Research Article

Journal of Supply Chain Engineering and Logistics Optimization

Steering Toward a Sustainable Future: A Comparative Technical- Economic Review of Maritime Industry Options

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Submitted: 21 October 2025 **Accepted:** 31 October 2025 **Published:** 07 November 2025

https://doi.org/10.63620/MKJSCELO.2025.1003

Citation: *Almeida. J. (2025). Steering Toward a Sustainable Future: A Comparative Technical- Economic Review of Maritime Industry Options. J Sup Cha Eng and Log Opt, 1(1), 01-14.*

Abstract

Over the past two decades, the world has faced record-high temperatures and increasingly extreme weather events, underscoring the urgency of addressing climate change. Responsible for approximately 2-3% of global CO_2 emissions, the maritime sector faces increasing regulatory pressure under the International Maritime Organization (IMO) to align with its greenhouses gas reduction strategy, which aims for net-zero emissions by 2050. Since the adoption of MARPOL annex VI in 2005 and the subsequent introduction of new air pollution and energy efficiencies regulations, shipowners have been compelled to implement a range of compliance and mitigation measures, including low sulfur fuels, installation of exhaust gas systems and developments of innovative alternative propulsion technologies. This study presents a comprehensive technical-economic assessment of retrofit alternatives for a 1998-built vessel to evaluate realistic pathways toward compliance and sustainability within the sector. Using mathematical modeling and real operation data, the analyses quantify the energy and emission impacts of each option, highlighting their respective environmental and financial implications for aging ships. The findings provide critical insight into the trade-offs between immediate regulatory compliance and long-term decarbonization, contributing to the broader discussion on the technological and operational strategies required to achieve sustainable maritime transport.

Keywords: Biofuels, Decarbonization, Energy Efficiency, Sustainability, Regulations, Shipping Industry.

Introduction

Global warming remains one of the most urgent environmental challenges of our time, primarily driven by the escalating emissions of greenhouse gases. Among the various sources of pollution, maritime transportation plays a pivotal role in the deterioration of air quality. Large vessels, which predominantly rely on high-sulfur fossil fuels, emit significant quantities of sulfur dioxide (SO_2), nitrogen oxides (NO_x), and particulate matter. These emissions not only accelerate climate change but also pose severe risks to human health, highlighting the critical need for sustainable alternatives in the maritime industry.

In light of this situation, mitigating emissions from the maritime sector is both a critical and time- sensitive imperative. Achieving this objective is guided by three fundamental principles: the implementation of environmental regulations and policies, the evolving expectations of shipowners and consumers, and the availability of investment and financial resources [1]. As emphasized by Eirik Ovrum, Principal Consultant at DNV GL and lead author of the Maritime Forecast to 2050: "The maritime sector needs knowledge and evidence of designs, fuels, and fuel technologies that are effective, available, and affordable."

The pathway toward decarbonization requires the large-scale adoption of advanced technologies capable of achieving measurable reductions in greenhouse gas emissions while maintaining vessel performance, safety and economic viability. Current developments include the optimization of propulsion and power systems through hybridization and electrification, the application of energy- efficient hull and propeller designs, the use of digital performance monitoring tools, which can reduce fuel consumption by up to 10-15% through optimized voyage and engine management [2, 1]. In parallel, alternative fuels such as liquefied natural gas (LNG), methanol, ammonia and hydrogen are undergoing comprehensive "well-to-wake" life-cycle assessments, demonstrating potential GHG emission reductions ranging from approximately 20% for LNG to over 90% for renewable hydrogen and ammonia, depending on the production pathways [3, 4]. The integration of these technological and operational innovations establishes the foundation and a decisive shift in maritime engineering toward sustainable and low-emission operations.

Journey Toward Sustainability

Concerns regarding air pollution from the shipping industry have persisted for several decades, reflecting the sector's substantial contribution to global greenhouse gas and pollutant emissions. The International Maritime Organization (IMO) has addressed these challenges through its technical committees since the 1970s, stablishing the foundation for systematic regulation of maritime air quality.

Following the adoption of the Kyoto Protocol in 1997, the IMO introduced Annex VI to the MARPOL Convention, which set specific air pollution control standards for ships and entered into force in 2005. This regulatory framework represented a critical step in recognizing the environmental impact of maritime operations and in providing a basis for subsequent measures aimed at reducing emissions from the sector.

A major regulatory milestone was achieved in 2013 with the implementation of the Energy Efficiency Index (EEDI) for new constructions and the Ship Energy Efficiency Management Plan (SEEMP). This was a critical step for the sector, marking the first mandatory application of energy efficiency measures to ships. Although the concept was initially somewhat abstract, its practical relevance gradually increased and became more tangible and realistic in subsequent years through the IMO's development of strategic plans and initiatives aimed at fostering industry-wide transformation.

To complement these measures, the IMO later introduced the Energy Efficiency Existing Ship Index (EEXI), designed to assess and enhance the energy performance of ships already in service. This measure, alongside the recently implemented Carbon Intensity Indicator (CII), applies to both new and existing ships, providing an operational metric for measuring carbon emissions per transport work. Further, the adoption of IMO's Initial Greenhouse Gas (GHG) Strategy in 2018, served to integrate these mechanisms, accelerating the transition toward decarbonization. Together, these indices provide a robust framework for ensuring consistent monitoring and regulatory compliance, constituting a key component of the IMO's broader strategy to reduce maritime emissions, facilitating fleet modernization, and promoting data-driven energy management. A detailed discussion of these indices is presented in Sections 4.3 and 4.4.

In response to the significant progress made in the sector, IMO has revised its strategy in 2023, setting more ambitious emission reduction targets relative to 2008 levels: a 40% reduction by 2030, 70% by 2040, and a net-zero goal by 2050 [2]. Achieving these targets requires a multidimensional approach, integrating alternative fuels, technological innovation, operational efficiency, and digital transformation. Research emphasizes that no single solution can ensure full decarbonization; rather, a portfolio of complementary measures is essential [5, 6].

As a result, the energy transition within maritime sector has gained significant momentum, according with the Green Technology Tracker, released beginning of 2025 by Clarkson Research group, by mid-2024, approximately one-third of all newly built vessels were designed to operate on alternative fuels. Newbuilding orders for such vessels represented about half of total tonnage ordered that year, reflecting a substantial shift in investment priorities toward low and zero carbon technologies. The data summarized in Table 1 illustrates the increasing adoption of a range of alternative fuels, including Liquefied Natural Gas (LNG), methanol, ammonia, Liquefied Petroleum Gas (LPG), hydrogen and fuel cells [4, 7].

Table 1: Orders of alternative fuels vessels in 2024, compared with 2023 by fuel type

Fuel Type	Orders* in 2024	Orders* in 2023	Growth (%)	"Ready" Vessels	Notes
LNG	390	109	258%	–	Excludes LNG carriers
Methanol	118	49	141%	320**	Predominant "ready" fuel
Ammonia	25	15	67%	130**	Predominant "ready" fuel
LPG	72	42	71%	–	–
Hydrogen	12	4	200%	–	Only 3 in service currently
Fuel Cells	1	0		–	Only 4 in service currently

* "Orders" refers to vessels newly ordered within the year.

**"Ready Vessels" indicates ships designed or equipped to operate on the respective alternative fuel immediately or in the future once the fuel becomes available.

Source: Clarkson Research, Green Technology Tracker, 2025; DNV, Veracity website [4, 7].

Clarkson Research projects that by the end of the decade, more than 20% of total fleet capacity will be capable of operating on alternative fuels. Furthermore, orders for "ready" vessels have increased around fifth percent of all orders. Among these fuels' types, ammonia and methanol have emerged as the predominant "ready" options, with 130 and 320 vessels ordered, respectively, indicating that shipowners are positioning for future market availability of these fuels [4].

