülmüştür. Ayrıca, motorların sürekli gaz modunda çalışmaması nedeniyle beklenen yakıt tasarrufunun tam olarak gerçekleşmemesi, LNG sistemine yapılan yatırımın geri dönüş süresinin öngörülenden %12,1 daha uzun sürmesine neden olmaktadır. Yine de LNG kullanan gemilerin uzun vadede finansal olarak daha avantajlı konumda olacağı öngörülmektedir. Ayrıca, LNG'nin bir geçiş yakıtı olarak güçlü ve zayıf yönlerini değerlendirmek amacıyla SWOT analizi uygulanmıştır.

Bu çalışma, LNG'nin denizcilik sektörünün karbonsuzlaşma sürecinde önemli bir geçiş yakıtı olduğunu doğrulamaktadır. LNG, SO_x ve PM emisyonlarını neredeyse tamamen ortadan kaldırması ve mevcut altyapı uygunluğu ile kısa ve orta vadede 2030 hedefleri için en uygun çözümdür. Ancak, IMO'nun 2050 yılındaki net sıfır hedefine ulaşmak için LNG tek başına yeterli değildir. Metan kaçağı sorunu ve fosil kökenli olması, uzun vadeli sürdürülebilirliğini sınırlamaktadır. Geleceğe yönelik projeksiyonlarda, mevcut LNG altyapısının bio-LNG veya sentetik LNG gibi karbon nötr yakıtlarla kullanılması gerektiği sonucuna varılmıştır. Bu yakıtlar, gemide herhangi bir teknik değişiklik gerektirmeden mevcut tank ve motor sistemlerinde kullanılabilir. Ayrıca, LNG tanklarının ve yakıt sistemlerinin, ileride amonyak veya metanol gibi sıfır karbonlu yakıtlarla uyumlu hale getirilmesi gemi sahipleri için stratejik bir yatırım olacaktır. Sonuç olarak, LNG operasyonel zorluklara ve maliyetlere rağmen, çevresel regülasyonlara uyum sağlamada şu an için vazgeçilmez bir köprü vazifesi görmektedir.



1. INTRODUCTION

Over the last 20 years, as industrialization and production activities have increased to meet the growing global population and rising consumption, greenhouse gas emissions have rapidly increased. The world agenda now frequently discusses global warming and glacier melting due to this increase (Faber et al., 2020). Greenhouse gases trap heat in the atmosphere, warming the planet. Exhaust emissions not only contribute to greenhouse gas emissions but also to air pollution. Air pollution adversely affects human health. The main greenhouse gases include carbon dioxide, methane, nitrous oxide, water vapor, and fluorinated gases. Carbon dioxide is among the gases produced through combustion. Recent international regulations have begun to control and limit greenhouse gas emissions (IMO, 2018).

Greenhouse gas emissions from shipping account for approximately 3% of global greenhouse gas emissions. Additionally, engines burning fossil fuels emit air pollutants such as sulfur oxides (SO_x), nitrogen oxides (NO_x), volatile organic compounds, and particulate matter (Bach & Hansen, 2023). Maritime transportation is carried out by ships, and efforts to reduce ship emissions include the search for alternative fuels and the development of compatible power-generating machinery (Hansson et al., 2019).

Unlike cargo ships engaged in commercial voyages, passenger cruise ships are subject to the same international regulations. Ships above a certain tonnage must comply with IMO rules. According to IMO reports, annual fossil fuel consumption in maritime transport is approximately 250–325 million tons, corresponding to 2.89% of global CO_2 emissions (Ye et al., 2022). The IMO strategy aims to reduce carbon dioxide emissions per transport effort by at least 40% by 2030 and 70% by 2050 compared to 2008 levels, and to reach net-zero annual greenhouse gas emissions by 2050 (IMO, 2020).

IMO has developed a roadmap for greenhouse gas (GHG) reduction in maritime transport (Andersson, 2015). Mandatory limits have been introduced for the Energy Efficiency Design Index (EEDI), the Energy Efficiency Existing Ship Index (EEXI),

and the Carbon Intensity Indicator (CII) to reduce CO₂ emissions during both design and operation (IMO, 2011). The European Union has adopted a common GHG reduction strategy for the shipping sector (European Commission, 2022). To fit with more stringent rules, many ways have been proposed, particularly the use of alternative fuels. Engine manufacturers have begun producing engines capable of operating on alternative, environmentally friendly fuels like methanol (CH₃OH), hydrogen (H₂), ammonia (NH₃), and liquefied natural gas (CH₄) (DNV-GL, 2019). The availability of alternative marine fuels is decided not only by their exhaust emissions reduction potential but also a complex interaction of technical, economical, and operational factors that influence their suitability for short, medium, and long-term use in global shipping (Balcombe et al., 2019; Gilbert et al., 2018). Fuel selection requires a complex assessment including energy density, storage conditions, safety performance, infrastructure readiness, technological engagement, and life-cycle emissions.

Hydrocarbon-based transitional fuels such as LNG currently offer technologically ready and operationally easy ways to reduce carbon intensity in the short-term period. LNG provides really low SO_x and particulate emissions and benefits from a well-developed bunker network, and its climate advantage is somewhat offset by methane slip problem, which crucial influence life-cycle carbon performance (Päivärinne & Eskeland, 2020). LNG includes high energy density and also obtained by cooling natural gas to approximately -162 °C, making it a lower-emission alternative to conventional marine fuels such as heavy fuel oil (Päivärinne & Eskeland, 2020). Its clean combustion characteristics, LNG clearly minimizes SO_x and PM emissions. Also significantly reducing NO_x, fit with IMO Tier III standards (International Maritime Organization [IMO], 2020). Conversely, conventional marine fuels, LNG must be stored in liquid form in cryogenic conditions. LNG fuel systems onboard require special components such as insulated storage tanks, pressure control systems, and safety relief valves to be sure operational integrity and safety (IMO, 2024). A cruise vessel operates 7-day voyages in the Eastern and Western Caribbean, which were taken as examples to make case studies. Data from a Cruise vessel powered by dual-fuel engines and using LNG as an alternative fuel were collected and analyzed. The reduction in exhaust gas emissions during LNG usage as an alternative fuel has been examined. Based on real data, a cost-benefit analysis was conducted to see the cost of the emission reduction. The use of LNG as alternative fuel on cruise vessel examined

in comparison to other alternative fuels, evaluating LNG strengths, weaknesses, threats and opportunities. In this way SWOT analysis was conducted.





2. SHIPBOARD EMISSIONS FROM THE COMBUSTION OF CONVENTIONAL MARINE FUELS

In maritime transportation, conventional fuels, particularly HFO and MGO, contain elevated levels of sulfur, nitrogen, and small metals, which contribute to the formation of numerous harmful gases and particulate matter during combustion. These exhaust emissions are mainly categorized into airborne pollutants such as SO_x, NO_x, and PM, and greenhouse gases; CO₂, CH₄, and N₂O (IMO, 2020).

The conventional fuel burned in the engine and used aboard ships emits CO₂ as a result of the oxidation of carbon in the fuel. Also, high combustion temperatures cause the reaction between atmospheric nitrogen and oxygen, producing NO_x which contributes to ozone layer depletion and the formation of photochemical smog (Det Norske Veritas, 2024).

When burned, high-sulfur fuels emit SO₂ and SO₃. These exhaust gases react with atmospheric water vapor, converting to sulfuric acid aerosols that are a primary lead to acid rain (American Bureau of Shipping, 2023). This process is very harmful in port close to cities with excessive maritime traffic. Also, it accelerates ocean acidification and causes biodiversity loss in marine ecosystems in the oceans. (Balcombe et al., 2019).

Incomplete combustion releases various toxic pollutants, including CO, volatile organic compounds (VOCs), polycyclic aromatic hydrocarbons, and heavy metals. As an example, nickel, vanadium, and iron. These substances have harmful effects on human respiratory health and increase the risk of cardiovascular and pulmonary diseases in time (World Health Organization, 2022).

In conclusion, emissions emitted from the burning of conventional marine fuels not only contribute to global warming but also cause severe risks to air quality, public health, animal life and marine environments. This environmental and air threat is one of the main reasons behind the IMO's post-2020 implementation of the global sulfur cap (0.5% m/m) and its long-term GHG reduction strategies (IMO, 2020). International maritime shipping serves as the carrier of global logistics, simplifying

nearly 90% of the world's trade volume (International Chamber of Shipping, n.d.). Also, this economic advantage comes with a high environmental cost. The combustion of conventional marine fuels, particularly HFO and VLSFO, releases significant amounts of greenhouse gases (GHG) and harmful pollutants (IMO, 2020). According to data from the Fourth IMO Greenhouse Gas Study (2020), the maritime shipping sector caused approximately 1.076 billion metric tons of CO₂-equivalent in 2018, which accounted for 2.9% of global GHG emissions. This figure is projected to increase further by 2050 due to anticipated growth in global trade volumes (IMO, 2020).

According to the IMO Greenhouse Gas Study 2022, the proportional distribution network of maritime shipping caused emissions is as follows: CO₂ accounts for approximately 76%, NO_x for 15%, SO_x for 7%, particulate matter and carbon monoxide combined for 2% of total emissions (IMO, 2020). Also, PM and CO quantities a really small quantity of overall emissions, their localized effects on air and human health. they are particularly intense in port cities or near-port cities. It is a disproportionately high amount.

These emissions can cause to global atmospheric warming and, also cause direct threats to marine and coastal ecosystems. Pollutants such as SO_x, NO_x, and PM degrade air quality, increase ocean acidification, and also increase the risk of respiratory illnesses in humans' health (Intergovernmental Panel on Climate Change [IPCC], 2023). As a result, climate change strategies start to target the reduce maritime emissions.

Under Annex VI of the MARPOL Convention, the IMO introduced stricter emission limits that took effect in 2020. The global sulfur content cap for marine fuels was reduced from 3.5% to 0.5% m/m, and more stringent Tier III NO_x standards were implemented in 2020 (IMO, 2020).

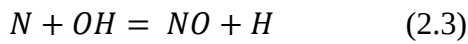
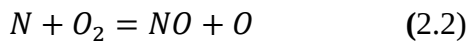
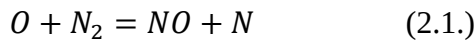
2.1 Carbon Dioxide (CO₂)

Carbon dioxide emissions from fossil fuels are the direct consequence of carbon oxidation during fuel combustion, so they scale fundamentally with fuel carbon content, engine efficiency, and operating conditions. In conventional diesel combustion, hydrocarbon fuels undergo high-temperature oxidation, in which carbon

atoms are progressively converted to CO₂. Via intermediate species such as CO, formaldehyde, and other partially oxidized content, at sufficiently high temperatures and adequate oxygen availability, the dominant end product is CO₂ (Turns, 2012). CO₂ constitutes the largest share of GHG emissions in the maritime shipping sector. The combustion of 1 metric ton of HFO causes approximately 3.114 tons of CO₂. CO₂ causes significantly to rising ocean temperatures and subsequent ocean acidification when released into the atmosphere as the primary driver of global warming. These changes negatively affect ocean ecosystems, particularly the life cycles of organisms such as plankton, corals, and shell-forming species, all of which are sensitive to variations in seawater chemistry (Balcombe et al., 2019).

2.2 Nitrogen Oxides (NO_x)

Nitrogen oxides primarily NO and NO₂ are produced during high-temperature combustion of fuels, particularly in two-stroke diesel engines that dominate marine propulsion systems. These emissions significantly contribute to tropospheric ozone formation, which is associated with respiratory illnesses such as asthma and cardiovascular complications (WHO, 2022). In engines, exhaust NO_x arises primarily from high-temperature oxidation of atmospheric nitrogen during the main heat-release period and the early expansion, when peak burned-gas temperatures and radical pools are highest. (Tadros & Boulougouris, 2025) Under typical diesel combustion conditions, the controlling pathway is “thermal NO,” commonly represented by the Zeldovich mechanism, in which NO is produced via the elementary reactions (Tadros & Boulougouris, 2025);



Dissociation of N₂ by O atoms, is rate limiting because of the high activation energy associated with breaking the N to N bond, making thermal NO formation strongly temperature dependent and highly sensitive to the residence time of gases in zones exceeding roughly 2000 K. (Tadros & Boulougouris, 2025) To control NO_x emissions, the IMO introduced a three-tier regulatory framework under Annex VI of MARPOL, targeting progressive reductions in NO_x output (IMO, 2020; ABS, 2023).

Table 2.1 : IMO NO_x Emission Tier Standards and Expected Reduction Levels

Implementation Period	Scope	Expected NO _x Reduction
Tier I (2000–2010)	All ships	Baseline level
Tier II (2011–2015)	New engines	~20–25% reduction
Tier III (2016–present)	ECA Areas	~80% reduction

(IMO, 2020; ABS, 2023)

2.3 Sulfur Oxides (SO_x)

Sulfur oxides are primarily generated during the combustion of marine fuels inside the combustion chamber. It appears with sulfur content from fuels. Sulfur with oxygen comes together and create sulfur oxides. The combustion of one ton of high-sulfur fuel typically produces about 50 to 60 kilograms of SO₂ (DNV, 2024). Once released into the atmosphere, SO₂ reacts with water vapor and change form and become sulfuric acid (H₂SO₄). A major contributor to acid rain, which poses risks to both terrestrial and marine ecosystems. Acid very harmful for eco plant.

With the introduction of the IMO 2020 regulation, which lowered the allowable sulfur content in marine fuels to 0.5% by mass. This helps to reduce sulfur oxide emissions and reduce acid rains. Global SO_x emissions are estimated to have declined by approximately 8.5 million tons annually (IMO, 2020). These emissions, comes from sulfur present in ship fuels. These fuels are associated with well-documented adverse effects. It is including ocean acidification, biodiversity loss in aquatic systems, and negative human health outcomes such as respiratory disorders (World Health Organization [WHO], 2022). The IMO progressively tightened sulfur limits to mitigate the environmental and public health impacts of shipping-related SO_x emissions to response to these concerns.

Table 2.2 : Timeline of Global and ECA Sulfur Content Limits

Year	Global Sulfur Limit (m/m)	ECA Sulfur Limit (m/m)	Regulation
2005	4.50%	1.50%	Initial entry into force of MARPOL Annex VI
2012	3.50%	1.00%	MEPC 176(58) amendment
2015	—	0.10%	North European and North American ECAs
2020	0.50%	0.10%	IMO 2020 Global Sulfur Cap

(IMO, 2020; DNV, 2024)

2.4 Carbon Monoxide (CO)

Carbon monoxide emissions from marine fuel come from the carbon content of the fuel. It arises primarily from the incomplete oxidation of fuel carbon to CO₂. It serves as a sensitive indicator of locally fuel-rich combustion and insufficient oxygen availability. It is sensitive to an inadequate time-temperature history for completing CO burnout. (Turns, 2012; Schnapp et al., 2021) CO is formed in rich flame zones and in partially premixed regions in diffusion-controlled diesel combustion. Low local equivalence ratio stratification, spray-wall interaction and limited mixing suppress radical pools that drive the key conversion step. (Turns, 2012; Schnapp et al., 2021) Marine engines can increase carbon monoxide production because large-bore cylinders, strong spatial inhomogeneity, and transient turbocharging conditions produce pockets with reduced oxygen and lower effective residence time. Also, during maneuvering and low-load operation, pocket production and reduced oxygen production increase (Moldanová et al., 2009; Ma et al., 2021). CO is a toxic gas produced by the incomplete combustion of marine fuels during normal operation. If a person's exposure to CO is long-term, CO can lead to negative effects. It is harmful for oxygen transport in the bloodstream and causes neurological damage (IMO, 2020).

2.5 Particulate Matter (PM)

PM emissions come from fuels. They are a complex mixture of carbonaceous material. They include elemental carbon, organic carbon, and inorganic constituents such as sulfate and fuel or lubricant-derived ash, and their chemical composition. It is integrated with fuel quality and engine operating mode (Di Natale et al., 2015; Moldanová et al., 2009). Engine operating parameters, for example, engine load, injection timing, fuel and air mixing rates, and scavenging or boost conditions, affect PM production. Need to keep a balance between soot formation and oxidation. It leads to substantial variability in PM emission factors and particle size distributions under real ship operating conditions (Karjalainen et al., 2022; Di Natale et al., 2015). PM is a major component of soot and black smoke emitted from ship exhaust systems. These ultra-small particles can penetrate deep into the lungs and are associated with severe health risks. Risks include lung cancer, cardiovascular diseases, and premature mortality (WHO, 2022).

2.6 Atmospheric and Climatic Effects of Maritime Emissions

Emissions which come from maritime shipping, particularly CO₂ and NO_x, contribute to the formation of tropospheric ozone. it causes regional atmospheric warming. According to the International Maritime Organization (IMO, 2022) maritime shipping sector is responsible for 3.1% of global warming effect. Also sulfur oxides (SO_x) and particulate matter (PM) disrupt the Earth's radiative balance, influence cloud formation dynamics, and leads to atmospheric stability corruptions (IPCC, 2023).

2.7 Impacts on Marine Ecosystems and Human Health

Exhaust gases emitted from ships decrease air quality and also affect marine environments and systems. Dissolved atmospheric SO₂ and NO_x into ocean waters, increasing acidification levels. This process increases of coral bleaching and weakens the calcium carbonate structures of various marine organisms. Also threatening biodiversity and disrupting marine ecosystems (Ocean Conservancy, 2023).

Air pollution from maritime transport causes approximately 60,000 premature deaths annually across Europe, according to the European Environment Agency (EEA, 2023). It doesn't cause direct deaths; it's just linked. Populations living in coastal and port

cities are particularly vulnerable due to elevated levels of fine particulate matter. Published that SO₂ and NO_x emissions from shipping contribute to exceeding limits of urban air quality standards by 15% to 30% in many cities. Standards are trying to keep the world safe, but conventional fuels create risk for future populations (WHO, 2022). Data from the EEA report in 2023 mentions the health consequences. According to the report, 42% of respiratory diseases, and 33% cardiovascular conditions, and 25% of premature mortality are caused by shipping-related emissions in Europe.

As results underscore that maritime transport represents not only an economic sector but also a significant environmental and public health challenge and, also reducing ship exhausts emissions is a main priority for both ecological sustainability and human well-being.





3. EMISSION RULES AND REGULATIONS

Reducing carbon emissions since the early 2010s has become a central focus in the maritime sector. The International Maritime Organization (IMO) adopted its initial strategy on the reduction of GHG emissions from Ships in 2018 and also outlining the following goals relative to 2008 levels (IMO, 2020):

- 40% reduction in carbon intensity by 2030
- 50% reduction in total GHG emissions by 2050
- In 2023, the IMO revised its strategy and introduced more ambitious targets (IMO, 2023):
 - At least 20% reduction in total GHG emissions by 2030 (preferably 30%)
 - At least 70% reduction by 2040 (preferably 80%)
 - Achieving net-zero GHG emissions in international shipping by around 2050

Additionally, the updated strategy aims to have at least 5% of onboard energy consumption come from near-zero- or zero-carbon fuels by 2030. This initiative has accelerated the adoption of alternative fuels, such as methanol, ammonia, and hydrogen, in the maritime industry (DNV, 2024; IEA, 2024).

IMO implemented some indices to observe and rate the vessels. EEDI, SEEMP, CII, and the newest one, GFI, are examples of these observations. Each of them has a different target and application area. In this study, each of these indices was clarified.

3.1 Energy Efficiency Design Index (EEDI)

EEDI is a mandatory performance indicator that assesses the energy efficiency of ship designs. Introduced by the IMO in 2013 under MARPOL Annex VI, Regulation 21, the regulation requires that all newly built ships comply with a specific CO₂ emission standard (IMO, 2014). The primary objective of the EEDI is to enhance energy efficiency during the ship design phase and also ensuring a gradual reduction in the average emission intensity of newly constructed vessels. According to IMO targets, by

2025, CO₂ emissions from new ships are expected to be reduced by 30% to 50% compared to the 2008 baseline levels (IMO, 2023; DNV, 2024).

3.1.1 Scope and applicability

The Energy Efficiency Design Index is mandatory for all newly constructed ships engaged in international voyages with a GT above 400.

It applies to the following ship types:

- Bulk carriers
- Tankers (crude oil, chemical, LPG, LNG)
- Container ships
- General cargo ships
- Passenger and Ro-Ro vessels (IMO, 2014)

IMO has published specific reference lines for each ship type and it define the relationship between the vessel's capacity, measured in DWT, GT, or TEU, and the reference CO₂ emissions allowed. These parameters are used to evaluate whether a ship design meets the required efficiency standards based on its size and function.

3.1.2 Calculation method

The Energy Efficiency Design Index quantifies the theoretical CO₂ emissions of a ship during its design phase. EEDI calculated based on parameters such as engine power, fuel type, and specific fuel consumption. The general formula is:

$$EEDI = \frac{\sum(P_{ME} \times CF_{ME} \times SFC_{ME}) + (\sum(P_{AE} \times CF_{AE} \times SFC_{AE})) - P_{PTI}}{\text{Capacity} \times V_{ref}} \times (1 - F_{efficiency}) \quad (3.2)$$

Energy Efficiency Design Index Formula (IMO Guidelines)

- *P_{ME}*: Rated power of the main engine(s) (kW)
- *P_{AE}*: Rated power of the auxiliary engine(s) (kW)
- *CF*: Fuel-specific CO₂ conversion factor (gCO₂/g fuel)
- *SFC*: Specific Fuel Consumption of the engine (g/kWh)
- *P_{PTI}*: Shaft motor power (if any, e.g. for hybrid propulsion)

- **Capacity:** Deadweight tonnage (DWT) or gross tonnage (GT), depending on ship type
- **V_{ref} :** Reference speed of the vessel (knots)
- **$f_{efficiency}$:** Correction factor for energy-saving technologies or operational enhancements

EEDI formula shows the design efficiency of a vessel and enables regulatory boundaries to compare emissions performance across different ship types and sizes under standardized conditions. (IMO, 2018; DNV, 2023)

This formula represents the amount of CO₂ emitted per unit of transport work performed by the ship. The lower the EEDI value shows that the vessel is more energy-efficient.

3.1.3 EEDI phases

The International Maritime Organization has implemented the EEDI in progressively stricter phases, known as “Phases” of compliance:

Table 3.1 : Energy Efficiency Design Index Phases and Emission Reduction Targets

Phase	Implementation Year	Emission Reduction Target (compared to 2008 baseline)
Phase 0	2013–2014	Baseline (no reduction)
Phase 1	2015–2019	10% reduction
Phase 2	2020–2024	20% reduction
Phase 3	2025 onward	30–50% reduction (depending on ship type)

(IMO,2023)

For instance, under Phase 3, container vessels are required to achieve up to a 50% reduction in carbon emissions relative to 2008 levels.

It has encouraged shipbuilders to develop smaller engines, optimized hull designs, and low-friction coating systems. Engines powered by alternative fuels such as LNG, methanol, and ammonia tend to achieve lower EEDI scores due to their reduced carbon conversion factors (DNV, 2024). EEDI has also been used in ship financing decisions by financial institutions and has become one of the criteria for “green ship

certification” (World Bank, 2023). The most significant criticism of EEDI is that it applies only to newly built ships; the energy efficiency of existing vessels is monitored through indicators such as EEXI or CII and also EEDI focuses on design speed. It not reflects actual operational conditions. IMO has placed the draft plan for EEDI Phase 4 on the agenda for the post-2027 period and agenda is mentioned increasing the reduction target to 60% (IMO, 2024).

3.2 SEEMP (Ship Energy Efficiency Management Plan)

The Ship Energy Efficiency Management Plan (SEEMP) is a plan that must be developed for every ship to improve energy efficiency at the operational level and its mandatory. This plan introduced as a requirement in 2013 also SEEMP has since evolved through the introduction of Part II and Part III extensions (IMO, 2023).

The SEEMP serves several key purposes:

- Reducing fuel consumption,
- Planning optimal routes and speeds,
- Establishing annual operational strategies to meet CII targets,
- Ensuring continuous emission reduction (IMO, 2024; ABS, 2023).

Under post-2023 regulations, ships that receive a CII rating of "D" for three consecutive years or "E" in any single year are required to submit a formal improvement plan within their SEEMP. Which technical operational measures and precautions will be implemented to lower the ship's CII rating must be written (IMO, 2023).

A standard SEEMP document generally includes the following elements targeting that at enhancing operational energy performance:

- Speed management strategies, such as slow steaming,
- Ballast water optimization,
- Scheduled maintenance programs for hull and propeller efficiency,
- Route planning algorithms that incorporate weather forecasting,
- Scenarios for alternative fuel usage,

- Energy-saving technologies, including air lubrication systems and waste heat recovery units (DNV, 2024).

SEEMP serves as a structured operational management tool that institutionalizes how a vessel's CII rating can be improved in practice with these strategies.

3.3 Carbon Intensity Indicator (CII)

IMO developed a metric, and it's called CII. It is used to assess a ship's annual operational carbon intensity by calculating as the ratio of CO₂ emissions to transport work. The primary objective of CII is to enhance energy efficiency in shipping operations and to achieve a 40% reduction in carbon intensity per vessel by 2030, compared to 2008 levels (IMO, 2023). Conversely design-based indices, the CII reflects the ship's actual in-service performance by incorporating real operational data such as fuel consumption, cargo carried, distance traveled, and CO₂ emissions. CII is fundamentally different from the EEDI because it is not based on theoretical design parameters like EEDI. CII offers a more accurate representation of a vessel's environmental footprint during real sailing condition (DNV, 2024).

$$CII = \frac{\text{Annual CO}_2 \text{ emissions}(g)}{\text{Gross Tonnage} \times \text{Annual distance traveled}(nlm)} \quad (3.1)$$

The CII value is calculated based on a vessel's actual operations for an entire of a calendar year and must be documented through verified annual CO₂ emission reports. It must be submitted to the IMO Data Collection System. The ship's CII is compared to a reference line published by the IMO when completed. Also, the vessel is rated on a five-tier scale from A to E based on its performance relative to the benchmark. If a ship is rated D for three consecutive years or E in any single year, it is required to submit a CII correction or improvement plan to reach better rates (IMO, 2023). CII calculations are become mandatory for all ships above 5,000 GT engaged in international voyages as of 2023. The reporting procedure follows these key steps:

- Measurement is conducted at the end of each calendar year.
- The data must be verified and submitted through the IMO Data Collection System (DCS).
- Each vessel has an annual CII score and performance rating from A to E.

CII is a framework that serves as an effective tool for monitoring carbon intensity. It is subject to several criticisms. It does not reflect real-time operational conditions. For example, weather patterns, routing constraints, or cargo loading variability. Ships can improve their CII rating by using slow-steaming strategies. This approach can reduce commercial efficiency on certain trade routes if the vessel speed was high before. The IMO has announced plans to revise the methodology after 2026 under the “CII Phase 2”. It is aiming to improve accuracy and fairness in performance assessment (IMO, 2024).

3.3.1 Relationship with carbon taxation

CII is not only a performance indicator but is also being used as a key parameter in carbon taxation systems. Under the FuelEU Maritime Regulation, introduced in 2025 by the European Union, CII data are used to calculate the carbon cost. CII index calculated according to the vessel’s CO₂ emission intensity (European Commission, 2024).

3.4 Use of Terms EXI / EEXI

EXI used a general reference to the energy efficiency index for existing ships in both academic literature and classification society guidelines. In practice, this refers to the EEXI as defined by the IMO (ABS, 2023; DNV, 2024). Also, when referring to a ship's “EXI compliance,” it means whether the vessel meets the EEXI targets. EEXI for new ships, EXI for existing ships. This is the main difference.

This classification helps clarify the distinctions between key efficiency indicators:

- EEDI → Design efficiency of newly built ships
- EEXI (EXI) → Technical efficiency of existing ships
- CII → Operational carbon efficiency of ships
- SEEMP → Action plan for managing and improving that efficiency

Thus, EEDI, EEXI, and CII are not just metrics for performance evaluation, but also integral components of a broader energy efficiency management cycle (IMO, 2024).

Table 3.2 : Differences Between EEXI, EEDI and CII

Feature	EEDI	EEXI	CII
Scope of Application	Newbuild ships	Existing ships	All international operating ships
Calculation basis	Design parameters	Design data (post-retrofit)	Actual operation data
Evaluated Criterion	Design efficiency	Existing ship energy efficiency	Operational carbon intensity
Mandatory Since	2013	2023	2023
Update Frequency	At time of delivery	At certificate renewal	Annually

In this context, EEXI functions as a “transitional bridge”, enabling older vessels to align more closely with EEDI standards and establishing a foundation for operational metrics like CII (ABS, 2023).

3.5 GHG Fuel Intensity (GFI)

GFI is a metric intended to regulate the decarbonization of ship energy use on a lifecycle basis. GFI expresses WTW greenhouse gas emissions per unit of energy used on board. Its formula is gCO_{2e}/MJ. CO₂-equivalents aggregate CO₂, CH₄, and N₂O using specified global warming potentials and system boundaries (IMO, 2024; Kramel et al., 2021). IMO net zero framework attained annual GFI is computed as an energy-weighted average. All energy carriers consumed during the reporting year are included. The formula is:

$$GFI \left(\frac{gCO_{2e}}{MJ} \right) = \frac{Total\ WTW\ GHG(gCO_{2e})}{total\ energy\ used\ on\ board\ (MJ)} \quad (3.5)$$

$GHG_{WTW/j}$ is the WTW emission factor of energy carrier and is shown gCO_{2e}/MJ (IMO, 2024). The regulatory purpose is to create a technology-neutral performance standard that minimizes fuel switching and energy substitution toward low-GHG fuels. While internalizing upstream emissions that can materially change apparent climate performance. It is not captured by tank-to-wake accounting alone (Ha et al., 2023;

Sagot et al., 2025). Literature reviewed and work support this lifecycle framing by showing that upstream production. Transport and conversion stages can dominate WTW intensity for certain fuels, and that pathway assumptions can significantly shift gCO_{2e}/MJ rankings relevant to intensity standards (Kramel et al., 2021; Wang et al., 2025). GFI functions can be affected by operational conditions. Currency of the policy links ship-level energy consumption to verified lifecycle emission factors. Each fuel has a different GHG intensity. GFI calculation enables comparable compliance accounting across different fuels and highlights where improved measurement is pivotal for credible WTW intensities. (IMO, 2025; Sagot et al., 2025).

3.6 FuelEU Maritime Regulation

The FuelEU Maritime Regulation is a regulation which is aiming to bring legislative framework. It is adopted by the European Union in 2023 and scheduled to enter into force in 2025.

Its primary goal is to decarbonize maritime transport by progressively reducing the carbon intensity of fuels used by vessels arriving at, departing from, or operating within EU ports between 2025 and 2050. It is aiming to create pathway the sector toward net-zero emissions (European Commission, 2024). It is not like the IMO's technical indicators, such as CII or EEDI. FuelEU Maritime introduces a regulatory and economic mechanism. It not only evaluates ship performance also it directly links the CO₂ emissions and carbon footprint of marine fuels. It is legal and financial obligations.

The FuelEU Maritime Regulation applies to all vessels that meet the following criteria:

- Gross Tonnage (GT) of 5,000 or more,
- Calling at, departing from, or sailing within EU ports,
- Regardless of their flag state, including non-EU flagged ships, the regulation is globally impactful.

In addition, the regulation is based on the WTW emissions principle, meaning that it considers the entire life cycle of the fuel, from production (e.g., refining or electrolysis) to final combustion onboard (DNV, 2024).

3.6.1 Fuel carbon intensity limits

The EU has set limits on the average GHG intensity of marine fuels, measured in grams of CO₂-equivalent per megajoule (gCO₂e/MJ) of energy content.

The table in the original text outlines the stepwise reduction targets for fuel carbon intensity from 2025 to 2050, as part of the EU's broader climate goals (European Commission, 2024).

These targets aim to achieve an 80% reduction in the greenhouse gas intensity of marine fuels used within EU boundaries by 2050, compared to the 2020 baseline. These string rules are designed to speed up the transition to low-carbon fuels and renewable fuels in the maritime sector. Also, to reinforcing the EU's commitment to climate neutrality. Ships carbon intensity is calculated based on their report about annual fuel consumption according to mentioned in the FuelEU Monitoring Plan.

$$GHG_{intensity} = \frac{\sum_i (Energy_i \times EmissionFactor_i)}{\sum_i Energy_i} \quad (3.3)$$

Where:

- $Energy_n$: Energy content of fuel type i (measured in MJ).
- $EmissionFactor_n$: Well-to-Wake CO₂ equivalent emission factor of fuel type i (in gCO₂e/MJ).