Recent studies assessing potential fuels for maritime decarbonization evaluated their respective GHG reduction potential, financial viability, and environmental impact. For instance, in my master's thesis at the Infante D. Henrique Superior School, I conducted an experimental study exploring in depth these fuels' prospects, focusing on their GHG reduction potential, cost- effectiveness, and environmental implications.

Basically, the majority of alternative fuels under consideration follow a similar developmental trajectory: from fossil-based fuels, commonly designated as grey fuels or so- called blue fuels when produced through carbon capture and storage technology to reduce the greenhouse gases (GHG) generated during their production process, to bio-derived options, fuels generated from renewable electricity, also designated as green fuels. It's crucial to note that most of these alternative fuels are presently being developed in both blue and green forms but due to higher costs, the use of blue options still a better option and it has been considered as transitional fuels, until necessary infrastructure, market availability and technological maturity of green alternatives are fully established [8].

Regarding the use of grey methanol, grey ammonia and grey hydrogen, while currently the most affordable option today as marine fuels would, when assessed on well-to-wake basis, result in a higher GHG emissions than the conventional marine fuels they are intended to replace. It demonstrates that such options are not viable decarbonization pathways, even in the short term. Conversely, grey Liquefied Natural Gas (LNG) offers an immediate GHG reduction potential of up to 23%, once methane slip is accounted for, in two stroke engines typically used by large vessels that transport the majority of global cargo [9]. Therefore, methanol, ammonia and hydrogen used in maritime transport must be produced as green fuels to achieve parity with Very Low Sulfur Fuel Oil (VLSFO) and to comply with regulatory frameworks such as FuelEU Maritime [10].

Ammonia synthesis, through Haber-Bosch process, designated as green ammonia, has not been widely explored as a marine fuel until recently, but Clarkson Research orders numbers reveals that this option is emerging as a compelling carbon-free option, however safety concerns, are considered more critical than those associated with hydrogen and methanol [10]. Risk studies emphasize that large ammonia leaks pose significant potential impacts, underscoring the necessity for developing clear guidelines for safe bunkering and port operations, a context where regulatory instability currently contributes to uncertainty [11]. Furthermore, ammonia as a marine fuel is further facilitated by 58-DNV-classes vessels already operating with 'ammonia ready' notation, indicating preparedness for future conversions and the other 130 orders on the way [1, 4].

With regards to methanol, although is classified as a toxic substance, it has become the predominant choice among shipowners after LNG, as economically viable alternative to fossil fuels for the near future, as evidenced by Clarkson Research, which reports 118 vessels currently on order [4]. Methanol is considered a technically feasible option for reducing emissions, with several studies indicating significant environmental improvements, regardless of whether it is produced from natural gas or renewable sources [12]. The findings suggest lower emissions of nitrogen oxides (NOx) and a more favorable carbon footprint compared with conventional fuels.

However, the use of methanol as a marine fuel presents several challenges. Its immiscibility with Diesel Oil requires modifications in the marine diesel engines, including adjustments to injection systems, fuel tanks and piping arrangements. Safety in onboard storage also represent a major concern. Moreover, methanol has a flash point below the minimum requirements established by the International Convention for Safety of life at Sea (SOLAS) and the IMO, thereby mandating full compliance with the provisions of the International Code of Safety for Ships Using Gases or Other Low-Flashpoint Fuels (IGF Code). These requirements include comprehensive risk Assessments to ensure the prevention of fire and explosion hazards, as well as the construction of all installation in accordance with the Code's technical specifications, subject to prior approval before operation.

Consequently, methanol has so far been less favored by shipowners compared with Liquefied Natural Gas (LNG), primarily due to infrastructure limitations. According to a report by FC Business Intelligence Ltd. (FCBI Energy), commissioned by the Methanol Institute, the current global infrastructure for methanol is primarily based on its distribution within the chemical industry, providing it with widespread availability. However, it is imperative to develop dedicated supply chains specifically for maritime applications [12, 13].

Nonetheless, methanol is increasingly viewed as a promising alternative for the near future – a perspective shared by a growing number of shipowners who have already placed orders for methanol-ready vessels. According to Clarkson Research, 320 ships designated and equipped to operate on methanol have already been ordered, reflecting a strong expectation of its expanded adoption in the coming years [4].

Finally, technologies such as liquid hydrogen and fuel cells are beginning to appear in the maritime scenario through pilot projects and smaller vessels operating partially with these solutions, however their high cost, significant storage complexity (in the case of liquid hydrogen), and limited infrastructure currently render them less realistic for achieving immediate large-scale objectives [14-16]

The global transition toward sustainable maritime transport aims to reduce environmental impact and combat global warming, now supported by a more defined roadmap for achieving these goals. However, the successful realization of these objectives requires a coordinated effort among governments, businesses, and research institutions to implement effective and economically viable solutions. Analysis of the global fleet age, based on data from Marine Traffic, reveals that currently, 77% of all vessels are 15 years old, with 59% exceeding 25 years [17]. This aging fleet profile raises critical questions regarding how existing vessels can be adapted to meet evolving sustainability requirements and what measures are necessary to achieve compliance without compromising operational viability. Addressing this challenge is the central objective of this paper, which undertakes a technical-economic assessment to identify the most feasible options for the current fleet - particularly older vessels- to comply with current and future environmental regulations. Such analysis is essential for enabling the maritime sector to effectively balance sustainability objectives with operational and economic efficiency.

Case Study

Since 2020, strict limits on sulfur content in marine fuels have led shipowners to adopt various compliance strategies, with exhaust gas cleaning systems (scrubbers) emerging as a leading solution. Although effective in reducing sulfur oxides (SOx), scrubbers raise concerns about increased fuel consumption and the resulting emissions of other pollutants, thereby questioning their alignment with broader decarbonization goals. Despite ongoing research, comprehensive assessment of the sustainability impact of scrubbers remains limited, highlighting the need for deeper evaluation of their role in maritime emission reduction.

Contribution and Structure of the Study

This paper provides a comprehensive technical-economic analysis of various retrofitting options for a 1998-built ship to align with the current push towards decarbonization. Three retrofit possibilities are considered:

1. Use of low-sulfur fuel Oil (LSFO).
2. Installation of an exhaust gas scrubber system, enabling the continued use of heavy fuel oil (HFO).
3. Conversion to LNG as an alternative fuel.

Furthermore, the study includes a detailed technical evaluation of integration, focusing on its role in reducing operational costs associated with the use of heavy fuel oil in diesel engines. The analysis offers a broader perspective on scrubber installation, exploring its potential to promote sustainability in maritime transport despite the challenges related to non-biofuel combustion.

The paper includes a technical evaluation of the impact of scrubber installations on a cruise ship, examining their precise role in the decarbonization process. This analysis is supported by mathematical calculations based on real operational data from existing onboard equipment and machinery.

Scrubber System

With the implementation of sulfur (SOx) restrictions by the International Maritime Organization, three primary alternatives have emerged for ensuring environmental compliance in maritime transport: the use of low-sulfur fuels, the adoption of liquefied natural gas (LNG) as fuel, and the installation of exhaust gas cleaning systems.

The application of exhaust gas cleaning systems has been extensively studied and compared with the use of LNG in the literature. Due to the high investment costs associated with LNG systems, they are generally considered more viable for new vessels, while scrubbers have become increasingly popular for retrofitting in response to the 2020 regulations [18]. Experimental studies suggest that these systems can reduce SOx emissions by up to 99%, though their effectiveness is influenced by factors such as engine type and operational load regime [19]. However, a key question remains: do scrubbers merely displace pollutants rather than eliminate them, potentially increasing the emissions of other pollutants, such as CO2 and NOx.

Another important consideration is the selection of the most suitable scrubber system for a particular vessel. Open-loop scrubbers offer a simpler and more cost-effective solution but may face restrictions in certain port areas due to stringent wastewater discharge regulations, which could affect operational efficiency. In contrast, closed-loop scrubbers require careful management of wash water, including the implementation of additional treatment or storage systems, which shipowners must thoroughly assess.

Data Collection

A typical cruise ship with 272.8m was selected as the model for this study. Its characteristics and specifications are detailed in table 2. The data for the analyzed voyages were collected from the ship's electronic logbook, covering the month of April 2024.

To conduct this analysis, energy consumption data for a one-month period of the studied vessel's voyage were initially gathered. The ship typically operates on routes between the United States and the eastern Caribbean. Using real-time voyage data collected during April 2024, the average duration spent in each operational mode of the passenger ship is presented in figure 1.

Table 2: Ship's Main Specifications

Type of Ship	Cruise Ship
Gross Tonnage	102,239 tons
Deadweight	9,470 tons
Length Overall	272.8 m
Breadth Moulded	35.5 m
Propulsion Power	Diesel-Electric / max. Prop Power = 2x 20 MW a at 150 RPM
Diesel Generator	6 sets x Wartsila Sulzer ZA40S diesel generators
Generator Power	4 Sets x 11.2MW + 2 Sets x 8.4 MW = 61.6 MW Tot. Nom. Power.
Scrubber type	6x Open-Loop Scrubber

Source: Provided by shipowner

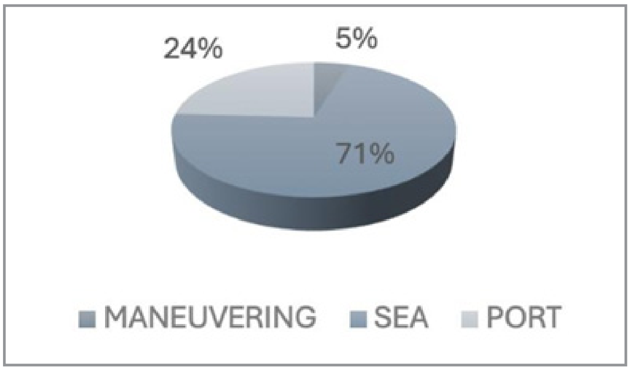

Figure 1: Ship operational profile

In the absence of pre-installation data for the exhaust gas cleaning systems and considering the specific characteristics of the studied vessel, a new methodological approach was adopted. Given that the vessel is equipped with diesel-electric propulsion, energy demand and specific fuel oil consumption (SFOC) were utilized to estimate fuel consumption and pollutant emissions for each scenario considered.

Methodology

This study explores the role of exhaust gas cleaning systems in the decarbonization of maritime transport, assessing their effectiveness in reducing SOx and other harmful gases that impact both the environment and human health. Additionally, it examines complementary technologies that may contribute to the sustained reduction of emissions, employing a detailed methodological approach, as illustrated in figure 2.

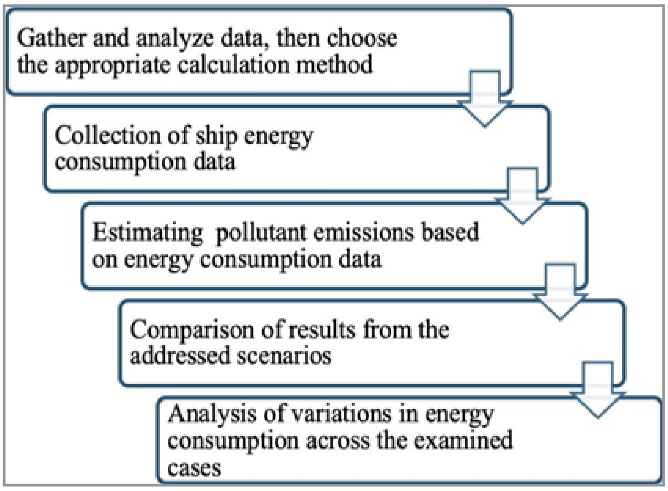

Figure 2: Study Methodology

To estimate total pollutant emissions, a method outlined in the Emission Inventory Guidebook 2023, published by the European Environment Agency (EEA), was used. The guidebook, first published in 1996, included a chapter on estimating emissions from navigation starting in 2009. Since then, it has been continuously updated and adopted by numerous scientists, also being referenced in the Fourth IMO Greenhouse Gas Study – 2020. [2, 20]. According to the EMEP/EEA, emissions can be categorized into three levels of increasing complexity. These methodologies, which exhibit slight variations, are generally grouped into three approaches: the bottom-up approach, the top-down approach, and a combination of both. In the literature, these approaches are often referred to as Tiers 1-3, differing in the emission assessment process and the geographic characterization of the ship [20, 21].

The complete "bottom-up" approach assesses emissions from an individual ship by considering its characteristics, such as type, construction date, cargo, engine power, and fuel consumption under specific load conditions. This method helps identify the primary contributors to emissions, offering a clear understanding of their impact. In contrast, the "top-down" approach takes a broader perspective, relying on generalized factors such as fuel use statistics and engine types across ships to estimate emissions. This study employs a hybrid method, known as the Tier 3 algorithm, which combines both "bottom-up" and "top-down" approaches. The hybrid method is recommended when detailed data on ship movements and technical characteristics (e.g., size, engine technology, installed power, fuel consumption, and operating hours in different activities) is available. This enables the estimation of emissions during open-sea navigation, port approach maneuvering and docking.

$$E_{trip} = E_{port} + E_{maneuvering} + E_{sea} \qquad \text{(Eq.1)}$$

Where:

E trip: Emissions throughout a complete journey (tons);

E port, maneuvering, sea: Emissions throughout each different activity. The Tier 3 methodology calculates emissions by using installed capacity and fuel consumption, considering both main and auxiliary engines. Emissions for a trip are determined by summing the emissions from each segment of the journey. When fuel consumption is known, emissions can be calculated using fuel-specific emission factors for different phases of navigation (cruise, dock, and maneuvers) [21]. Thus, pollutant emissions can be calculated by using Equation 2.

$E_{trip} = \Sigma_p(FC_{j,m,p} \times EF_{fi,j,m,p})$ (Eq.2)

Where:

E trip: emissions throughout a complete journey (tons); FC: fuel consumption (tons);

EF: emission factor (kg/ton);

i: pollutant (NOx, SOx, CO2, PM);

m: fuel type (HFO, MDO/MGO, LNG);

j: engine type (low, medium, and high speed);

p: different phases of the journey (cruise, hotel, and maneuvers).

Emissions Factors

Accurate emission estimation requires specific emission factors at each calculation level. While some methodologies use predefined tabulated values, this study adopts a more advanced approach that calculates load-dependent emission factors. It is important to note that variations in emission factor calculations can lead to discrepancies of up to 30% in total emissions [2].

Emission factors are determined using two primary methods. The energy-based approach estimates emissions based on engine power output (Wi), applying an energy-based emission factor (EFe) in grams per kilowatt-hour (g/kWh). This method is used for pollutants such as NOx, CH_4, CO, N_2O, PM, and NMVOC. In contrast, the fuel-based approach calculates emissions by multiplying hourly fuel consumption (FCi) by a fuel-based emission factor (EFf), expressed in grams per gram of fuel (g/g), and is used for CO_2 and SOx emissions.

Extensive testing on engines operating with heavy fuel oil (HFO) and marine gas oil (MDO), along with manufacturer data, suggests that energy-based emission factors (EFe) should be converted into fuel-based equivalents (EFf) using baseline specific fuel consumption (SFC), as emission calculations are primarily conducted using fuel-based factors [22], as expressed in the following equation:

EFf= EFe

SFCbase (Eq.3)

The baseline specific fuel consumption (SFC) for main engines, auxiliary engines, and boilers represents the minimum specific fuel consumption along the load curve, indicating the point of maximum fuel efficiency for the engine [2]. Table 3 displays the baseline SFC values used in this study.