3.6.2 Penalty and carbon taxation mechanism

When ships exceed the defined carbon limits, they are subject to financial penalties according to the FuelEU regulation. The penalty is calculated according to the number of excess emissions and the carbon price associated with the fuel type:

$$Penalty = ExcessEmission(tCO_2e) \times CarbonPrice \left(\frac{\text{Euro}}{tCO_2e} \right) \quad (3.4)$$

For 2025, the projected carbon price is €100 per ton of CO₂e (European Commission, 2025). This price is expected to increase by time with in parallel with the EU Emission Trading System (ETS).

3.6.3 Criticisms and implications

FuelEU has been subject to several criticisms, including:

- It may undermine global competition in maritime shipping, as the regulation is considered “regional” by the IMO and not globally uniform.
- The introduction of high carbon taxes could significantly increase operational costs for small shipowners.
- The European Union argues that the system will accelerate fuel innovation and infrastructure investment across the sector (IMO, 2024).

FuelEU is expected to be aligned with the IMO's GHG Strategy 2050 in the 2025 period to check global consistency which is about climate goals.

3.7 Carbon Pricing and Market-Based Measures

Carbon pricing in the maritime sector refers to assigning a monetary cost to the amount of CO₂ emissions generated by ships and also this system generally takes two main forms:

1. Carbon tax or minimum carbon price.
2. Emissions trading schemes.

The main target of both mechanisms is to punish vessels which had high-emission level and incentivize low-emission operations. Also trying to creating economic pressure to decarbonize (European Commission, 2024; IMO, 2023). The European Union has officially included maritime shipping in the EU Emissions Trading System in 2024. Ship operators are required to purchase carbon allowances based on the volume of CO₂ emissions generated during voyages within the EU under these rules for incoming and outgoing international voyages (European Commission, 2024).

In practice, this means:

- Each ton of CO₂ emitted incurs a financial cost of approximately €80–100.
- More efficient vessels with lower CII ratings and cleaner fuel blends, will incur lower costs.
- High carbon emission will bring vessel owner significant increases in operational expenses.

High cost will motivate vessel owners to transform from fossil fuels to carbon-free fuels. Carbon free renewable fuels will become strategic and economic advantage within a competitive maritime market.

On a worldwide scale, the IMO has been discussing market-based mechanisms for 2024–2025. One important suggestion is to apply a harmonized carbon price of USD/ton CO₂ on international shipping. Some of the revenues generated would be redistributed to help low- and middle-income countries reduce carbon emissions from their fleets (IMO, 2024).

Several proposals suggest a price point near \$100 per ton of CO₂, which would economically disadvantage older ships burning high-sulfur heavy fuel oil while favoring modern vessels using alternative fuels (e.g., LNG, methanol, ammonia) or equipped with carbon capture technologies (DNV, 2024; European Commission, 2024).

As a conclusion, carbon taxation and emissions trading systems have moved beyond being mere subjects of political debate. They now directly impact a ship operator's profit and loss statements. Also, carbon tax payments should be used for decarbonization targets. Shipowners still have concerns about this tax mechanism. Shipowners are torn between economic instability and environmental low performance. Shipowners must manage not only technical compliance like EEXI but also economic compliance to maintain competitiveness and financial sustainability (DNV, 2024).



4. ALTERNATIVE FUELS

In the maritime transport sector, methods to reduce exhaust gas emissions are broadly categorized into three strategic approaches: fuel-based measures, engine and combustion optimization, and exhaust gas treatment and emission control technologies like scrubbers, exhaust gas recirculation, selective catalytic reduction, and carbon capture methods. To comply with international regulations such as MARPOL Annex VI and the European Union Emissions Trading System vessel owner need to plans. Fuel-based measures focus on reducing emissions at the source by modifying the chemical composition of marine fuels or opting for alternative fuels with lower sulfur and carbon content.

LNG, methanol, ammonia, biodiesel, and hydrogen as an alternative fuel have gained importance for their high combustion efficiency and lower carbon footprints. Alternative fuels such LNG can reduce SO_x emissions by nearly 100%, NO_x emissions by up to 85%, and CO₂ emissions by 20–25% (Det Norske Veritas [DNV], 2024). In line with the IMO's strategy to reduce shipping-related greenhouse gas emissions by 50% by 2050 (IMO, 2020). The maritime sector is switching toward low or zero-carbon fuels from fossil fuels. Alternatives include LNG, which offers high energy density and benefits from a well-established supply infrastructure. Also, the existence of established regulations and guidelines. LNG had also practical application and contributes to positioning it as a more systematic and safer alternative fuel. In fact, its use is already present on cruise ships with dual-fuel engines. It is demonstrating industry confidence and operational feasibility in large-scale maritime operations. Methanol is gaining traction due to its compatibility with conventional fuel handling and storage systems. Green methanol which from renewable sources, can cut lifecycle CO₂ emissions by up to 95% (ABS, 2023). Ammonia and Hydrogen classified as zero-carbon fuels because they do not release CO₂ during combustion. Safe storage, toxicity risks, and high production costs are challenges for them, and they still limit their operational spreads (DNV, 2024).

It emphasizes the critical role that hydrogen and hydrogen-derived fuels will play in the critical role. Long-term decarbonization of the maritime industry needs carbon-zero fuel (IEA, 2024). Not only hydrogen, but also bio-LNG has potential. The American Bureau of Shipping mentioned in its pathways. To achieve low-carbon shipping, alternative fuels are key elements. Operational factors affect fuel selections. Operational conditions influencing fuel selection. They include energy density, storage conditions, safety considerations, and compatibility with existing infrastructure (ABS, 2023). These criteria define the rate at which alternative fuels can be easily adopted by the shipping sector. Both for newbuild vessels and retrofitting opportunities are considered. Some of the port and itineraries require different alternative fuels.

In this study feasibility of alternative fuels be evaluated on the basis of their environmental performance. Also, comprehensive matrix considered to involving economic viability, technological maturity, global fuel supply chain resilience, and fit to safety regulations. Alternative fuels have become a strategic option due to carbon-pricing system. Vessel owner prefers to use low carbon fuel do not pay tax. Strict rules and financial pressures are reshaping fleet fuel selection. Consequently, major shipping companies are turning to dual-fuel engines for LNG, methanol, and ammonia in newbuilds to enhance both operational flexibility and regulatory compliance. Many shipping companies are adopting hybrid approaches. Vessels powered by low-carbon fuels such as LNG or methanol are also equipped with SCR systems and particulate filters which are preferred to maximizing overall emissions reductions (IEA, 2024).

The medium-term outlook for the maritime sector can be summarized based on current order books and supporting infrastructure investments as follows: LNG will remain dominant until at least 2030. According to DNV and other analysts, the global fleet of LNG dual-fuel ships is projected to reach ~1,400 vessels by 2030. LNG demand is expected to at least multiply the bunkering network. LNG's role as a transitional fuel over the next several years will increase. Currently, the maritime sector is undergoing a dual-phase transformation. Also, existing vessels are retrofitted with emission-control systems to comply with regulations while continuing to operate on conventional fuels with exhaust cleaning systems. In additions, long-term strategies emphasize a shift toward alternative low-carbon fuels such as LNG, methanol, ammonia, and hydrogen. This transition brings not only technical innovation but also

a strategic balancing act between operational cost, energy efficiency, and environmental sustainability (International Energy Agency [IEA], 2024).

Alternative fuels are no longer a niche or exceptional feature in newbuild ship design. they start to become a fundamental design parameter in global newbuilding shipbuilding strategies. According to Clarkson's research approximately 50% of all new ship orders by gross tonnage included capabilities for alternative fuel use, marking the highest share recorded in maritime history throughout 2024.

According to Clarkson's research, 820 ships with alternative fuel capability were ordered in 2024, totaling approximately 62.2 million GT. LNG carriers even when excluding, 727 ships around 52.1 million GT were designed to use alternative fuels. This is indicating that these technologies have expanded beyond their early "natural fit" segments like LNG tankers and are now widely adopted across containers, bulk carriers, tankers, RoPax vessels, and car carriers.

This shift clearly illustrates that the single-fuel design which is used conventional HFO and MGO, is being replaced by dual-fuel and fuel-ready concepts. New vessel preferred to delivered with conventional engines but structurally and technically pre-configured for conversion to low-carbon fuels such as methanol or ammonia. Notably, about 20% of new orders in 2024 were classified as "fuel-ready", showing that owners are strategically hedging fuel transition risks through proactive design according to Clarkson's riviera research. According to DNV's Alternative Fuels Insight, around 150 ships were ordered with alternative fuel capabilities in the first half of 2025, a slight decline in number compared to 179 in the first half of 2024. Also, total GT increased by 78%, indicating a shift toward larger dual-fuel ships. Vessel type and sail route effects to fuel selections. Especially in the container, bulker, and tanker segments. This confirms that the fuel transition is no longer limited to small-scale pilot projects and also, it is now being implemented in mainstream commercial fleets (DNV AFI, 2025). Current data shows that nearly half of all newbuild vessels are now ordered with either alternative fuel capabilities or fuel-conversion-ready configurations. The conventional single-fuel designs preferred just half of the newbuilding. LNG remains the most prevalent option and also most selected alternative fuel in the 2024–2025 orderbook, followed by methanol in commercial viability and ammonia in long-term strategic planning (Reuters, 2023).

4.1 Ammonia (NH₃)

Ammonia formula is NH₃). It is preferred because of zero-carbon fuel candidate for maritime applications and also primarily due to its carbon-free molecular structure. During combustion, ammonia does not emit CO₂ emission. This makes it particularly suitable for long-term decarbonization strategies. According to the Fourth IMO GHG Study 2020, ammonia can reduce lifecycle CO₂ emissions by up to 80% when used with appropriate engine technologies with the use of green ammonia. Green ammonia produced through renewable hydrogen pathways (i.e., green ammonia and renewable ammonia) and it can achieve carbon neutrality (IMO, 2020).

Even its volumetric energy density is very low compared to conventional marine fuels, ammonia offers advantages. It has high efficiency and compatibility with hydrogen-based production and distribution systems. These characteristics of ammonia suggest that it could be adopted in international shipping with an expanding bunker network. Especially within the ocean-going vessel owner, there is concern because of low energy density and toxicity (Valera-Medina et al., 2021).

Its application on board has challenges. LHV becomes problematic because producing the same amount of energy requires more ammonia, so greater storage capacity is needed. Ammonia has a low flame speed and a high autoignition temperature. It becomes complicated to use in internal combustion engines. These limitations often require advanced combustion strategies. In dual-fuel engines, higher compression ratios and pilot-fuel injection systems are very important to use ammonia (Bicer & Dincer, 2018). Ammonia is also highly toxic and poses risks through inhalation or physical contact. It's safe to integrate into maritime fuel systems. Demands rigorous engineering in storage, ventilation, and operational safety are key factors (American Bureau of Shipping, 2023). Ammonia combustion eliminates CO₂, CO, and SO_x emissions, but it may increase NO_x emissions and require selective catalytic reduction or other NO_x-reduction systems. And this brings extra cost for vessel owners.

Ammonia has low lifecycle emissions. An ammonia-powered vessel starts to set sail. It is easily compatible with large-scale maritime infrastructure. Green ammonia is increasingly seen as a viable long-term alternative to LNG and methanol in global shipping due to its zero-carbon characteristics. (Balcombe et al., 2019).

In 2024, the International Energy Agency anticipates broader adoption of ammonia-based fuels after 2035. Ammonia's commercial deployment is expected to remain limited due to cost barriers. Bunkering limitations are expected to be a key challenge for ocean-going vessels. Green ammonia is seen as one of the few synthetic fuels capable of replacing both LNG and methanol over time because of the zero-carbon level of green ammonia. Green ammonia offering not only a low carbon footprint but also logistical feasibility for integration into global energy trade but it is still under development (Balcombe et al., 2019).

4.2 Biofuels

Biofuels are produced from renewable biomass sources such as vegetable oils, waste oils, lignocellulosic feedstocks, and algae. Biofuels are considered a critical component of carbon-neutral transition strategies in maritime transport (Gilbert et al., 2018). Biofuels usage in marine applications commonly includes fatty acid methyl ester and hydrotreated vegetable oil. These biofuels are typically designed for use with conventional diesel or low-sulfur fuel oils to reduce carbon footprint. Biofuels enabling compatibility with existing marine engines and fuel systems (IMO, 2020).

According to the Fourth IMO GHG Study 2020, biofuels can reduce lifecycle CO₂ emissions by approximately 50% to 90%, depending on feedstock origin and processing methods. They are considered an alternative fuel under the MARPOL Annex VI energy-efficiency regulations. Vessel owners prefer to use biofuels to reduce emissions without retrofit. (IMO, 2020).

The academic literature said that the greenhouse gas reduction potential of biofuels varies. It depends on the feedstock type, production method, and conversion technology in lifecycle assessments (Balcombe et al., 2019). Biofuels produced from waste cooking oils can achieve up to an 80% reduction in lifecycle emissions. Biofuels based on palm oil may offer limited benefits due to indirect land-use change. HVO-based biofuels have lower oxygen content. Generally, they indicate higher combustion efficiency and require fewer engine modifications, but fatty acid methyl esters biofuels require major engine modifications (Gilbert et al., 2018). The large -scale use of biofuels in maritime sector is limited by several operational technical problems. They include oxidative instability, susceptibility to microbial contamination, and sensitivity to long-term storage conditions. These challenges show the need to further develop

marine-specific fuel standards and quality assurance protocols for biofuels (Balcombe et al., 2019). The International Energy Agency (IEA, 2024) mentioned that biofuels will remain a practical short-term decarbonization solution. The plan requires integrating advanced biofuels to achieve long-term carbon-neutral exhaust gases. Bio-methanol, bio-hydrogen, and bio-based synthetic fuels are part of the plan in hybrid configurations. Biofuels are currently viewed as transitional fuels for now. They are strategically important solutions and offer partial emission reductions on the existing shipboard systems (IMO, 2020; IEA, 2024).

Biofuel usage also has performance-related concerns. For example, ship operators who replaced 50% of MGO with biodiesel have observed higher fuel consumption due to biodiesel's lower energy density. More biodiesel consumption is required to generate the same energy output per kilowatt-hour. The actual CO₂ emission reduction is often less significant than expected. In some cases, CII scores remain unchanged because the total amount of carbon emitted per unit of work doesn't show significant improvement. Extra fuel consumption effects of the evaluating fuel performance not only on carbon content but also on energy output and operational efficiency throughout the fuel lifecycle.

4.3 Hydrogen (H₂)

Hydrogen (H₂) is considered a highly promising zero-carbon fuel candidate for maritime applications. Because it contains no carbon atoms and does not produce CO₂ during combustion when used in fuel cells (IEA, 2024). Hydrogen can be used in fuel cells or ICE to produce power and electricity. Its main byproduct is H₂O. Positioning hydrogen as a key component in achieving the IMO goal of net-zero emissions by 2050 (IMO, 2020). Green hydrogen is produced via renewable electricity. Blue hydrogen is produced from fossil sources with carbon capture and storage. They are expected to play a major role in decarbonizing global shipping over the coming decades (IEA, 2024).

Hydrogen has CO₂ advantages, but it has several significant technical challenges. One of the main challenges is its high combustion temperature. It leads to the formation of NO_x during combustion. NO_x is a critical environmental and regulatory issue, especially in ECAs. Liquid hydrogen has a boil-off problem. It significantly limits its storage duration, and it is necessary to use complex thermal insulation systems. The

hydrogen supply chain is still undeveloped. Refueling infrastructure, bunkering standards, and port safety regulations are still under development in most regions. It is the negative side of Hydrogen. All alternative fuels have a bunker problem; even LNG has a bunker problem.

Hydrogen's low volumetric energy density and its complications make it difficult to use on board ships. It requires big storage tanks. Whether stored in liquid or compressed form, hydrogen requires considerably more energy for storage than conventional marine fuels such as MGO. Low energy density reduces overall system efficiency. On-board storage is very important for carrying cargo. Vessel owners pay attention to the storage capacity requirement. Hydrogen's high flammability introduces serious safety risks. Especially for passenger vessels, flammability is very important. Strict safety protocols and containment systems are required to mitigate ignition hazards.

Hydrogen can be combusted in internal combustion engines. Combusted hydrogen requires advanced injection and exhaust treatment technologies to manage NO_x emissions (Brynolf et al., 2018). As a result, proton exchange membrane fuel cells are generally seen as a suitable option. Hydrogen offers high energy efficiency and zero-emission electricity generation. It is especially for short-sea or hybrid electric vessels due to the storage problem (IEA, 2024).

DNV's projects in 2024, looking forward to seeing that hydrogen will see limited deployment in small and medium-scale vessels. Ferries or coastal support vessels can be given as examples. The decarbonization potential will likely be realized indirectly in the long term through hydrogen-derived synthetic e-ammonia and e-methanol fuels. These derivatives offer greater compatibility with existing fuel systems and bunkering infrastructure. Hydrogen enables a smoother transition to zero-carbon shipping.

As a result, hydrogen is a strategic energy source rather than another alternative maritime fuel. Its role is enabling the production of other clean fuels and supporting carbon-neutral fuels and systems, rather than serving as a standalone fuel for ocean-going vessels (Balcombe et al., 2019).

4.4 LPG (Liquified Petroleum Gas)

Liquefied petroleum gas (LPG), composed primarily of propane (C_3H_8) and butane (C_4H_{10}). It is classified as a mid-carbon hydrocarbon fuel because it has a cleaner emissions profile compared to conventional marine fuels. LPG is increasingly recognized as a viable transitional fuel in the maritime sector for the short term (Brynolf et al., 2018). One of its notable advantages over LNG is its higher volumetric energy density and its liquefaction at approximately $-42\text{ }^{\circ}\text{C}$. This eliminates the need for deep cryogenic storage. This LPG's characteristic simplifies fuel handling, and it reduces the complexity and cost of storage systems (Bicer & Dincer, 2018).

Under the emission regulations set out in IMO MARPOL Annex VI, LPG usage can virtually eliminate SO_x and PM emissions. It can also reduce NO_x by 10% to 30%, depending on the engine type and the emissions control technologies used (IMO, 2020).

According to life-cycle assessments with WTW, it is indicated that LPG has a 17%–20% lower carbon intensity than HFO. Methane slip is a major concern with LNG-powered systems. Unlike LNG, LPG does not contain methane, meaning it completely avoids methane slip (Balcombe et al., 2019). LPG doesn't include methane and is a competitive short-term solution for reducing carbon emissions in maritime operations (Brynolf et al., 2018).

However, despite its environmental advantages, LPG is still a carbon-based fuel and therefore does not align with long-term decarbonization targets, such as the IMO's 2050 net-zero ambition. Zero-carbon fuels such as ammonia or hydrogen deliver, but LPG cannot achieve the emissions reductions required to meet these long-term climate goals (DNV, 2024).

Global fleet data suggests that LPG is becoming increasingly common as a secondary fuel, especially in LPG carriers and certain product tankers (DNV, 2024). According to the IEA 2024, LPG's require lower investment and technical feasibility support. It's useful in short- and medium-term decarbonization strategies. It is expected to be replaced by biofuels and synthetic hydrogen-based fuels.

LPG is categorized as a bridge fuel in this context. A transitional energy option that offers operational practicality, ease of storage, and substantial reductions in SO_x emissions. It serves as an economic short-term solution for ship owners. It is seeking

to reduce emissions with minimal infrastructure investment (Balcombe et al., 2019; Brynolf et al., 2018).

4.5 Methanol (CH₃OH)

Methanol is a low-carbon fuel. It is produced from biomass or natural gas. It's in liquid form at ambient conditions and is compatible with existing fuel infrastructure. It is a rapidly growing alternative energy carrier in the maritime sector (Gilbert et al., 2018). Methanol requires lower storage pressure. It can be integrated into current fuel systems with relatively minor modifications. It is positioned as a promising transitional fuel (IEA., 2024).

During methanol combustion, methanol virtually eliminates SO_x and PM emissions, and significantly reduces NO_x, depending on engine technology (IMO, 2020). It is carbon-neutral variants such as bio-methanol and e-methanol that are being developed. Methanol aligns with IMO's net-zero emissions targets for 2050 (IEA, 2024).

Methanol has a different carbon-emission profile depending on its production pathway, according to lifecycle analysis (Gilbert et al., 2018). Gilbert reports that fossil-based methanol can reduce CO₂ emissions by 5–15%. Bio-methanol can offer up to a 70% reduction in greenhouse gas emissions (Balcombe et al., 2019). Methanol may be a more sustainable option than LNG due to its lower toxicity, ease of storage, and high combustion efficiency. Methanol has relatively low LHV, and it requires higher consumption to produce the same energy output, which may increase operational costs and storage capacity. (Gilbert et al., 2018).

Methanol is flammable and also very toxic, which necessitates strict safety protocols in marine applications, and it brings risk for passenger ships (American Bureau of Shipping, 2023). It requires specialized handling systems, leak detection, fire suppression, and crew training to ensure safe and secure operation.

According to DNV's *Maritime Forecast to 2050*, methanol-fueled vessel orders are expected to grow substantially by 2030. For now, the majority of current orders in the container and chemical tanker segments are due to safety concerns in the passenger vessels (Det Norske Veritas., 2024). Methanol is increasingly considered a scalable “drop-in” fuel, offering a viable alternative to LNG in the short- and medium-term especially for long-term (IEA, 2024; Balcombe et al., 2019).

4.6 LNG (Liquefied Natural Gas)

LNG is a high-energy-density fuel obtained by cooling natural gas to approximately –162 °C. Cooling makes it liquid and increases storage requirements and lowers emissions, an alternative to conventional marine fuels such as HFO (Päivärinne & Eskeland, 2020). LNG has clean combustion characteristics and effectively eliminates SO_x and PM emissions, while also significantly reducing NO_x, aligning with IMO Tier III standards (IMO, 2020). CO₂ emissions from LNG-fueled vessels can be up to 30% lower compared to traditional marine fuels. However, this environmental benefit cannot be captured in full lifecycle assessments due to methane slip during combustion (IMO, 2020).

LNG systems have been commercially available and in operation for decades. From a technological standpoint, and they are now considered mature and reliable. Recent developments in fuel injection systems and electronic control technologies have notably enhanced combustion efficiency and NO_x control in dual-fuel engines. Especially for those operating on LNG and MGO blends (Päivärinne & Eskeland, 2020). LNG can be integrated into dual-fuel propulsion systems and, also offering flexibility in fuel use and contributing to operational resilience (Det Norske Veritas [DNV], 2024). Additionally, LNG's volumetric energy density is higher than that of many other alternative fuels, and since it is stored at around –155 °C in cryogenic tanks. LNG does not require significantly more storage space onboard than other alternative fuels (International Energy Agency, 2024).

LNG is not sufficient on its own to meet the IMO's 2050 target of a 50% reduction in greenhouse gas emissions from shipping. Despite its advantages in reducing SO₂ and CO₂, it has disadvantages. Supplementary systems such as onboard carbon capture or blending with bio-LNG or e-LNG are necessary to extend LNG's viability within long-term decarbonization pathways (Balcombe et al., 2019; IMO, 2020).

4.6.1 The role of LNG as an alternative fuel

The use of LNG as an alternative fuel on board is primarily driven by its low SO_x and PM emissions, its compatibility with existing infrastructure, and its potential as a transitional solution in maritime decarbonization. LNG nearly eliminates SO_x and PM emissions, also reducing CO₂ emissions by 25% (ABS, 2023; DNV, 2024).

However, methane slip, which is unburned methane released during combustion, and upstream supply chain emissions are key limitations that reduce the overall climate benefit of LNG. According to a study by Pavlenko et al. (2020), LNG-fueled vessels with high-pressure dual-fuel engines may offer up to a 15% reduction in greenhouse gas emissions compared to MGO over a 100-year GWP horizon. The warming effect of methane emissions can offset most of LNG's environmental advantages when evaluated over a 20-year GWP timeframe. This methane slip problem determines the long-term viability of LNG as a sustainable marine fuel.

4.6.2 Storage safety and fuel supply systems

LNG must be stored in liquid form under cryogenic conditions, approximately -162°C , instead of conventional marine fuels. As a result, LNG fuel systems onboard tankers and passenger ships require specialized components such as insulated storage tanks, pressure control systems, and safety relief valves to ensure operational integrity and safety (IMO, 2024). The IGF Code defines specific requirements for machinery spaces, piping systems, tank arrangements, and crew training for vessels using LNG, which has low-flashpoint fuels (IMO, 2024).

Typical LNG storage technologies include Type C pressure vessels, cylindrical or spherical, and membrane-type containment systems. The most critical elements are effective management of BOG, the integration of methane detection systems, adequate ventilation, and fire suppression systems. These are all considered in the safety design and operation of LNG-powered vessels (Marine Insight, 2022).

LNG fuel systems liquefied methane is vaporized and subsequently supplied to the engines. This process is implemented through two main supply strategies: low-pressure and high-pressure fuel delivery systems. In low-pressure configurations, such as those used in certain four-stroke dual-fuel engines, methane gas is pressurized to 5–16 bar and combusted with pilot-diesel ignition. High-pressure systems compress the methane to around 250–300 bar and spray natural gas into the combustion chamber in a manner similar to the diesel cycle (ABS White Paper, 2022).

These technologies offer fuel flexibility while also contributing to reduced NO_x emissions through improved combustion control (ABS, 2022). LNG fuel supply systems include several critical components. BOG management, piping isolation systems, and safety valves are critical components. Those systems ensure operational

reliability and compliance with international safety standards. LNG engines have different combustion systems. It depends on the type of fuel supply system used. The first system introduces a premixture of methane and air into the cylinder. This is called low pressure system. Ignition is initiated by a small pilot injection of diesel fuel. This method offers in reducing NO_x emissions, but it carries a higher risk of unburned methane slip (IMO, 2020).

A high-pressure system is a direct injection system to the combustion chamber. Inject methane directly into the combustion chamber at pressures around 250–300 bar. It operates similarly to a diesel cycle. This high-pressure system provides higher thermal efficiency, but the system is more complex and involves higher capital and operational costs (MAN Energy Solutions, 2023; DNV, 2024).

Dual-fueled marine engines capable of operating on both LNG and MGO. These systems offer significant fuel flexibility. Dual fuel allows vessels to switch to diesel mode if the engine trips by sensor. If LNG bunkers are unavailable in certain ports, the engine can also produce power using MGO (ABS, 2023). LNG operations reduce SO_x, NO_x, and CO₂ emissions. It provides regulatory compliance in ECAs (DNV, 2024).

Advanced engine control systems monitor in-cylinder pressure, combustion temperature, torque, and unburned gas concentrations. Advanced engine control systems aiming to minimize methane slip (MAN Energy Solutions, 2023). These dual-fuel engines reduce the risk of remaining out of service and provide shipowners with a strategic advantage if the vessel remains without LNG.

LNG is a transitional fuel for current decarbonization efforts. Technological development on LNG platforms facilitates a shift toward lower-carbon alternatives such as methanol, biomethane, and ammonia. LNG engines can also be adapted to operate with other methane-based fuels. The LNG fuel system allows flexibility in fuel switching throughout the vessel's operational lifetime with lower investment (DNV, 2024).

4.6.3 LNG bunkering operations and standards

The LNG bunkering network is one of the most critical factors in the widespread adoption as a marine fuel. Compared with conventional fuels such as HFO or MGO, LNG bunkering involves more complex procedures and requires stricter safety protocols. It has the most common alternative fuel bunker network. LNG is stored at

cryogenic temperatures around -162°C degree. The bunkering process must manage risks associated with thermal stress and potential gas leak problems.

The IMO and ISO have developed ISO/TS 18683:2015 – guidelines for systems and installations for the supply of LNG as ship fuel. Equipment standardization, safety requirements, and environmental precautions for LNG bunkering operations are standardized to minimize these challenges (ISO, 2015).

LNG bunkering can be carried out using four primary methods according to DNV:

1. Truck-to-Ship (TTS)
2. Ship-to-Ship (STS)
3. Terminal-to-Ship (TPS)
4. Portable Tank Exchange:

There are four methods. During all bunker methods, there are mandatory precautions. Emergency shutdown systems, double-hose transfer lines, gas detection sensors, and inert gas purging procedures are mandatory. Also, LNG bunkering operations are further regulated by local safety guidelines. They can be issued by national maritime authorities, such as the Singapore MPA LNG Bunkering Standards for Singapore ports. The Rotterdam LNG Bunkering Code for Rotterdam ports (MPA, 2023).

4.6.4 Risk and safety analysis of LNG systems

LNG usage on board as a fuel requires comprehensive risk assessments. Established methodologies are Formal Safety Assessment, Hazard Identification, and Hazard and Operability Study (ABS, 2023). On board gas leaks, fire outbreaks, collisions, or tank damage are the most common emergencies that can occur. These analyses aim to create a clear page about system behavior under both normal operating conditions and emergency scenarios.

Key Risk Categories:

- Gas leakage and explosion hazard: Methane in gas forms a flammable mixture when mixed with air at concentrations between 5% and 15%. Integrating gas detectors with mechanical ventilation systems is essential for safe operations.

- Cryogenic burns: if LNG comes into contact with steel, it can cause the steel to become brittle, leading to structural deformations.
- Overpressure due to boil-off gas: Vaporization of LNG inside tanks leads to pressure build-up. This is controlled via BOG compressors, venting systems, and pressure relief lines. Relief valves release methane to the atmosphere and cause methane slip.
- Human factor: LNG system operator errors, like incorrect valve operations or inadequate crew training, are a primary cause in nearly 40% of LNG-related incidents (DNV, 2024).

The mandatory implementation of the rigorous safety protocols defined in the IGF Code has had a positive impact. The IGF Code has helped to establish a strong safety culture in LNG-powered ship designs. These safety protocols and safety measures report that the probability of fatal accidents on LNG-powered ships is approximately 30% lower compared to ships powered by conventional fuels. This improvement is a positive aspect of LNG (DNV, 2024).

4.6.5 Economic analysis and operational efficiency of LNG

LNG-powered vessels typically follow a cost structure characterized by higher capital expenditures CAPEX but lower operational expenditures OPEX due to lower fuel prices. The LNG-fueled version of a 15,000 TEU container vessel is approximately 20% more expensive to build than an equivalent HFO-powered vessel. LNG can offer a fuel cost advantage of around USD 100–150 per ton, and it reduces OPEX (Clarksons, 2024).

Price changes during the years due to economic and political reasons. ETS and the FuelEU Maritime Regulation about the carbon tax mechanism directly influence LNG's economic competitiveness. Projections for the 2024–2030 period indicate that if carbon prices reach €100 per ton of CO₂, the energy-adjusted unit cost of LNG may become up to 25% more competitive than MGO (IEA, 2024). Combustion characteristics of LNG are cleaner, so that maintenance intervals for LNG engines are expected to be longer. A longer maintenance interval can result in a 2–3% increase in vessel availability. It is a critical factor in operational efficiency (ABS, 2023).

4.6.6 The methane slips problem and greenhouse gas potential

Methane slips on the engines powered with LNG is a main problem. Methane slip is unburned methane that escapes into the atmosphere during combustion. Methane has a global warming potential 84 times that of CO₂ over a 20-year horizon, and it's more dangerous than CO₂ (IPCC, 2023).

Different engine type and different LNG fuel supply systems has different methane slip percentages. For example, in low-pressure Otto-cycle engines, methane slip rates can reach 2–3%, but when LNG is sent to the combustion chamber in a high-pressure ME-GI system, the slip can be reduced to below 0.2%, but this brings extra energy consumption due to pressurized natural gas up to 200 bars. (MAN Energy Solutions, 2023).

Technologies aimed at reducing methane slip include oxidation catalysts, aftertreatment systems, and engine-optimization algorithms. Studies by Wartsilla and DNV (2024) indicate that, when these technologies are effectively spread, the overall GHG reduction potential of LNG can be restored to approximately 20%.

LNG is not determined solely by fuel choice but also by a combination of engine configuration, operational profile, and maintenance strategy. These findings highlight the environmental sustainability of LNG. As such, LNG is better described not as a "clean fuel," but as a “manageable transitional solution” in the path toward full decarbonization (DNV, 2024; IEA, 2024).

4.6.7 Physical properties and cryogenic behavior of LNG

LNG is mainly composed of CH₄ in concentrations ranging from 85% to 95% a hydrocarbon mixture. It becomes liquefied at approximately –162 °C under atmospheric pressure. At this cryogenic temperature, its density decreases to around 450 kg/m³, and LNG requires about 1.7 times as much volume as diesel fuel to deliver the same energy content, but the LHV of LNG is higher than MGO by mass. (IEA, 2024).

Due to these extremely low temperatures, LNG storage systems must be engineered with specific attention to heat transfer management strategies. Pressure management and material selection are critical. Storage tanks are typically constructed using

austenitic stainless steels such as AISI 304 or 316L or nickel-alloyed steels, which retain ductility at cryogenic conditions (ABS, 2023).