The methodologies and formulas used in this study were initially introduced in the IMO Third Greenhouse Gas Study and later refined in the Fourth IMO Greenhouse Gas Study [2, 23]. This revision integrated findings from literature reviews, engine manufacturers, research institutions, academic studies, and classification societies, providing a more accurate and up-to-date framework for emission calculations.

Table 3: Specific Fuel Consumption (SFC)

Heavy Fuel Oil (HFO)	205
Marine Gas Oil (MGO)	190
Liquefied Natural Gas (LNG)	156
Methanol (MeOH)	370

Source: IMO Fourth GHG Study, 2020 [2].

Carbon Dioxide (CO2)

IMO has released the CO2 emission factors expressed in emissions by fuel quantity in document MEPC.1/Circ.684 [24]. These emission factors represent the predefined set to be used in the Monitoring, Reporting and Verification of CO2 emissions (MRV Regulation), as detailed below.

Table 4: Emission factors for different types of fuels and their carbon content

Fuel	Carbon Content	EFf (gCO_2/gfuel)
HFO	8.493	3.114
MGO/MDO	8.744	3.206
LNG	0.75	2.75
MeOH	375	1.375
LSFO 1.0%	8.493	3.114

Source: IMO, 2009. MEPC.1/Circ.684 [24].

The HFO emission factor is primarily based on the carbon content and calorific value of the fuel. However, the sulfur content of HFO can also impact the emission factor, with a typical sulfur rate ranging from 2.5% to 3.5% generally used for calculations [2].

For engines that employ pilot fuel injection in LNG-consuming systems, the CO2 produced by the pilot fuel is incorporated into the EFf by weighting the mixture of main and pilot fuels in the total mass of CO2 emitted [2].

Sulphur Oxides (SOx): As is well known, SOx emissions vary depending on fuel consumption and sulfur content, although they can be reduced through the use of scrubbers. Initially, the absence of scrubbers on the ship under study will be considered to estimate the total untreated emissions, providing a basis for comparison. The SOx emission factor, based on fuel (g SOx/g of fuel), is calculated as follows:

$EF_{f,SOx} = 2 \times 0.97753 \times S$ (Eq.4)

In this equation, it is assumed that 97.753% of the sulfur in the fuel is converted to SOx (with the remainder converted to sulfate/sulfite aerosol and classified as part of the particulate matter). The "2" reflects the ratio of the molecular weight of SO_2 to sulfur, as the majority of SOx emissions from ships are in the form of SO_2 [2].

Nitrogen Oxides (NOx): Nitrogen oxides (NOx) emissions result from the high combustion temperatures in the engines, which cause the oxidation of nitrogen present in the intake air as well as nitrogen particles in the fuel. For engines operating on the Diesel cycle, the NOx emission factor depends on the engine speed and the ship's Tier (i.e., the year the engine was manufactured), regardless of whether the ship is operating in a Nitrogen Oxide Emission Control Area (NECA). This is based on the assumption that no engine can have an emission factor higher than the limit set by Annex VI of IMO MARPOL Regulation 13 [25]. Table 5 presents the NOx emission factors as a function of engine rotational speed.

Table 5: NOx Emission Factors

Tier	Date of Ship Construction (on or after)	Total weighted cycle emissions limit (g/kWh)		
		n=rpm (Engine rate speed)		
		n>130	n=130-1990	n≥2000
I	1 January 2000	17.0	45 n^(-0.2)	9.8
II	1 January 2011	14.4	45 n^(-0.2)	7.7
III	1 January 2016	3.4	9 n^(-0.2)	1.96

Particular Matter: According to the IMO's Fourth Greenhouse Gas Study, the emission factors for particulate matter are influenced by the sulfur content of the fuel and are therefore reduced when operating with lower sulfur fuels, such as those used in Emission Control Areas (ECAs). For engines running on heavy fuel oil (HFO) and marine diesel oil (MDO/MGO), the particulate emissions, based on the sulfur content of the fuels used in april 2024, are estimated in this study using the following formulas.

HFO

$$EFe = 1.35 + SFCi \times 7 \times 0.02247 \times (S - 0.0246) \qquad (Eq.5)$$

MDO/MGO

$$EFe = 0.23 + SFCi \times 7 \times 0.02247 \times (S - 0.0024) \qquad (Eq.6)$$

The number 7 in the equations represents the molecular weight ratio between the sulfate of the particles (PM) and sulfur, while the value 0.02247 reflects the proportion of sulfur in the fuel that is converted to PM sulfate [2].

Table 6: Emission factors used in the emission calculation

Fuel	CO2	NOx	SOx	PM
Heavy Fuel Oil	3.114	62.980	72.337	8.220
Marine Gasoil	3.206	67.960	196	990
Liquefied Natural Gas	2.750	8.333	0	5.320

Emission Estimation

By collecting energy consumption data with and without the use of exhaust gas treatment systems, along with other installed technologies, the ship's fuel consumption in the analyzed scenarios was estimated. This analysis enabled the quantification of pollutant gas emissions, with the results presented in table 7.

Table 7: Pollutant Emission

Fuel	CO2	NOx	SOx	PM
HFO	8419.3	170302.6	195576.6	22227.4
HFO + Scrubber +FID*	8726.5	176516.5	6081.4	20734.6
MGO	8033.8	170302.6	489.9	2481.6
LNG	5657.9	17145.3	0.4	10946.6

*FID – Equipment designed to reduce the formation of nitrogen oxides and particulate matter, while improving combustion efficiency through the emulsification of fuel in water.

The analysis of the calculated scenarios indicates that the implementation of scrubbers and other emission reduction technologies has effectively reduced sulfur and particulate matter emissions. However, this reduction is currently associated with an increase in the vessel's energy consumption, primarily due to the greater utilization of heavy fuel oil (HFO). The continued reliance on HFO, facilitated by these technologies, allows the vessel to operate more frequently without transitioning to lower-sulfur alternatives such as marine diesel oil (MDO). Consequently, the observed increase in energy consumption and the sustained combustion of HFO result in elevated carbon dioxide (CO_2) and nitrogen oxides (NOx) emissions. This outcome underscores the imperative for developing and adopting alternative, lower-carbon solutions to address the holistic scope of maritime environmental impact.

The use of two distinct fuel types, each with different pollutant emission factors during the considered periods, led to variations in the emissions released into the atmosphere. The conclusions regarding pollutant emissions are presented in table 7. It is observed that, with the installation of the scrubbers, SOx emissions were reduced by 97%. However, the increased consumption of heavy fuel oil resulted in a 4% rise in CO_2 and NOx emissions. While particulate emissions were reduced by 7%, they continue to present a challenge that needs to be addressed.

Compared to other fuels, such as MGO, there is a notable difference in emission levels. While the installation of scrubbers results in an 8% reduction in carbon emissions, this remains a concern. In contrast, sulfur and particulate emissions are significantly reduced by 92% and 88%, respectively. These results confirm that scrubbers are effective in meeting sulfur emission regulations but do not align with the IMO's decarbonization strategy. To support this strategy, scrubbers must be integrated with additional technologies to further reduce greenhouse gas emissions and contribute more effectively to decarbonization efforts.

In comparison, liquefied natural gas (LNG) leads to immediate reductions across all pollutants analyzed in this study. Specifically, CO2 emissions decrease by 35%, nitrogen oxide emissions by 90%, while sulfur emissions are eliminated, and particulate matter is reduced by 47%. However, variations exist within LNG systems, depending on factors such as whether natural gas is fully combusted or supplemented with pilot fuel, which can introduce additional emissions.

In addition to meeting general regulatory requirements, shipowners must consider the duration their vessels operate within Emission Control Areas (ECAs). Newly built ships subject to IMO Tier III NOx emission standards while operating in a Nitrogen Emission Control Area (NECA) are required to adopt NOx reduction technologies, such as exhaust gas recirculation (EGR) or selective catalytic reduction (SCR) systems. Alternatively, they may install engines that operate on the Otto gas cycle, dual-fuel systems, or low-pressure gas injection engines.