LNG tanks have boil-off gas (BOG) problems. Evaporation of LNG increases the internal tank pressure. LNG tanks must be equipped with advanced insulation and BOG management systems. Insulation thickness should range from 250 to 300 mm, and the thermal conductivity should be around 0.025 W/m·K (DNV, 2024).

4.6.8 Storage tank types and design criteria

LNG storage tanks are classified into three main types under the IGF Code: Type A, Type B, and Type C tanks. On the cruise vessel, the most common tanks are B type (IMO, 2020).

Table 4.1 : Classification of LNG Tank Types

Tank Type	Structural Characteristics	Pressure Resistance	Typical Application
Type A	Prismatic, low-pressure	< 0.7 bar	LNG carriers (membrane systems)
Type B	Spherical or cylindrical, medium-pressure	0.7–2 bar	LNG shuttle tankers
Type C	Cylindrical pressure vessels	2–10 bar	Ro-Pax, container and ferry ships

Type C tanks are the most commonly used in LNG-fueled cargo ships due to their ability to control BOG under pressure. The cylindrical or spherical form provides both installation and manufacturing advantages. LNG tanks located on the deck in cargo carriers (ABS, 2023).

Membrane-type tanks, such as Mark III and NO96, developed by Gaztransport & Technigaz, are primarily used in LNG carriers. In these systems, a thin stainless-steel membrane does not bear the cargo. Instead of a bear, the pressure is transferred to the ship’s hull via perlite-core insulation panels that system provides approximately 5% volumetric efficiency compared to independent tank systems (GTT, 2022).

Thermal management of LNG tanks is critical for minimizing evaporation losses. In well-insulated tanks, the typical boil-off rate (BOR) ranges from 0.1% to 0.15% per day (DNV, 2024). Vacuum-Insulated Double Wall: Uses vacuum space and multi-layer insulation (MLI) foil between dual walls. Foam Insulation is economical but has higher heat transfer coefficients. Membrane Insulation predominantly used in LNG carriers. Pressure Control and Boil-off gas management due to natural vaporization of LNG: boil-off gas can lead to pressure build-up in tanks. This gas is either reused as engine fuel or reliquefied by compressors.

According to DNV (2024), three main BOG management strategies are implemented in modern LNG-fueled ships:

1. Vent-to-Atmosphere: Releasing excess gas directly into the air is allowed only in exceptional emergencies.
2. BOG Re-Liquefaction: Cooling and returning vaporized gas to the storage tank.
3. BOG Consumption: Direct feeding into dual-fuel engines as a primary fuel source.

The most environmentally friendly methods are options 2 and 3. Pressure regulation is typically managed via a combination of High-Duty Compressors and Low-Duty Compressors (ABS, 2023). The normal operating pressure of LNG tanks ranges between 4 and 8 bar. According to the IGF Code, each tank must be equipped with Pressure Relief Valves, gas detection systems, and vapor return lines.

4.6.8.1 Storage safety under the IGF code

The International Code of Safety for Ships Using Gases or IGF Code came into force in 2017 and was revised in 2024. It outlines safety requirements for the design, storage, and operation of LNG fuel systems (IMO, 2024).

Key safety principles under the IGF Code:

- Fuel systems must be installed in gas-safe machinery spaces or emergency shutdown (ESD)-protected compartments.
- LNG tanks must be located at least 8 meters away from passenger and crew areas.

- All piping systems must be double-walled and equipped with leak detection sensors.
- In the event of a tank rupture, a secondary barrier must be capable of containing 100% of the tank's volume.
- Electrical systems must comply with Zone 1/ Zone 2 classifications and be explosion-proof (Ex-rated).

According to ABS (2023), these safety precautions reduce the probability of LNG-related fire or explosion incidents to below 10^{-6} , equating to fewer than one incident per one million ship-years.

4.6.8.2 Gas detection and ventilation systems

Gas detection and ventilation systems are among the most critical safety components of LNG fuel systems. CH₄ becomes explosive when mixed with air at concentrations between 5% and 15% by volume, known as the Lower and Upper Explosive Limits (LEL–UEL). The IGF Code mandates the use of continuous monitoring devices, such as catalytic or infrared gas detectors, across all LNG fuel installations and mandatory monitoring with sensors (IMO, 2024).

Gas detection systems are typically installed in tank tops and pump room compartments, engine rooms classified as gas-safe zones, ventilation ducts, ESD-protected compartments, bunker manifolds, and fuel transfer pipelines. Alarms are triggered when methane levels reach 20% of the LEL, and automatic fuel shut-off (via the ESD system) is activated at 40% LEL (ABS, 2023). Ventilation systems must ensure at least 30 air changes per hour and maintain negative pressure in all potential gas-accumulation zones (DNV, 2024).

4.6.9 Function of emergency shutdown systems

Emergency Shut Down (ESD) systems are designed to automatically isolate LNG fuel lines in the event of a leak or overpressure scenario. According to the IGF Code:

- ESD Level 1 immediately shuts down the entire LNG bunkering line.
- ESD Level 2 isolates the main engine's fuel supply and activates the inert gas system.

ESD valves operate on a fail-safe closed principle, meaning they shut automatically in the event of power loss. The system logic must comply with Safety Instrumented System (SIS) standards and meet SIL 2 (Safety Integrity Level 2) (ABS, 2023).

As noted by DNV (2024), modern LNG vessels use PLC-based Integrated Automation Systems (IAS) to process input from gas detectors, fire sensors, and pressure transmitters, and to react within 100 milliseconds.

4.6.10 Double walled piping and the gas safe cone concept

All LNG pipelines are constructed using double-walled designs. The inner pipe is made of cryogenic-resistant stainless steel, while the outer pipe is insulated and gas-tight. Gas leak detection sensors are placed between the walls (ABS, 2023).

Machinery spaces are classified into two types (DNV, 2024):

1. Gas-safe machinery space: LNG systems are located outside the engine room.
2. ESD-protected machinery space: LNG systems are inside, protected by ESD, ventilation, and sensor systems.

This classification determines the placement of electrical components. Ex-proof devices are required in Zone 1 and Zone 2 areas, in accordance with IEC 60079 standards.

4.6.11 Safety requirements under the IGF code

In the IGF Code, the following essential safety principles for LNG-fueled vessels are explained (IMO, 2024):

- LNG may only be used if classified as a low-flashpoint fuel under certified standards.
- All LNG tanks must have a double-barrier structure, and pipes must have a double wall.
- A pre-transfer checklist and gas-free certificate are mandatory prior to bunkering.
- Crew competence: All personnel must undergo IGF Code-certified training.
- Fuel systems must be controlled by an engineer and designed to comply with fail-safe principles.

DNV published its Safety Audit Report in 2024. There have been zero major fire or explosion incidents recorded on LNG vessels in the past five years. These reports indicating the high safety performance of LNG systems. IGF code provides guidelines for design and operation frameworks.

4.6.12 Emission characteristics of LNG

LNG carbon content is up to 30% lower CO₂ emissions per unit of energy than that of conventional diesel fuel (IEA, 2024). LNG-powered engines have a higher thermal efficiency. It is 47–50%, compared to 42–45% for traditional engines. LNG has advantages for long-distance shipping from both environmental and operational perspectives due to this efficiency gap. Newbuild vessels operating on LNG exhibit an average 25–30% lower CII compared to their conventional engines, according to the EEXI report published by the IMO in 2023. The combustion of conventional marine diesel fuels produces a range of exhaust gas emissions, including CO₂, SO_x, NO_x, CO, PM, and VOCs. For that reason, LNG is not a clean fuel; it is a transition fuel (IMO, 2024).

Since the primary component of LNG is CH₄, which contains no SO_x, and PM emissions are virtually eliminated during combustion. However, the overall GHG impact of LNG depends mainly on two critical factors: the amount of CO₂ produced during combustion and the extent of methane slip, unburned methane released into the atmosphere but for low pressure fuel supply systems this methane slips just 2 percent (DNV, 2024).

The table below presents a comparative analysis of average emission levels for diesel and LNG-fueled marine engines, based on data from DNV (2024) and MAN Energy Solutions (2023):

Table 4.2 : Comparative Emission Levels of Diesel and LNG Marine Engines

Emission Type	Diesel Engine (g/kWh)	LNG Engine (g/kWh)	Reduction (%)
CO ₂ (Carbon Dioxide)	620–670	460–500	≈ 25–30%
SO _x (Sulphur Oxides)	10–12	≈ 0	≈ 100%
NO _x (Nitrogen Oxides)	12–14	8–9	≈ 20–30%
PM (Particulate Matter)	0.4–0.6	< 0.05	≈ 90%
CH ₄ (Methane Slip)	≈ 0	2–4	+ % additional impact

LNG provides clear environmental benefits by reducing SO_x, NO_x, and PM emissions. For that reason, vessel owners prefer LNG as alternative fuel. However, methane slip remains a major climate concern because methane has a GWP about 28 times higher than CO₂ over 100 years (IPCC, 2021). Methane slips partially offsetting LNG's CO₂ reduction advantages.



5. FEASIBILITY OF ALTERNATIVE MARINE FUELS

The feasibility of alternative marine fuels is shaped not only by their emissions reduction potential but also by a complex interaction of technical, economic, and operational factors that influence their suitability for short-, medium-, and long-term use in global shipping (Balcombe et al., 2019; Gilbert et al., 2018). Selecting an alternative fuel for a new vessel requires a multidimensional assessment encompassing energy density, storage complexity, safety performance, infrastructure readiness, technological maturity, and overall life-cycle emissions. In studies, a result was observed. It is widely recognized that no single fuel can meet all operational and decarbonization requirements simultaneously. Studies highlight the need for a vessel-specific, multi-fuel transition pathway tailored to vessel class, cargo characteristics, and voyage profiles and voyage itineraries (IEA, 2024; DNV, 2024).

Hydrocarbon-based transitional fuels such as LNG and LPG currently offer technologically mature and operationally feasible pathways to reduce carbon intensity in the short term, but it is not enough to fit 2050 targets. LNG produces relatively low SO_x and particulate emissions and benefits from a well-developed infrastructure network, although its climate advantage is partly offset by concerns about methane slip. Methane slip significantly influences life-cycle carbon performance (Päivärinne & Eskeland, 2020). LPG offers similar operational advantages with the added benefit of avoiding methane slip. So far, it remains a carbon-containing fuel and therefore cannot meet long-term net-zero targets (Brynolf et al., 2018). Methanol and biofuels have emerged as promising mid-term “drop-in” options due to their compatibility with existing storage and bunkering systems and relatively low retrofitting requirements, but the bunker network still remains a concern (Gilbert et al., 2018). Biofuel use can reduce emissions by up to 90% if produced from sustainable feedstock streams. Uncertainties about feedstock availability and oxidative stability remain a major problem for production, and this has an effect on bunker availability at the port (Balcombe et al., 2019).

Long-term decarbonization efforts increasingly focus on hydrogen and ammonia, which offer zero CO₂ combustion profiles and strong alignment with future net-zero strategies. Both alternative fuels bring vessel owners storage, handling, and safety challenges that restrict their near-term deployment. Hydrogen suffers from an extremely low volumetric energy density, requiring highly cryogenic or high-pressure storage systems. Higher storage capacity requirement is always a problem for vessel owners. Ammonia poses toxicity risks, corrosive behavior, and NO_x formation during combustion (Valera-Medina et al., 2021; IEA, 2024). When synthetic fuels are produced with clean power, they are called e-methanol and e-ammonia. These fuels constitute an additional long-term solution to reach the net-zero target. For carbon-neutral fuels, their current production methods must be carbon-neutral and cost-prohibitive due to the limited availability of large-scale renewable power and CO₂ capture systems (DNV, 2024; IEA, 2024).

The global fleet of alternative-fueled vessels has continued to grow. Alternative fuel-powered vessels increased from 2% of the global fleet in 2020 to approximately 6% in 2024. More than 30% of newbuild vessels are designed to operate on or be compatible with alternative fuels (DNV, 2024). LNG and Methanol dominate current newbuild orders, and the methanol fleet is experiencing particularly rapid growth of over 150% between 2023 and 2024. Methanol use is increasing across major shipping segments, such as container lines (IEA, 2024). However, LNG accounts for 55% of the active alternative fuel fleet, and methanol accounts for 25%, LPG at 8%, biofuel demonstration projects at 5%, and ammonia and hydrogen at less than 1% due to ongoing pilot-stage development (DNV, 2024).

Energy density remains a central consideration in fuel feasibility assessments because it directly determines required tank volume, vessel range capability, and impacts on cargo capacity. LNG offers moderate energy density but still requires larger tanks than conventional marine diesel. The positive and negative aspects of these alternative fuels are presented in a table to facilitate comparison of their advantages and disadvantages. Methanol's comparatively low volumetric energy density further increases storage needs, making it more suitable for short-distance operations. Ammonia and hydrogen pose even greater challenges due to their very low volumetric densities. That making them difficult to accommodate on ocean-going vessels without major design compromises (DNV, 2024; IEA, 2024; ABS, 2023).

Table 5.1 : Comparative Assessment of Alternative Marine Fuels

Fuel	Carbon Emissions Profile	Energy Density (Volumetric MJ/L)	Storage Conditions	Key Strengths	Key Limitations
LNG	15–25% lower than HFO	22–24	~–162 °C	Mature infrastructure, low SO _x /PM	Methane slip, cryogenic storage
LPG	17–20% lower than HFO	~25	Pressurized or –42 °C	No methane slip, simpler storage	Carbon-based, not net-zero aligned
Methanol	Fossil: moderate CO ₂ ; Bio/e-methanol: up to 70% reduction	15–16	Ambient	Easy handling, infrastructure-ready	Low energy density, higher consumption
Biofuels	50–90% lifecycle reduction	35–40	Ambient	Drop-in compatible, sustainable if waste-derived	Feedstock limits, oxidative instability
Ammonia	Zero tank-to-wake CO ₂ ; 80%+ lifecycle reduction if green	11–12	Pressurized or –33 °C	No CO ₂ emissions, high decarbonization potential	Toxicity, NO _x formation, slow flame speed
Hydrogen (LH ₂)	Zero CO ₂ combustion	8–9	–253 °C	Fuel-cell compatible, zero emissions	Very low volumetric density, extreme cryogenics
Diesel (MGO)	High CO ₂ /SO _x /PM	35–36	Ambient	High energy density	Not compatible with decarbonization goals

(Päivärinne & Eskeland, 2020) (Balcombe et al., 2019) (Gilbert et al., 2018) (Balcombe et al., 2019) (Brynolf et al., 2018) (Valera-Medina et al.) (IEA, 2024).

Alternative marine fuels are compared according to their specification. This assessment brings a more comprehensive approach to fuels. Beyond emissions and energy density, operational safety plays a decisive role in fuel feasibility. LNG's flammability is manageable under the IGF Code, but supported by double-walled systems and advanced detection technologies, which are mandatory. (IMO, 2024). Methanol has toxicity risks but benefits from non-cryogenic handling requirements, while ammonia's extreme toxicity demands enhanced personal protective protocols. Segregated tank placement and advanced emergency response measures are mandatory to maintain safety on board (ABS, 2023; DNV, 2024). Hydrogen is really flammable and has a long range. When hydrogen is combined with a high propensity for leakage and ultra-cryogenic temperatures, it requires sophisticated ventilation and detection systems (IEA, 2024). When LNG is compared with all other fuels, it has the most mature regulatory and operational framework. Ammonia and hydrogen remain at early development stages with evolving safety standards (DNV, 2024).

When making strategic decisions, the transition to low- and zero-carbon fuels is expected to proceed in sequential phases, and should be evaluated. LNG serves as the dominant near-term solution enabling compliance with existing and emerging emissions regulations through 2030. Methanol and bio-LNG are expected to play crucial roles between 2030 and 2040 by enabling the achievement of low-carbon emission levels without requiring major vessel redesigns. Hydrogen and ammonia, supported by expanding renewable energy and power production, are anticipated to become central pillars of maritime decarbonization pathways because hydrogen and ammonia fit the net-zero carbon target. These fuels still require technological development for use in passenger vessels. (DNV, 2024; IEA, 2024).

6. CASE STUDY OF LNG POWERED CRUISE VESSEL

In this study, the data from a cruise vessel were collected and analyzed. Cruise vessel powered with dual fuel engines and using LNG as an alternative fuel with MGO. If a malfunction occurs in the LNG system and LNG cannot be used for power production in the engines, the backup fuel MGO can be used instead. In general, cruise voyages last 3-4 days or 7 days. Market research indicates that the US demographic generally prefers one-week vacations; consequently, most cruise lines design 7-day itineraries. In contrast to 7-day voyages, longer and shorter itineraries are also available. In this study, a cruise vessel with a 7-day voyage was evaluated. The data used in this study were collected on board. The name of the cruise vessel and the owner company from which the data were collected are not disclosed for confidentiality reasons. The cruise vessel in this study operates 7-day voyages in the Eastern and Western Caribbean. The vessel sails an average of 2,000 nautical miles per week. Ship specifications are shared in Table 6.1.

Table 6.1 : Vessel Specifications

Specification	Details
Passenger + Crew Capacity	8,000 people
Length of the Ship	300 meters
Draught	8 meters
Propulsion System	2 × Azipod type
Main Generator Engines	4 units
Fuel Type	Dual fuel
Engine Type	Four-stroke
Engine Modes	2 modes: Gas mode & Diesel mode
Gross Tonnage	183,000

Electrical power is generated by 4 dual-fuel generators. The LNG storage tank system and gas fuel supply system on the example vessel are shown in Figure 6.1. In the fuel gas supply system, LNG is delivered from the LNG storage tanks to the vaporizers by fuel gas pumps. Excess liquid LNG is returned to the tank to cool the tank dome and maintain appropriate thermal conditions. Within the vaporizer, LNG is converted to a gaseous state using glycol-water as the heat transfer medium. The vaporized natural gas is then conveyed through double-walled piping to the fuel gas (FG) superheater.

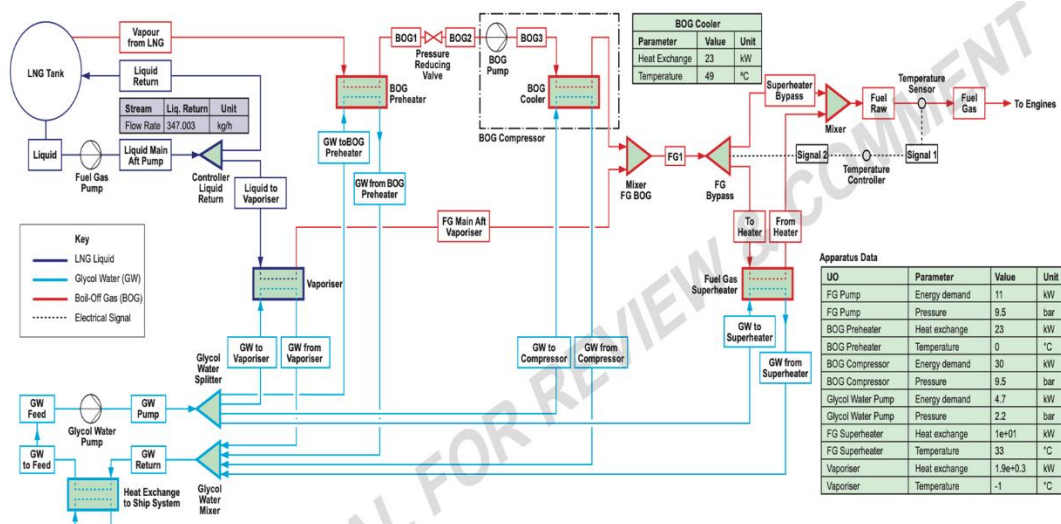


Figure 6.1 : LNG System of Cruise Vessel (WMT, 2021).

In the FG superheater, the fuel gas temperature is increased to approximately 33 °C prior to admission to the engine. Simultaneously, boil-off gas (BOG) generated in the LNG tanks is routed to the BOG preheater and subsequently compressed by the BOG compressors. Following compression, the natural gas pressure is increased to approximately 9.5 bar. The temperature rises to around 49 °C. The compressed gas is then directed to a gas cooler, where its temperature is reduced by approximately 33 °C. Gas streams from the LNG tanks and the LNG vaporizers are combined in a mixer to ensure homogeneous fuel-gas conditions. The mixed fuel gas is supplied to the engines at approximately 9.5 bar and 33 °C.

The dual-fuel engines are capable of operating in conventional diesel mode without an LNG supply. However, during gas mode operation, a small amount of diesel fuel is required for ignition and lubrication. This pilot fuel is delivered by a high-pressure fuel pump and injected into the combustion chamber through a dedicated pilot injector at pressures of approximately 1000 bar. In addition, the main diesel injector supplies

diesel fuel to the combustion chamber at pressures of around 500 bar when required. During gas mode operation, natural gas is introduced into the cylinder together with the combustion air during the intake stroke, enabling premixed combustion initiated by the pilot diesel injection.

Some of these engines or all of them can be run in diesel mode due to technical reasons or a lack of LNG bunker supply. Even the activation of a single sensor can trigger an instant fuel mode safety trip. Fuel mode safety trip means that the engine fuel mode switches to diesel mode due to a safety trip. Due to a malfunction or incorrect reading of the Integrated Cylinder Pressure Monitoring (ICPM) sensor, which is used to measure cylinder pressure on the engine, the engine way frequently experiences a fuel mode safety trip. The engine turns to diesel mode and supplies the gas line purges with inert gas. Turning back to Gas mode takes about 45 minutes. On a weekly basis, an engine experiences 5 to 8 fuel mode safety trips. While the vessel is at port, one generator is sufficient to produce the required power. However, during sailing, depending on the required speed, two or three generators are running. On average, the generators experience a total of 10 to 16 fuel mode safety trips per week. Furthermore, the sensors are highly sensitive. The maintenance required for a faulty sensor took approximately two hours. Due to all these reasons, all engines can't run in gas mode at all times. Some cruises have low diesel consumption, and some cruises due to operational reasons have high diesel consumption.

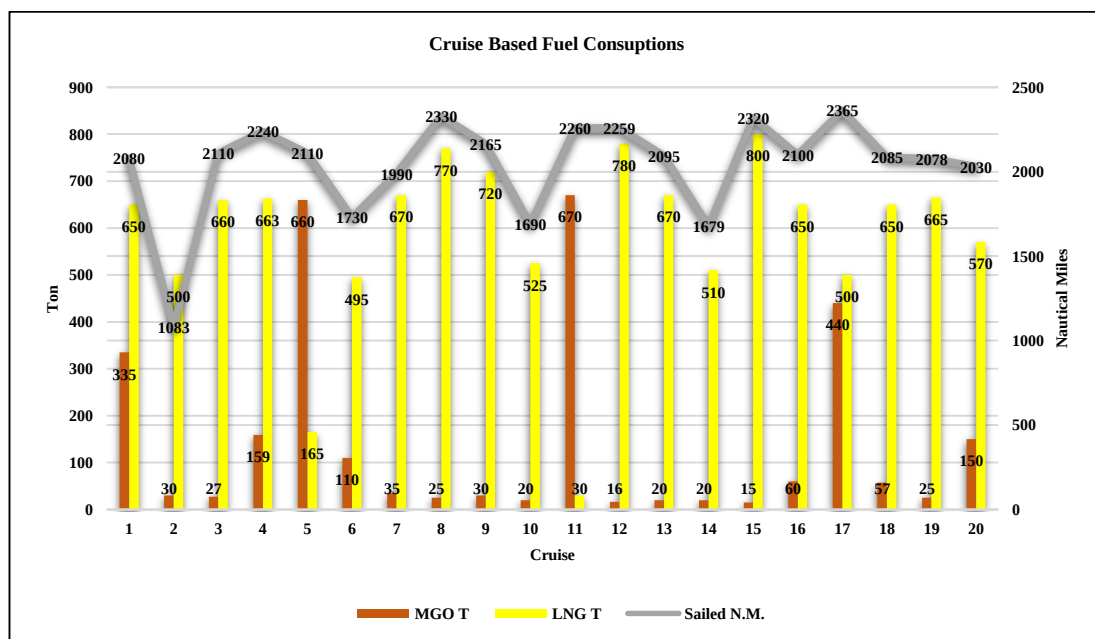


Figure 6.2 : Fuel Consumption per Cruise Voyage for Dual-Fuel LNG Vessel

In this study, 20 cruises were evaluated as an example in Figure 6.2, each with a 7-day voyage. Per cruise total distance sailed by the vessel is shown in nautical miles in figure 6.2. LNG and MGO consumption are segregated and shown in tons for each cruise voyage. MGO and LNG consumption can vary depending on vessel operations. 20 cruise voyages, fuel consumption, and per cruise total distance sailed in nautical miles are compared. When 20 cruises were averaged, it was observed that 150 tons of MGO and 570 tons of LNG were consumed. Vessel carried out 2-week cruise voyages just with MGO usage due to operational reasons, as seen in Figure 6.2. That can cause of extra carbon and other exhaust gas emissions. Although the engines are dual-fuel, they can be operated in diesel mode due to long supply times for some critical spare parts, simultaneous maintenance of multiple engines, or the inability to make LNG bunker fuel.

Exhaust test data show that the engine reduces carbon emissions by up to 27% in LNG mode compared with MGO mode. In real life, the engines do not operate in gas mode all the time, as shown in Table 6.2. The longer the engine is operated in diesel mode, the lower its carbon-emission-reduction capacity. Additionally, engine running hours were recorded by fuel mode.

Table 6.2 : Generator Running Hours According to Fuel Mode

Generators	MGO Mode	Gas Mode	Total Running hours
Generator No1	1388	12793	14181
Generator No2	1497	10002	11499
Generator No3	1419	12126	13545
Generator No4	1413	6357	7770
Total	5717	41278	46995

According to the average of running hours, the engine runs on MGO mode %12,1 during its lifetime. Based on analysis of actual engine data, it is evident that using LNG reduces emissions; however, LNG cannot be relied upon as a consistently sustainable alternative fuel. Due to operational reasons, MGO is still used in these engines.

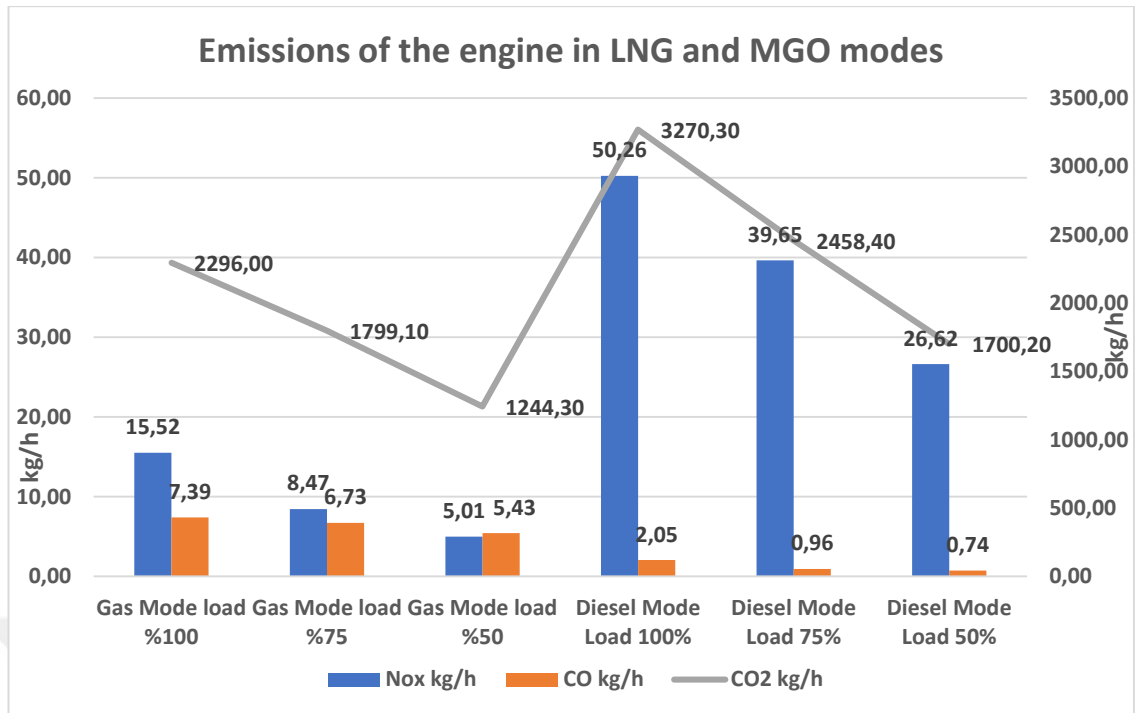


Figure 6.3 : Emissions of engines in LNG and MGO mode

LNG mode and MGO mode were compared according to engine loads in Figure 6.3. The engine loads used in the study were 100 percent, 75 percent, and 50 percent. NO_x emissions, CO and CO_2 emissions values shared on the table according to load and fuel mode. When Gas mode and MGO are compared, the first thing that stands out is that NO_x emission values are much lower in gas mode operating with LNG. Also, NO_x emissions are observed to be lower per kg/h at higher loads.

When the emission values of the engines are compared for gas mode and MGO mode, the engine data shows a 79% decrease on NO_x emissions. NO_x did not increase linearly with the increase in engine load. From this point of view, it is observed that the operation of the engines at optimum load has a positive effect on NO_x emission values. When the CO_2 emission values in the graph are compared, a decrease of up to 26-28% is observed in gas mode. In the same way, since the amount of engine emissions increases linearly despite the increase in engine load, it was found that operating the engine at high load has a positive effect on reducing CO_2 emissions. CO emission has very low values compared to CO_2 in terms of quantity. Although the engines emit more CO emissions when operating in gas mode, this is negligible because CO emission 300 times lower in grams/hour than CO_2 .

Although LNG contains 17,3% less carbon than MGO, engine exhaust data showed 27% less CO_2 emission. The main reason is that LNG has a higher LHV than MGO. Using less LNG is sufficient to produce the same energy. This is also evident in the engine data. While the engine consumes 195 g/kWh in MGO mode, the engine consumes 163,3 g/kWh in LNG mode. If the vessel runs just on MGO mode NO_x emission will increase 3,2 time more and CO_2 emission will increase up to 36% according to engine exhaust data.

6.1 CII Calculation

$$CII = \frac{\text{Annual } CO_2 \text{ emissions LNG and MGO}(g)}{\text{Gross Tonnage} \times \text{Annual distance traveled}(nlm)} \quad (6.2)$$

For this cruise vessel, LNG and MGO emissions factors are specified in the vessel's SEEMP. Emission factors are 3.2 kg CO_2 per kg of MGO and 2.75 kg CO_2 per kg of LNG. In this study, CII is calculated using 20 cruise datasets, and annual consumption and annual sailed nautical miles are computed as the average of the 20 cruises. Vessel is 183.000 gross tonnage, and 24000 nautical miles distance has sailed. This cruise vessel CII is 5.59, and the CII grade is A, as shown in Figure 6.4. If the engine were operated continuously in gas mode, the CII could be as low as 5.23, and if these engines were operated only in MGO mode, the CII of the ship could be as high as 7.26 and still an A grade. Required annual operational CII for this cruise vessel is 8.3 for 2024 and 8.1 for 2025. The CII index decreased by 23,1% with the use of LNG.

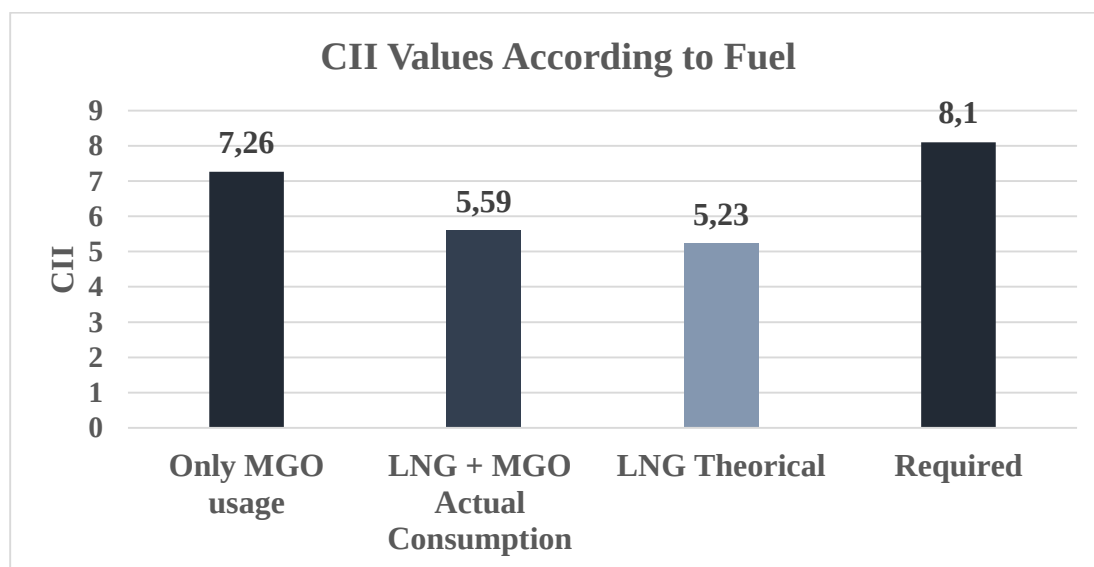


Figure 6.4 : CII Values according to Fuel

6.2 Carbon Dioxide Emission Calculation

$$GHG_{intensity} = \frac{\sum_i (Energy_i \times EmissionFactor_i)}{\sum_i Energy_i} \quad (6.3)$$

In the formula of GHG, $Energy_i$ represent the total energy produced on board. $EmissionFactor_i$ represent fuel emission intensity and $\sum_i Energy_i$ represent the total energy consumed onboard. C_f values shared for both fuels in the vessel SEEMP document. LNG C_f is $2,75 \frac{ton\ CO_2}{ton\ fuel}$ and MGO C_f is $3,2 \frac{ton\ CO_2}{ton\ fuel}$. The vessel's total annual fuel consumption is 7.800 tons of MGO and 29.640 tons of LNG. Total annual CO_2 emission due to both fuel consumptions is 106.470 CO_2 ton. LNG produces 6.255 kWh per ton and MGO produces 5.337 kWh per ton. Total annual fuel consumed on engines produced 226,940,800 kWh of energy. CO_2 intensity value for this example vessel is 469 gCO_2/kWh .