It is important to recognize that mitigating emissions also involves additional costs. For instance, carbon capture and storage require dedicated resources. Consequently, these costs should be carefully considered when evaluating the emission reduction measures implemented.

The ship under study is equipped with several technologies, in addition to the scrubbers, that aim to optimize fuel consumption and reduce pollutant emissions. One such device is the fuel improvement device (FID) or fuel homogenizer (WFE), which enhances engine combustion efficiency by homogenizing the fuel before injection. This device breaks down larger particles into smaller ones, ensuring even mixing and emulsifying the fuel with small amounts of water or additives. As a result, the combustion process becomes more complete, leading to reduced emissions of unburned hydrocarbons (PAH), soot, particulate matter, NOx, and carbon monoxide.

In this way, energy efficiency is enhanced, leading to reduced operating costs and maintenance needs. Additionally, the equipment's service life is extended due to smoother and more efficient operation. The water-in-fuel emulsification system can achieve a 60-90% reduction in soot and particulate matter in the exhaust gases, with a 10% reduction in NOx for every 10% of water added. Combustion efficiency can also be improved by up to 2%. Other benefits include a 60% reduction in visible smoke during engine start-up and at low loads, and up to 30% reduction at medium loads. Moreover, the system reduces water drag from the exhaust gases in the scrubbers. This study accounted for the operation of the water-in-fuel emulsification system in calculating emissions across the different scenarios.

It is also important to note that the study vessel does not currently have carbon capture and storage technology, and at present, this technology is not required, as the CII classification is still recent. However, as the CII values and classifications become more stringent, if the ship receives a D classification for more than three consecutive years or an E classification, an action plan for improvements should be implemented. This plan may involve the installation of carbon capture and storage equipment, with the CAPEX analysis, based on a study conducted under the Green Fuels Optionality (GFOP) project, presented in table 8 [26].

The economic feasibility of installing CCS in a newly constructed VLCC was analyzed. As shown in table 8, the cost per ton of carbon captured ranges from $220 to $290, depending on the fuel type, with each option having a distinct economic impact.

CCS implementation effectively reduces CO2 emissions by 74% to 78%. However, the additional equipment required increases energy consumption by 45%, leading to higher fuel use and potential pollutant emissions, which must be carefully considered.

Table 8: CO2 reduction cost for a VLCC ship

Item	LSFO	LNG	Methanol
CCS [Tons/year]	40700	31300	37700
CAPEX [$M/year]	4.4	3.2	3.9
OPEX [$M/year]	5	1.8	3.9
CO2 Storage [$M/year]	1	0.8	0.9
Total [$M/year]	10.4	5.8	8.8
CCS Cost WTW [$/tonCO2]	280-290	220-230	250-260

Source: Mærsk Mc-Kinney Møller Center, 2022 [26].

Energy Efficiency Existing Ship Index

The Energy Efficiency Index for Existing Ships (EEXI) was introduced in 2020 during the 75th session of the IMO Marine Environment Protection Committee (MEPC 75) and was formally adopted in June 2021 through resolution MEPC.328(76), amending Annex VI of the MARPOL Convention [25].

The EEXI, established by the IMO to reduce greenhouse gas emissions in the maritime sector, applies to existing ships, as a complementary framework to the Energy Efficiency Design Index (EEDI) for new builds. It is calculated as the ratio of CO2 emissions to a ship's carrying capacity [25].

For diesel-electric propulsion ships, including the vessel in this study, EEXI calculation involves determining CO2 emissions under normal operating conditions. It considers the installed propulsion power, energy conversion efficiency of the diesel-electric system, and differences from conventional propulsion, where mechanical energy is converted into electrical energy. The EEXI formula incorporates factors such as main engine power, propeller efficiency correction, and specific fuel consumption, as detailed below.

Emission of g
EEXI = CO2
Transport Effect (Eq. 7)

In this paper, the EEXI calculation was conducted to assess the shipowner's implementation of energy efficiency measures. Non-compliant ships may require modifications to improve efficiency, such as engine power limitations, fuel-saving technologies, or optimized operational practices. Regulations mandate that ships achieve an EEXI value below a specified threshold, which varies by vessel class and size.

For passenger ships with unconventional propulsion, the EEXI calculation follows MEPC.245(66) and MEPC.333(76). It is expressed as CO2 emissions per unit of transport at the reference speed (gCO2/t-Nm), as shown in equation 8 [27, 28].

$$EEXI_{attained} = \frac{(P_{hotel+aux}+P_{prop})\times Cf_{AE}\times SFC_{AE}}{GT\times V_{ref}} \qquad \text{(Eq.8)}$$

$$EEXI_{required} = \left(1-\frac{Y}{100}\right)\times a\times b^{-c} \qquad \text{(Eq. 9)}$$

Photel+aux = Service power at sea (including hotel load) at Vref
Pprop. = Propulsion engine power at 75% load
Vref = Ship's reference speed at 75% engine power
SFCAE = Specific fuel consumption of diesel generator engines
CFAE = Fuel emission factor
Capacity = Gross tonnage (specific to passenger ships)
a, b & c = Parameters for determining reference values for different ship types
Y = EEXI reduction factors relative to the EEDI reference line

These formulas were developed to establish a standardized energy efficiency framework for existing ships, promoting emission reductions and more sustainable operations in the maritime sector.
In this paper, the EEXI calculation was conducted under three scenarios:

1. Scenario 0 – The ship operates only on HFO.
2. Scenario 1 – The ship's EEXI is assessed before implementing energy efficiency measures but remains non-compliant.
3. Final Scenario – Includes power reduction measures, highlighting significant differences in results.

To comply with the required EEXI, certain variables in the formula can be adjusted through energy efficiency measures that either reduce energy consumption or limit the ship's propulsive power. Calculations determined an EEXIatt of 10.95, compared to an EEXIreq of 10.13, indicating that the ship does not meet the required efficiency standard. This justifies the shipowner's adoption of various energy efficiency strategies, including fuel optimization measures such as the installation of an FID.

Carbon Intensity Index

The Carbon Intensity Index (CII) is a key IMO regulatory measure designated to evaluate and reduce greenhouse gas emissions from ships. While the Energy Efficiency Existing Ship Index (EEXI) focuses on a ship's design efficiency, the CII targets the operational efficiency by measuring carbon emissions per unit of transport work over a vessel's service life. Established under resolution MEPC.328(76), as part of IMO's GHG reduction strategy, the CII is further detailed in resolutions MEPC.336(76), MEPC.337(76), MEPC.338(76), and MEPC.339(76) [29-32]. The framework assesses three main metrics: the Attained CII (CIIatt), Reference CII (CIIref) and Required CII (CIIreq). The CIIatt, calculated from real-world data reported through the IMO Data Collection System (DCS), represents a vessel's actual operational carbon intensity in grams of CO2 per ton-mile. The CIIref serves as the brechmark against which a ship's performance is evaluated for its type and size.

Compliance under the CII framework is determined by comparing a ship's Attained CII (CIIatt) with its Required CII (CIIreq). The CIIreq defines the maximum permissible carbon intensity for compliance and becomes progressively stricter over time through reference values, driving continuous improvements in operations. Vessels with CIIatt values at or below the CIIreq are considered compliant, while those exceeding it must implement corrective measures to enhance energy efficiency and reduce emissions.

The calculation of the CIIatt is represented by the following formula:

$$\text{CII attained} = \frac{\text{Emissions of } CO_{2\,[gramas]}}{\text{Transport Capacity[tons]}\times\text{Distancy [NM]}} \qquad \text{(Eq.10)}$$

The calculation of the required CII and the reference CII are expressed by the following equations:

$$CIIref = a\times Capacity^{-c} \qquad \text{(Eq. 11)}$$

$$CIIreq = \left(1-\frac{Z}{100}\right)\times CIIref \qquad \text{(Eq. 12)}$$

Where:
a & c = Tabulated parameters related to reference lines according to the ship type.
Z = CII reference factor for the calculation year [%].

The CII calculation for the ship under study was conducted with reference to the year 2024, considering the energy efficiency technologies already installed and operational up to that point. This was compared with data from 2022, prior to the implementation of any energy efficiency measures. Below is a presentation of the CII differences before, during, and after the installation of energy efficiency measures.

Table 9: CII calculation and comparison along the years

Index	Year		
	2022	2023	2024

CII attained	11.4	10.9	10.2
CII reference	11.2	11.2	11.2
CII required	11.215	11.209	11.204

The analysis of the indexes indicates a consistent improvement in ship's energy efficiency over the years. In 2022, the Attained CII (CIIatt) was 11.4, slightly above the Reference (CIIref = 11.2) and Required (CIIreq of 11.215) values, suggesting compliance but suboptimal performance. By 2023, the CIIatt improved to 10.9, well below both benchmarks, reflecting a significant enhancement in energy efficiency. In 2024, the CIIatt further decreased to 10.2, confirming that the vessel not only met but exceeded energy efficiency standards. This downward trend reflects continuous optimization of fuel consumption and CO2 emission management.

Throughout the evaluation period, the ship maintained a "C" rating, denoting standard performance. The CII rating system classified ships from "A" (superior performance) to "E" (poor performance), based on their attained carbon intensity relative to required branchmarks. As regulatory threshold become increasingly stringent, projections suggest that the vessel's rating could decline to "D" by 2030, signaling below-standard efficiency. To prevent this downgrade and maintain compliance, further optimization measures are essential. The implementation of these measures clearly results in a more sustainable and economical operational profile, in addition to allowing the fulfillment of regulatory goals, extending the useful life of the ship [32].

Financial Feasibility

The calculations outlined emphasize the importance of adopting both emission reduction methods and energy efficiency measures for more sustainable operations. The financial analysis considers three key elements for ensuring compliance with environmental regulations: energy efficiency improvements, scrubbers, and carbon capture and storage (CCS).

The financial feasibility assessment accounts for all costs, including the impact of scrubbers on fuel consumption. Capital expenditures (CAPEX) for open-loop scrubber tower installation in all six diesel generators and the CAPEX for energy efficiency improvements and projected fuel savings are shown in table 10. Fuel prices for VLSFO and HFO were set at USD 688.50 and USD 431.50, respectively. CAPEX for the CCS equipment was estimated based on its installation on a VLCC vessel, accordingly with reported on Green Fuel Optionality Project (GFOP) at the Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping (2022) [26].

Table 10: CAPEX for Scrubber retrofitting and energy efficiency technologies

Item	CAPEX [$]	Expected Fuel Savings [ton/year]	Savings [$/year]
Scrubbers	2,026,220.87	N/A	6,192,854.52
Carbon Capture and Storage	5,400,000.00	N/A	698,116.61
Frequency Converters SW System	150,000.00	372.00	186,000.00
Demand-Controlled Ventilation	2,053,597.00	177.00	88,500.00
High-Efficiency Reverse Osmosis	1,247,900.00	1770.00	885,000.00
LED Lighting	101,336.00	708.00	354,000.00

The initial cost of installing those technologies is significant. For the ship in question, the total investment amounted to $1.8 million for the installation of scrubbers on the six diesel generators and $2.2 million for the implementation of variable frequency drives in the seawater cooling and ventilation systems.

Variable frequency drives allow for the adjustment of electric motor speeds based on demand, leading to significant long-term energy savings. While the initial investment is considerable, the reduction in operational costs over time can quickly offset this expense.

To analyze profitability, several financial metrics were used, including Net Present Value (NPV), Internal Rate of Return (IRR), Payback Period (PBP), Return on Investment (ROI), and Profitability Index (PI). These metrics were calculated for a 10-years period, corresponding to the remaining estimated lifetime of the ship, using the usual discount rate of 10%. The results of the NPV and PBP calculations for each option are summarized in table 11, while the projected cash flows and payback periods are shown in figure 3.

Energy efficiency improvements represent a highly effective strategy, with a Net Present Value (NPV) of $5,128,825.86 at a 10% discount rate. This demonstrates that the initial investments are not only recovered but also generate significant additional cash flow over time. The Internal Rate of Return (IRR) of 38% and Profitability Index (PI) of 2.44 further validate the financial viability of these measures, with a payback period of 2.49 years, which is favorable considering the ship's remaining useful life of 10 years.

The scrubbers emerged as the most profitable component of the project, with an NPV of $37,492,507.05. With an impressive IRR of 300% and a PI of 1.05, these technologies offer substantial financial returns. The payback period is extremely short, estimated at 0.15 years, allowing for near-immediate recovery of the capital invested. This exceptional profitability is largely due to the significant cost difference between HFO and MGO, the latter being the fuel that would be used without sulfur emission reduction equipment. However, it is important to note that the financial feasibility of scrubbers is directly dependent on the continued price differential between these fuels.

Conversely, the installation of Carbon Capture and Storage (CCS) faces considerable challenges. Two scenarios were analyzed for the installation of this technology: one in 2030 and another in 2050. Immediate implementation was ruled out due to the current emission trading system, which results in a lower cost for the company compared to CCS operational costs, as shown in table 12. In the 2030 scenario, the projected NPV of -$4,657,067.47 indicates that CCS is not financially viable, with a negative IRR of -21% and a PI of 0.14. The payback period is long, estimated at 61.3 years. In the 2050 scenario, while the NPV remains negative at -$942,404.84 with a 10% discount rate, the payback period is shorter, estimated at 10.3 years. However, even in this case, the installation of CCS is not financially justified, as the ship's remaining useful life is only 10 years, and the installation would occur in 2024.

Table 11: Financial indicators with discount rate of 10%

Indicators	Energy Efficiency Projects	Scrubbers	CCS
Net Present Value (10%; $)	5,128,825.86	37,492,507.05	-942,404.84
Internal Rate of Return (%)	298	2903	-3
Project Profitability Index (10%)	2.44	1.05	0.83
Payback Period	2.51	0.15	10.3

Table 12: Comparative Analysis of the Installation Costs of CCS Technology with the Estimated Values Expected for the EU-ETS Pollutant Emissions Trading System

Item [$/ton]	CCS	EU ETS [$/Ton]	ETS Cost
CAPEX ($)	540		
OPEX ($)	70		
2024 ($)		50	436.322.88
2030 ($)		150	1.308.968.64
2050 ($)		200	1.745.291.52
Total cost	$610,852.03		

Therefore, the analysis concludes that the installation of CCS on the ship under study is not financially viable for the considered scenarios, even when accounting for the expected increase in carbon trading costs.

In parallel, the option of installing LNG propulsion, compared to the installation of scrubbers, requires a more detailed analysis. While LNG propulsion reduces certain emissions, it still generates carbon emissions, requiring payment under the emissions trading system or the installation of CCS, which, as previously analyzed, is not financially viable for the ship under study. The feasibility analysis of adapting the ship to LNG fuel shows an NPV of -$27,903,719.49 and a payback period of 87.9 years, making this alternative not realistic. Furthermore, replacing HFO with LNG would result in a significant increase in annual operational costs (FuelEx), with an additional $2,574,462.02, as calculated based on the ship's energy consumption.

This study involved an assessment of fuel consumption in the presented scenarios, along with fuel price forecasts for the coming years. In conclusion, LNG as a maritime fuel demonstrates a return on investment for newly built installations ranging from one to two years, a scenario not applicable for retrofitting.

The ship's age must be considered (installing scrubbers on an old ship may not be practical), as well as the future price differential between LSFO and HFO. The price difference is crucial, as potential savings from using scrubbers and burning HFO instead of LSFO can offset the installation costs. A substantial price gap results in a relatively short payback period, while a smaller difference leads to a longer payback period. The payback period for each option analyzed is more visually friendly in figure 3.

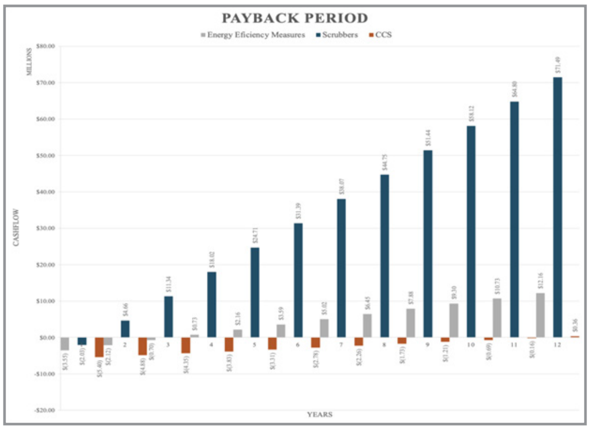

Figure 3: Cash flow and payback period for the project

In conclusion, the combined installation of scrubbers and energy efficiency measures, excluding CCS, should be viewed from an integrated approach. This ensures regulatory compliance while optimizing the project's financial feasibility. This technology combination is vital for meeting environmental requirements and maximizing financial returns, ensuring long-term sustainability. Given the ship's remaining useful life, it is clear why shipowners prefer retrofitting scrubbers over installing a full LNG system. Energy efficiency measures, in addition to their financial benefits, also contribute to fuel consumption reduction and, consequently, lower carbon emissions.

Furthermore, the crew of the studied ship made additional efforts to accelerate the VFD installation project. In addition to the already installed VFDs, necessary maintenance was performed to maximize their operation and minimize down-timings, resulting in considerable savings for the shipowner. Out of 64 VFDs installed, seven experienced issues and were repaired by the ship's electro-technical officers. Each VFD out of service resulted in an extra fuel consumption of 9 tons, costing approximately $7,300 per month and nearly $90,000 annually. The impact on fuel consumption for the seven out-of-service VFDs exceeds $600,000 annually.

In this specific case, the faulty VFDs were repaired by the crew, resulting in a savings of $44,300. This is because the cost of acquiring and replacing each VFD ranges from $5,000 to $8,000, while the cost of the parts needed to repair the seven VFDs was only $436.

Regarding the installation of LED lighting, with a relatively low investment of $100,000, it can yield a fuel savings of 708 tons per year, translating to an annual savings of approximately $380,000. This proves to be another wise decision by the shipowner.

Therefore, based on the financial feasibility analysis, it is evident that the installation of scrubbers is more cost-effective, leading to a reduced payback period. An illustrative example from Pacific Green Marine Technologies shows that the cost to convert an existing 8,500 TEU container ship to LNG would be $28 million, compared to $13 million for constructing a new vessel of equivalent size [33].

Using a similar comparison for VLCCs, the cost of installing an open-loop scrubber on a newly built ship is around $2.5 to $3.0 million, whereas the cost of modernizing and installing scrubbers on an existing VLCC is estimated to be between $4 million and $4.5 million [9]. It is also expected that new ships will operate more efficiently, further contributing to the reduction in the relative costs of installing a scrubber or LNG system in a newbuild.

However, it is important to note that the installation of a scrubber is significantly more economical than the implementation of an LNG unit in a more cost-effective newbuild scenario. It is reasonable to infer that this cost-saving advantage is further amplified in retrofits, where installation costs are higher, making a strong commercial case for installing scrubbers on existing vessels.

Since scrubbers are more affordable to install compared to a completely new propulsion system, their payback periods are up to three times faster than LNG, and inversely proportional to the size of the vessel. For larger ships, the payback period for scrubber installation can be less than a year. These findings are supported by the financial feasibility analysis presented in this study.

This is particularly relevant for retrofits, as the maximum benefit from fuel price differences is realized immediately after the installation of scrubbers. Once installed, the ship can continue burning more economical heavy fuel oil, with the savings over time offsetting the initial investment.

In addition to retrofitting scrubbers, a second option to consider, although seemingly extravagant, is one of the most viable alternatives despite its high cost. This involves adapting existing ships for LNG propulsion by extending the ship's length. This approach adds a prefabricated section containing LNG tanks and all necessary auxiliary systems. While this is an expensive project, it is not unprecedented. For example, the Royal Caribbean passenger ship MS Enchantment of the Seas underwent a 22-meter lengthening in 2005, with the conversion completed in one month.

A study conducted by Dr. Boulougouris E. from the University of Strathclyde, Glasgow, details the concept of ship elongation, including the technical considerations, benefits, project challenges, and costs involved, compared to retrofitting the same ship with scrubbers. The data from this study is presented in table 13. The financial analysis covers the scope necessary for converting a 14,000 TEU container ship to LNG propulsion through lengthening. This project was developed under a joint development program between GTT, Alwena Shipping, and CHI Zhoushan, with project supervision by the Bureau Veritas classification society [34].

Table 13: CAPEX Comparison of LNG Retrofit via Elongation vs. Scrubber Installation for a 75,000 GT Cruise Ship

Retrofitting cost estimation of a 75,000 GT cruise ship to LNG by elongation[M$]	
Engineering	7
Material and Elongation	7
Auxiliary Machinery	39
Engine	21
Total	74
Retrofitting estimation cost of a 75,000 GT cruise ship to scrubber [M$]	
Shipyard	5

Auxiliary machinery and equipment	15
Total	20

Source: Boulougouris, E., N/A. LNG Fuelled Vessels design Training: case study about new- building and retrofitting LNG Fuelled Vessels [34].

A study by the Oxford Institute of Energy Studies reveals that the substantial capital investment required for modernization has largely discouraged shipowners from retrofitting existing ships with scrubbers or LNG propulsion [35]. This is despite available options, such as converting cruise ships to LNG through elongation, and the surprisingly rapid optimization of refueling infrastructure in a short period. For shipowners cautious about capital investment, converting to LNG may seem a bold step, requiring confidence in the widespread adoption of LNG as a marine fuel, highly developed refueling infrastructure, and a persistently significant price difference between LNG and HFO.

For operators in such circumstances, early adoption of a scrubber solution, especially as a retrofit, appears to be not only the most economical option but potentially the only viable one, particularly for ships with a shorter remaining lifespan.

Conclusion

This study analyzed several realistic approaches to decarbonizing an existing vessel while maintaining its financial viability. Through mathematical calculations, the study quantified the impact that energy efficiency improvements measures have generated over the years in reducing the vessel's carbon footprint, as well as the corresponding financial benefits achieved through fuel savings.

The findings demonstrate that the implementation of energy efficiency measures emerges as a complementary strategy, equally as important as the search for, research on, and adaptation of vessels to alternative fuels. The financial investments required for shipowners to implement such measures is comparatively negligible when measured against the cost of conversion to alternative fuels.

However, while these measures have proven highly effective, their success also depends on well- trained crew capable of operating the equipment, machinery and voyage optimization tools efficiently. The rapid adaptation of seafarers to new technologies and emerging regulations, as well as the acceptance of long-experienced professionals who are reluctant to accept the imminence of these changes, must be considered a strategic priority for the industry.

With regard to alternative fuels, it is worth noting the strong market demand for new vessels powered by LNG and methanol, indicating that the industry has already identified its preferred transitional fuels. LNG-fuelled ships represent an excellent option for the short to medium-term transition, until green methanol and ammonia become widely available, supported by a reliable global infrastructure that ensures consistent supply and operational feasibility.

The inherent characteristics of LNG, along with the increasing practice of ordering vessels with “ammonia/methanol-ready” notations, make the transition process smother, as the future conversion of these vessels is expected to be more straightforward and less costly for shipowners.

For older ships, however, the most feasible option remains the installation of exhaust gas cleaning systems (scrubbers), preferably of the closed-loop type, as the discharge of wash water into the sea has become increasingly regulated in many ports. This approach allows compliance with sulfur and particulate matter emission limits without requiring fuel changeover operations to compliant fuel. Nonetheless, the use of scrubbers alone does not guarantee full compliance withenvironmental regulations, nor does it align with the ultimate objective of decarbonization. Therefore, the integration of additional systems for carbon capture and storage (CCS), as well as nitrogen oxides (NOx) reduction technologies, has been identified as a necessary step to make vessels ready for the final decarbonization goal.

A financial assessment of these technologies revealed that, depending on the vessel's remaining operational lifetime, the installation of a CCS system may or may not be economically viable. For this case study vessel, which has only ten years of service life remaining, installing such a system proved financially unfeasible. The current CCS technologies available on the market involve high capital costs, and the return on investment would not be achieved within the vessel's remaining lifespan. Consequently, it would be more cost-effective for the shipowner to offset emission through emission trading system than investing in onboard CCS systems.

In conclusion, the transition to alternative fuels, combined with the implementation of operational and technological energy efficiency measures, along with proper crew training, are vital to reducing greenhouse gas emissions in maritime transport and achieving complete decarbonization by 2050. The future of sustainable shipping will depend on the industry's ability to adapt to evolving regulations, invest in innovative technologies, and adopt an integrated approach that covers all aspects of maritime operations. Ongoing development of international policies and encouragement of research and development will be crucial to ensuring the maritime sector contributes positively to global sustainability and climate change mitigation goal.

References

1. Almeida, J. (2025). Desenvolvimento sustentável da indústria marítima: uma análise técnico-econômica das atuais opções do operador [Master's thesis, Escola Superior Náutica Infante D. Henrique].
2. Anderson, K., & Salazar, C. (2015). Methanol as a marine fuel report. FC Business Intelligence Energy, Methanol Institute. https://www.methanol.org/wp-content/uploads/2018/03/FCBI-Methanol-Marine-Fuel-Report-Final-English.pdf
3. Bouman, E., Lindstad, E., Rialland, A., & Strømman, A. (2017). State of the art technologies, measures, and potential for reducing greenhouse gas emissions from shipping – A review. Transportation Research Part D: Transport and Environment, 52(A), 408–421. https://doi.org/10.1016/j.

trd.2017.03.022
4. Bureau Veritas. (n.d.). FuelEU Maritime. https://marine-offshore.bureauveritas.com/sustainability/fit-for-55/fueleu-maritime
5. Clarkson Research. (2025). Green technology tracker report. Clarkson Research, London.
6. De-Troya, J., Álvarez, C., Fernández-Garrido, C., & Carral, L. (2016). Analysing the possibilities of using fuel cells in ships. International Journal of Hydrogen Energy, 41(4), 2853–2866. https://doi.org/10.1016/j.ijhydene.2015.11.145
7. DNV. (2023). Energy transition outlook 2023: Maritime forecast to 2050.
8. DNV. (n.d.). Veracity platform. https://www.dnv.us/data-platform/
9. European Maritime Safety Agency. (2017). Study on the use of fuel cell in shipping. DNV.
10. Green Shipping Programme. (2023). Ammonia powered bulk carrier pilot report. https://safety4sea.com/wp-content/uploads/2023/03/Ammonia-powered-bulk-carrier-GSP-pilot-report_2023.pdf
11. Horvath, S., Fasihi, M., & Breyer, C. (2018). Techno-economic analysis of a decarbonized shipping sector: Technology suggestions for a fleet in 2030 and 2040. Energy Conversion and Management, 164, 230–241. https://doi.org/10.1016/j.enconman.2018.02.098
12. International Energy Agency (IEA). (2021). Ammonia technology roadmap: Towards more sustainable nitrogen fertiliser production. IEA Publications.
13. International Maritime Organization. (2020). Fourth IMO greenhouse gas study.
14. Marine Traffic. (n.d.). Live vessel data and fleet statistics. https://www.marinetraffic.com
15. Methanol Institute. (2023). Marine methanol: Future-proof shipping fuel (pp. 46–48).
16. Pacific Green Marine Technologies. (2019). Why marine exhaust scrubbers are cheaper than LNG conversion. https://www.pacificgreen-marine.com/articles/why-marine-exhaust-scrubbers-are-cheaper-lng-conversion
17. SEA-LNG Foundation. (2022). LNG as marine fuel: The retrofit investment. https://sea-lng.org/wp-content/uploads/2022/08/VLCC_Retrofit_Investment_Case_Study.pdf
18. Van Hoecke, L., Laffineur, L., Campe, R., Perreault, P., Verbruggen, S., & Lenaerts, S. (2021). Challenges in the use of hydrogen for maritime applications. Energy & Environmental Science, 14(2), 815–843. https://doi.org/10.1039/D0EE01545H
19. Yang, J., Tang, T., Jiang, Y., Karavalakis, G., Durbin, T., Miller, J., Cocker, D., & Johnson, K. (2021). Controlling emissions from an ocean-going container vessel with a wet scrubber system. Fuel, 304, 121323. https://doi.org/10.1016/j.fuel.2021.121323
20. Boulougouris, E. (n.d.). Slides Module 1: LNG fuelled vessels design training—Case study about new-building and retrofitting LNG fuelled vessels [Visual projection]. University of Strathclyde Glasgow.
21. Cooper, D. G. T. (2004). Methodology for calculating emissions from ships: 2. Emission factors for 2004 reporting.
22. European Environmental Agency. (2023). EMEP/EEA air pollutant emission inventory guidebook 2023: Technical guidance to prepare national emission inventories. Denmark.
23. International Maritime Organization. (2009). MEPC.1/Circ.684 – Guidelines for voluntary use of the ship energy efficiency operational indicator (EEOI).
24. International Maritime Organization. (2014). Third IMO greenhouse gas study.
25. International Maritime Organization. (2014). MEPC.245(66) – Guidelines on the method of calculation of the attained energy efficiency design index (EEDI) for new ships.
26. International Maritime Organization. (2021). Resolution MEPC.328(76), Annex 1.
27. International Maritime Organization. (2021). MEPC.333(76) – Guidelines on the method of calculation of the attained energy efficiency existing ship index (EEXI).
28. International Maritime Organization. (2021). MEPC.336(76) – Guidelines on operational carbon intensity indicators and the calculation methods (CII Guidelines, G1).
29. International Maritime Organization. (2021). MEPC.337(76) – Guidelines on the reference lines for use with operational carbon intensity indicators (CII Reference Lines Guidelines, G2).
30. International Maritime Organization. (2021). MEPC.338(76) – Guidelines on the operational carbon intensity reduction factors relative to reference lines (CII Reduction Factors Guidelines, G3).
31. International Maritime Organization. (2021). MEPC.339(76) – Guidelines on the operational carbon intensity rating of ships (CII Rating Guidelines, G4).
32. Mckenney, T., Sato, K., & Unseki, T. (2022). The role of onboard carbon capture in maritime decarbonization. Green Fuel Optionality Project (GFOP), Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping.
33. Pacific Green Marine Technologies. (2019). Why marine exhaust scrubbers are cheaper than LNG conversion. https://www.pacificgreen-marine.com/articles/why-marine-exhaust-scrubbers-are-cheaper-lng-conversion
34. Steuer, C. (2019). Outlook for competitive LNG supply. The Oxford Institute for Energy Studies. https://doi.org/10.26889/9781784671310
35. Trozzi, C. (2010). Emission estimate methodology for maritime navigation. In Proceedings of the 19th International Emissions Inventory Conference (San Antonio, TX, USA, September 27–30, 2010). U.S. Environmental Protection Agency.