According to the fuel bunker delivery note, lower heating values are 49,3 MJ/kg for LNG and 42,7 MJ/kg for MGO. Weekly energy requirement is 4,260,000 kWh. If the vessel operates solely on MGO, total annual MGO consumption will be 43.160 ton. And it causes total annual CO_2 emission is 138,230 tons. If the vessel used only LNG, weekly consumption would be 695,6 ton, and total annual consumption would be 36.171-ton LNG.

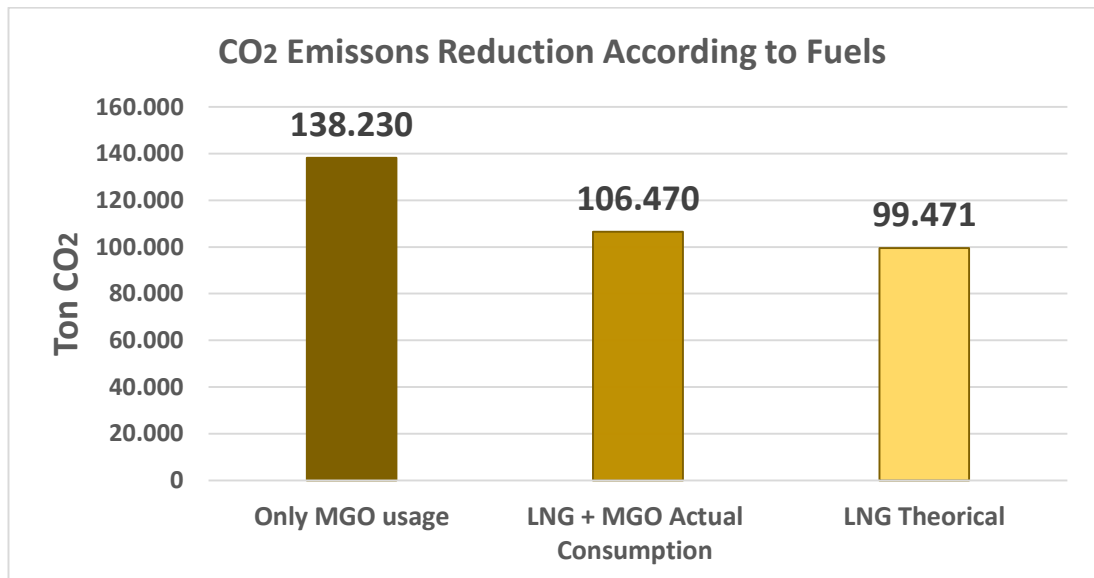


Figure 6.5 : CO_2 Emission According to Annual Fuel Consumption

Annual LNG and MGO consumption cause the total 106.470 Tons CO_2 emission. If the engines run only LNG mode, the total annual CO_2 emission reduces to 99.471 tons. As a result of calculations annually 31.760 ton CO_2 emission reduced with the usage of LNG as an alternative fuel in this cruise vessel. CO_2 reduction is 23,0% according to TTW reference values.

6.3 Well To Tank and Tank to Wake Calculation

A comparison of LNG and MGO based solely on engine exhaust emissions is not enough to evaluate their actual environmental performance. TTW emissions must be added with WTT emissions to reach realistic and comprehensive WTW values. LNG includes lower carbon content, and LNG usage emits lower engine exhaust emissions than MGO. Its production processes include natural gas extraction, processing, and liquefaction at approximately $-160\text{ }^{\circ}\text{C}$. During the production and preparation stage, LNG is more energy-intensive. WTT emissions reduce the apparent advantage of LNG relative to MGO. Since the engine does not operate continuously in gas mode during the voyage, the potential emission reductions are not fully reflected in voyage-average results.

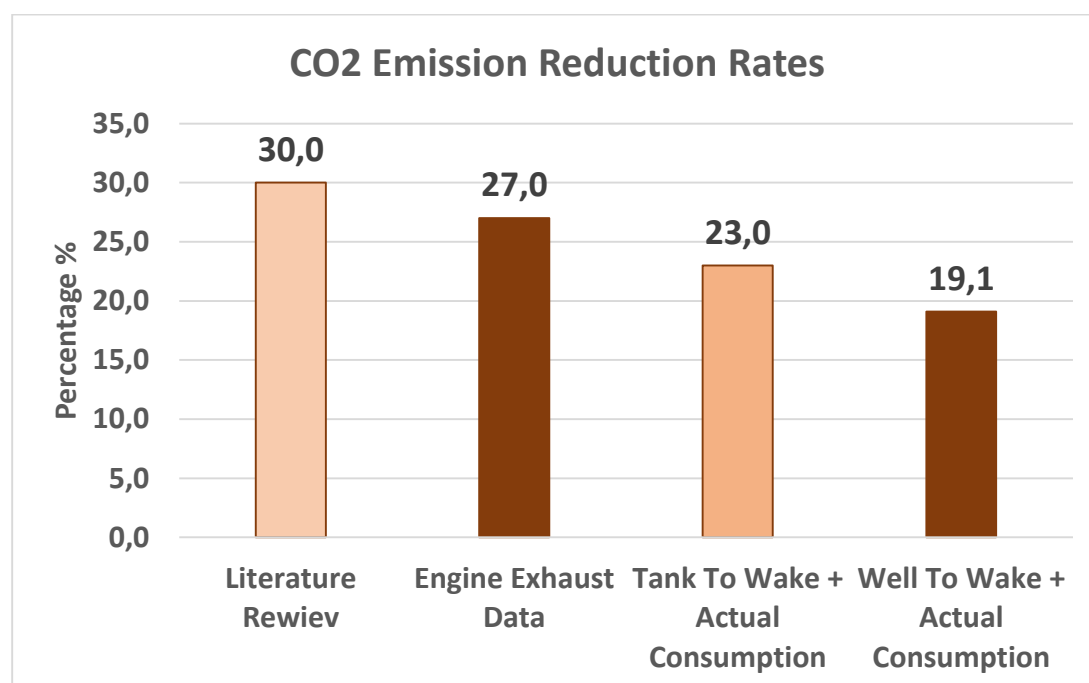


Figure 6.6 : CO_2 Emission reduction rates

Figure 6.6 illustrates the CO₂ emission reduction rates obtained using different references. The literature review indicates that LNG can reduce CO₂ emissions by up to 30%, depending on the on-board system used. Engine exhaust data collected in this study show a 27% reduction in CO₂ emissions. Emissions are evaluated using the TTW reference values, and the reduction rate decreases to 23.0%. Cruise vessel consumption calculated with the TTW reference does not represent actual life-cycle emissions. According to Pavlenko, producing and delivering 1 g of LNG to the tank results in approximately 0,45 gCO₂/g, and 1 g of MGO production and delivery results in 0,30 gCO₂/g. When WTT emissions are added to TTW emissions, the resulting WTW emission factors become 3,2 gCO₂/g for LNG and 3,5 gCO₂/g for MGO. Finally, when actual fuel consumption during the voyage is considered, and the system is compared with a reference case operating solely on MGO, an overall 19,1% reduction in CO₂ emissions is observed. This demonstrates that although LNG offers substantial reductions in engine exhaust emissions, its overall advantage diminishes when upstream emissions and real operational conditions are included.

6.4 GFI Calculation

$$GFI \left(\frac{gCO_{2e}}{Mj} \right) = \frac{Total\ WTW\ GHG(gCO_{2e})}{total\ energy\ used\ on\ board\ (MJ)} \quad (6.4)$$

In the GFI formula, GHG well to wake represents total greenhouse gas emissions, expressed in grams of *CO₂ equivalent*. Total energy used on board expressed in MJ. Unit of GFI expresses how many grams of *CO₂ equivalent* gases are emitted per megajoule of energy produced. Annual 7.800 ton MGO and 29.640 ton LNG consumed in this cruise vessel. LNG is 49,3 MJ/kg and MGO 42,7 MJ/kg.

Annually, a total of 1,813,500.00 Mj energy is used on board for propulsion and hotel consumption. Engine emits in LNG mode 692 *CO_{2e}/kWh* and in MGO mode 724 *CO_{2e}/kWh*. LNG WTW reference is 85,96 gram *CO_{2e}* per megajoule and MGO reference is 86,95 gram *CO_{2e}* per megajoule during energy production(Thinkstep Sea-LNG., 2019). Annual LNG fuel consumption emitted 125,609.222 ton of *CO_{2e}* and Annual MGO fuel consumption emitted 28,959.567 ton of *CO_{2e}*.

Total annual LNG and MGO fuel consumption emitted 154,568.789 to of CO_{2e} . As a result of calculations, greenhouse fuel intensity of this cruise vessel is 86.14 gCO_{2e}/MJ . GFI values shared according to fuel modes in Figure 6.7.

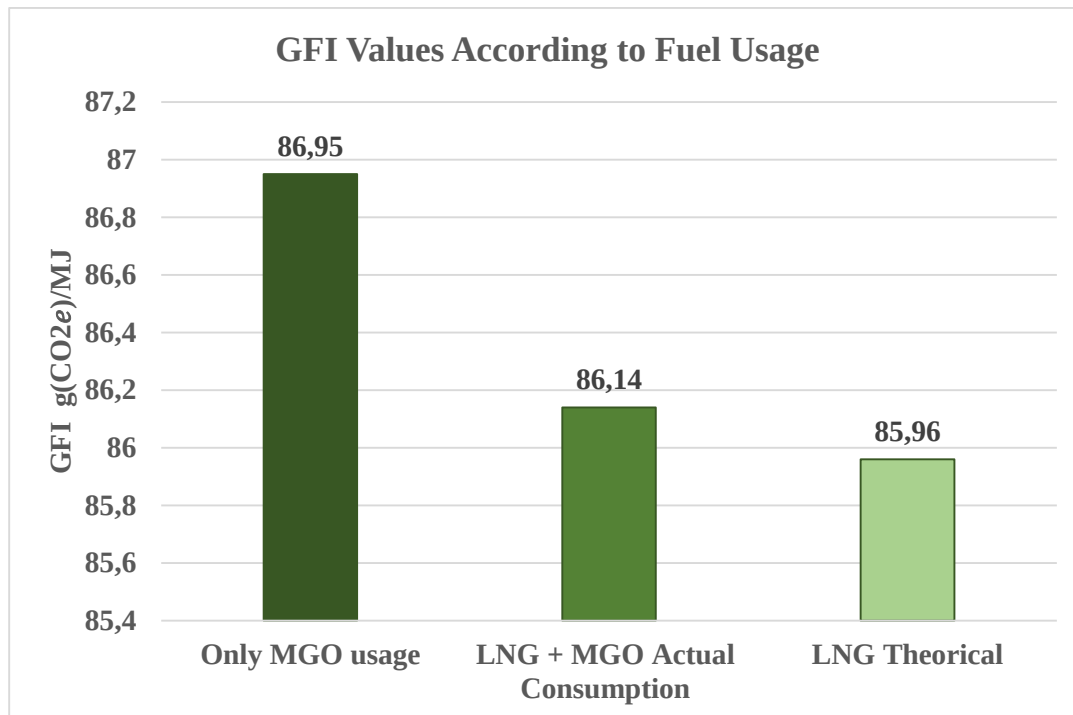


Figure 6.7 : GFI Values According to Fuel Usage

If this cruise vessel only had single fuel engines and only produced electricity by MGO fuel usage, this cruise vessel's greenhouse gas fuel intensity will be 86,95 gCO_{2e}/MJ . GFI value of this cruise vessel decreased to 86,14 gram CO_{2e} per megajoule due to the use of LNG as an alternative fuel. If this cruise vessel could theoretically operate solely with LNG, its GFI value would reduce to 85,96 gram CO_{2e} per megajoule,. GFI values very close each other because of methane slip and low pressure natural gas supply system.

WTW CO_{2e} include also methane slip and equal GHG emissions. CO_{2e} emissions factors offer a more comprehensive perspective. CO_{2e} emissions compared to theoretical values and actual values in Figure 6.8. With LNG alternative fuel usage, 1,2% CO_{2e} emission reduction is possible theoretically, but engines not only run on LNG mode but also must run on MGO mode. According to actual consumption, CO_{2e} emission reduction found 1,0% with the usage of LNG as an alternative fuel.

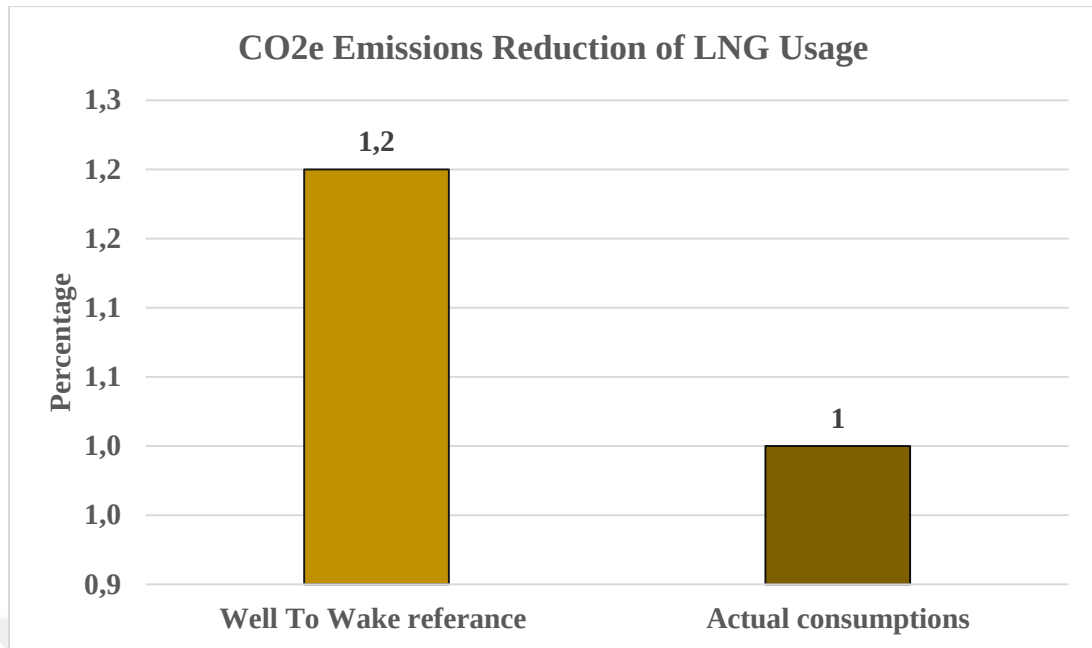


Figure 6.8 : CO_{2e} Emissions reduction of LNG usage

This vessel is just 2 years old. It is impossible to predict how often engine and gas system failures will occur in the future, and how political factors will affect the bunker network on certain routes. Not only CO_{2e} and CO_2 but also NO_x emissions compared. LNG and MGO mode NO_x emission data compared, and NO_x emission reduction found 79% on LNG mode. Engines don't operate in LNG mode for their entire lifetime for operational reasons. Engines run 12,1% on MGO mode. When running hours are included in the calculation, the NO_x reduction real value reduced to 69%.

6.5 Cost Benefit Analysis for LNG Fuel

To determine the annual LNG usage cost, one needs to know the annual LNG fuel cost, LNG storage, supply, safety, the annual maintenance cost of dual-fuel engines, LNG certification, and training costs. In this part, the Annual Average fuel consumption was examined. For a 7-day cruise voyage, 150 tons of MGO and 570 tons of LNG are used in this cruise vessel. MGO bunker price is 780 USD per ton. The price per metric ton of LNG cannot be directly compared with that of liquid fuels because LNG has a different energy density. The LNG bunker price is 745 USD per ton, but it may vary by port. In this study, prices were taken from bunker delivery notes. LNG and MGO prices vary throughout the year, as do bunker locations and political conditions. According to the fuel bunker price, LNG and MGO fuel cost

differences are just 35 USD per ton, but LNG's LHV is higher than MGO's. Fuel cost shared according to engine fuel modes in Figure 6.9 for a 7-day cruise.

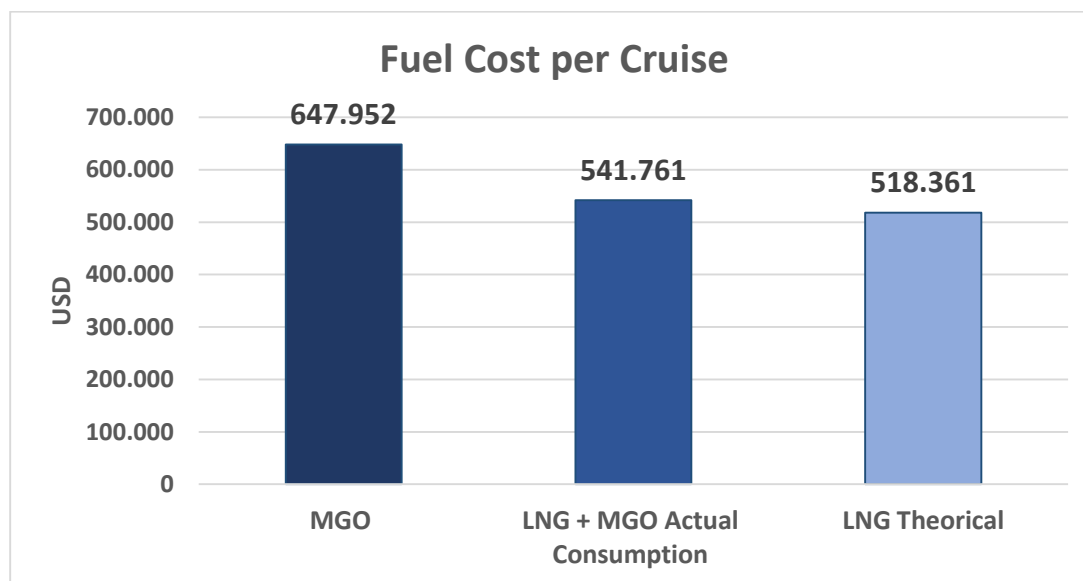


Figure 6.9 : Fuel Cost per Cruise1

The average fuel cost of a 7-day cruise voyage is 541.761 USD. If the vessel were to generate energy solely using MGO, the fuel cost would increase to 647.952 USD. In contrast, the theoretical fuel consumption cost for LNG is calculated as 518.361 USD. Based on these theoretical values, the use of LNG results in a fuel cost reduction of 20,1% compared to MGO. However, when actual operational conditions are considered, the fuel cost reduction decreases to 16,4%. This difference arises because the engines cannot operate exclusively in LNG mode throughout the voyage. As a result, the theoretical cost advantage of LNG is partially diminished under real operating conditions. Nevertheless, when evaluated annually, the lower fuel cost of LNG results in total savings of 5.51 million USD compared with MGO.

Based on DNV financial models, the payback period for LNG system investments generally ranges from 4 to 6 years, depending on fuel price differentials. The fuel price gap is 20%-25%, additional cryogenic and system infrastructure +20%, servicing needs, and reduced lubricants cause 10% lower maintenance cost. The carbon pricing effect is estimated at -30% by DNV (2024) and the IEA (2024). But in the actual cruise vessel, reality is different. Servicing needs and reduced lubricants instead of reducing its increasing. In this example, the cruise vessel experienced cylinder liner abrasion in the engine due to the use of LNG. Engines total 64 liners changed. The total 100-ton

engine oil was changed. Single-fuel engines typically use approximately 400 sensors, whereas dual-fuel engines typically use approximately 800 sensors. Some of these sensors are highly sensitive and, with LNG use, are damaged frequently. Due to these reasons, a 38,5% higher annual spare part and maintenance cost is observed.

Engines operating in LNG mode provide both fuel price and carbon tax reductions. The payback period is expected to be longer since the engine does not run in LNG mode continuously. Engines operated in MGO mode for 12,1% of total operating hours. Annual single-fuel engine maintenance costs 0.8 million USD (DNV, 2024). In the case study, the cruise vessel's annual maintenance cost for its dual-fuel LNG engine is \$1.3 million. Differences are 0.5 million USD. The total weekly cost associated with LNG fuel use, including dual-fuel engine operation and gas system related expenses, is calculated to be 566.376 USD. In comparison, the total weekly cost of MGO fuel usage combined with single-fuel engine maintenance amounts to 663.336 USD. Based on these values, LNG use yields a weekly cost advantage of 14.6% relative to MGO-based operations. Annual total cost savings reduced to 5.01 million, and the estimated payback period has increased by more than 12.1%. To accurately calculate the full payback period, the 5-year drydock expenses must also be accounted for. However, since the vessel is only 2 years old, such a date is currently unavailable. Additionally, future engine operating modes will be variable.



7. DISCUSSIONS ON THE FUTURE FUELS

Although this cruise vessel has dual-fuel engines and LNG systems, it still requires a retrofit to meet the IMO 2050 target. Without retrofit, biofuels may not be a solution to reach the IMO target. Bio-LNG is produced by liquefying biomethane derived from the anaerobic digestion of organic waste. E-LNG is synthesized through the Sabatier reaction, which combines H_2 with atmospheric CO_2 to form methane. Both e-LNG and bio-LNG are fully compatible with existing LNG infrastructure. Both include onboard cryogenic storage tanks and fuel distribution supply lines. Both fuels can be fit with current dual-fuel engine systems and can also be implemented without requiring significant modifications to current equipment or vessel architecture (DNV, 2024). This compatibility makes LNG not just a transitional solution, but also a future-ready fuel platform aligned with long-term decarbonization objectives. When Bio-LNG is used, WTW emission reductions can reach 70%-90%, depending on the feedstock and processing methods (IEA, 2024). This positions Bio-LNG as a viable pathway to substantially reduce lifecycle emissions by leveraging existing LNG technologies.

Instead of bio-LNG and E-LNG, regular LNG has a short-term decarbonization target to fit the decarbonization targets. It represents a permanent pillar within the maritime energy transition, owing to its balance of environmental benefits, technical maturity, and economic feasibility. Methanol, ammonia, and hydrogen as alternative zero-carbon fuels are becoming commercially available. LNG will remain relevant due to its established infrastructure and operational expertise. Also, LNG can serve as a foundation for the adoption of future fuels.

LNG is therefore expected to simplify the sector's progress toward the IMO's 2050 net-zero emissions target (IMO, 2024; DNV, 2024; IEA, 2024). More than 200 ports worldwide are expected to be equipped to provide LNG bunkering services around 2025 (DNV, 2024). These ports offer a robust logistics and supply network that gives LNG a 20–25-year advantage over ammonia and hydrogen, which require significant new infrastructure investment. The availability of this infrastructure also offers integration of Bio-LNG and e-LNG with actual dual-fuel engines. It minimizes the risk

of asset lock-in and prevents investments from losing value due to regulatory or market shifts (ABS, 2023). Consequently, today's investments in LNG technologies are laying the strategic groundwork for the long-term deployment of broader carbon-neutral fuel systems.



8. SWOT ANALYSIS

The SWOT analysis (Strengths, Weaknesses, Opportunities, and Threats) is a strategic decision-making tool. It used to systematically evaluate both internal and external factors affecting a technology or system (Gürel & Tat, 2017). In this study, a SWOT analysis is conducted to assess the suitability of LNG as an alternative marine fuel. Its technical, environmental, and economic characteristics are considered. Other alternative fuels, such as hydrogen, methanol, and ammonia, are mainly referenced for comparison with LNG. This study about LNG-powered vessels and SWOT analysis focuses primarily on LNG due to its technological maturity and current applicability in the maritime sector. SWOT analysis provides a balanced perspective.

8.1 Strengths

LNG is a technologically mature marine fuel. It has more than 50 years of operational experience. The first LNG carrier entered service in 1964. LNG-related production, storage, and maintenance technologies have become widely established last 50 years. (Gavory, 2009). A global LNG supply and bunkering network is already in operation and continues to expand. Bunker networks provide LNG with a significant advantage over emerging alternative fuels such as ammonia and methanol. Because new alternative fuels still don't have expanded bunker network.

LNG offers substantial reductions in air pollutants. Compared to MGO, LNG reduces SO_x and PM emissions by approximately 90–95%. With LNG usage, NO_x emissions can be reduced by up to 69%. LNG provides an overall CO₂ emission reduction of approximately 19.1% based on real operational data. Although methanol and ammonia may offer theoretical CO₂ reduction potentials comparable to or higher than LNG. LNG currently represents a more practical solution due to its established bunker network, system maturity, and operational reliability. LNG is non-toxic, non-corrosive, and non-explosive in its liquid state. It is very critical for safe usage on passenger vessels. The use of LNG is governed by the IMO IGF Code. It provides

comprehensive design and operational guidelines. For example, ammonia is highly toxic, and methanol is toxic and also flammable at ambient temperature. LNG presents a relatively lower safety risk on a cruise vessel.

LNG reserves are estimated to be enough for more than 250 years at current consumption rates (Gavory, 2009). LNG prices are generally lower than MGO prices around the world. LNG has a higher heating value than MGO and other alternative fuels. LNG usage on board provides a 14,6% total cost advantage in marine operations.

8.2 Weakness

LNG has several critical limitations. LNG has a lower energy density by volume than conventional fuel oils and some alternative fuels. LNG use on ocean-going vessels requires larger storage volumes to deliver the same energy output. Consequently, LNG fuel tanks are typically located on deck or on the vessel's outer surfaces, and these tanks may reduce cargo or passenger space.

LNG engines require pilot fuel for ignition. Typically, MGO is used for ignition. These pilot-injector systems prevent fully gas-only operation. As a result, LNG-fueled vessels cannot operate fully in gas mode for all operating hours. Also, LNG engine systems and gas plant installations require significantly higher capital expenses. LNG plant annual maintenance costs for dual-fuel engines are higher than single-fuel engines.

Although LNG usage can reduce CO₂ emissions. It cannot independently meet IMO's long-term decarbonization targets without additional technologies such as carbon capture or the use of bio-LNG or e-LNG. Instead of LNG, Ammonia and methanol offer a theoretical zero-carbon solution and can reach the IMO long-term target. Methanol provides easier integration into existing fuel systems. However, both alternatives currently face significant technical and safety challenges that limit their immediate usage on current vessels. The lack of a bunker network is also limiting other fuels.

8.3 Opportunities

Technological advancements in engine design are expected to increase of operating hours in LNG mode. If LNG usage can increase, both economic and environmental performance can also increase. Dual-fuel LNG engines also offer fuel flexibility, enabling future operation with bio-LNG or synthetic LNG. Also, zero-carbon LNG can be used without requiring major modifications to existing engine systems

The LNG bunker network continues to expand, and increased adoption is expected to reduce maintenance and spare part costs. Ammonia has insufficient bunkering infrastructure, and methanol is still undergoing regulatory and operational adaptation. LNG currently offers a more advanced supply chain for spare parts.

If LNG is combined with carbon capture systems or renewable LNG pathways, LNG has the potential to fit the IMO net-zero decarbonization target. This combination can increase LNG life during the maritime energy transition.

8.4 Threats

Several external factors pose challenges to LNG adoption. An increase in global LNG demand could lead to higher bunker prices and also reduce the fuel's economic attractiveness. The LNG bunkering network is still expanding, but regional limitations and supply interruptions may still occur, and this affects operational persistence.

Operational challenges such as methane slip and boil-off gas management remain key concerns. Methane slip is an important threat because it causes greenhouse gas emissions. Additionally, if future IMO regulations get more stringent about carbon reduction requirements, LNG may no longer be sufficient to meet this target of decarbonization. World shipping industry preference may shift toward fuels such as ammonia or synthetic methanol. There is a potentially slowing investment in LNG technologies and infrastructure. So, LNG investments can be a waste for vessel owners in the long term. Due to political and economic reasons, if IMO starts to change decarbonization targets, LNG can be disfavored.



9. CONCLUSION

In this case study, the difference in carbon emissions per kWh between MGO and LNG was observed 23% according to TTW reference values. Dual-fuel engines cannot operate continuously in gas mode. Due to this reason, the actual emission reduction achieved under real operating conditions is lower. Engines on board ran in MGO mode ranged from 13% to 18%. As a result, the WTW CO₂ emission reduction for the examined vessel decreased from an initial value of 23% to 19,1%. Furthermore, when upstream emissions are included, the overall WTW CO_{2e} emission reduction achieved through LNG use was limited to 1,0% due to methane slip.

To reach a meaningful conclusion, a cost–benefit analysis was conducted to assess whether the environmental and economic gains justify the required investments and operational expenditures. The cost figures used in this assessment are representative of real operational conditions and include the following assumptions:

- 70% higher engine production cost for dual-fuel engines compared to single-fuel engines.
- Additional capital investments for LNG storage, safety, and fuel supply systems.
- 38,5% higher annual spare part and maintenance costs due to increased system complexity.
- Additional operational risks and uncertainties associated with LNG systems.
- Operation in MGO mode for 12,1% of total engine running hours.

Despite these increased costs, the overall environmental and economic performance benefits of LNG usage can be summarized as follows:

- 19,1% reduction in CO₂ emissions and an 1,0% reduction in CO_{2e} emissions, based on actual fuel consumption and WTW reference values.
- 69% reduction in NO_x emissions.
- 90% reduction in SO_x and particulate matter emissions.

- Annual fuel cost reduction of 5.51 million USD.
- 1,0% Decrease in the GFI value.
- Total cost saving of 14,6% when fuel and maintenance cost components are considered, instead of 20,1%.

As a result, the examined cruise vessel is equipped with dual-fuel engines and LNG systems, but additional retrofitting is still required to achieve the IMO 2050 decarbonization targets. There is no fundamental difference between installing carbon capture systems or exhaust gas cleaning systems on LNG dual-fuel engines and on conventional diesel-only engines. Further investment is necessary to reduce exhaust gas emissions in both cases. To mitigate the long-term limitations associated with LNG, it may be more rational to select engine technologies capable of operating on multiple alternative fuels, such as LNG, methanol, and ammonia, from the initial design stage rather than relying on retrofitting. However, such decisions must account for the availability of alternative-fuel bunkering infrastructure along the vessel's operational routes.

Engine manufacturers have begun developing propulsion systems powered by hydrogen, ammonia, and methanol. These emerging technologies also introduce significant technical challenges. Failures in engines and fuel supply systems operating on new fuels can directly affect a vessel's maneuverability and navigation continuity, particularly in single-engine, single-propeller vessels. The solution of such failures may require direct intervention by the equipment manufacturer, while the limited availability of spare parts for alternative fuel systems can further disrupt maintenance and supply processes. Moreover, unforeseen malfunctions associated with these technologies often demand specialized technical expertise. Technical support may not be readily accessible during regular operations worldwide. Even this example vessel has a fixed home port, but still faces a lack of LNG bunkers and spare parts. Therefore, when selecting machinery for new ship designs, it is essential for technical decision-makers to evaluate not only the potential for emission reduction but also factors such as operational reliability, maintenance requirements, spare part availability, and the vessel's intended operating region.

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PUBLICATIONS, PRESENTATIONS AND PATENTS ON THE THESIS:

- **Altun R. Zincir B.** 2025: *Environmental and Economic Analysis of a Ship Using LNG-MGO as Alternative Fuel*. 7th International Cappadocia Scientific Research Congress, August 2–4, 2025, Göreme, Nevsehir, Türkiye, *The Proceedings Book*, pp. 1177–1178.

OTHER PUBLICATIONS, PRESENTATIONS AND PATENTS: