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Alternative Marine Fuels: A Comparative Analysis of Lower Heating Value, Specific Fuel Consumption, and Emission Performance in Relation to IMO 2050 Targets

Şeyma Özekinci [1], Kadir Mersin [1] & Biray Koçak [1]

[1] Istanbul Gelisim University, Department of Logistics Management, İstanbul, Türkiye

Abstract Although maritime transport constitutes the backbone of global trade, the conventional fossil fuels used contradict the sector's sustainability goals regarding greenhouse gas emissions. This study provides a comparison of the energy content, the specific fuel consumption (SFC) values, and the carbon dioxide equivalent (CO_2e) emissions associated with the use of heavy fuel oil (HFO) and other alternative marine fuels including liquefied natural gas (LNG), methanol, ammonia and hydrogen. For each alternative fuel option this study will utilize a Triple-E class ultra-large container vessel as an example ship, and it will also include results of calculations using a 24-hour operational cycle. The findings indicate that HFO produces the highest daily CO_2e emissions in current operations. Conversely, while LNG significantly reduces total emissions due to its SFC advantage, it cannot completely eliminate potential climate impacts due to methane slip (CH_4 slip). Due to methanol's lower carbon content, methanol achieves around a 50% reduction in emissions as compared to HFO. Both ammonia and hydrogen are chemically carbon-free, therefore they will have no CO2 emissions generated at the tank-to-wake stage, but a life cycle assessment based on their production processes would be needed to provide an accurate comparison. In this study, hydrogen and ammonia are treated as zero-carbon fuels only from a tank-to-wake perspective because they do not generate direct CO_2 emissions during onboard use. However, their overall climate performance depends strongly on how they are produced. Fossil-based production pathways may result in substantial upstream emissions, whereas renewable pathways such as green hydrogen and green ammonia can provide significantly lower life-cycle emissions. The results indicate that shifting to transition fuels such as LNG and methanol are logical for the sector for the short term, but the technological, economic, and safety aspects of carbon-free fuels (NH3 and H2) need to be rapidly developed for the medium to long term. Therefore, this study provides a numerical reference that compares the energy and emission performance of alternative fuels within a holistic framework.

Keywords Alternative marine fuels · Heavy fuel oil · Liquefied natural gas · CO_2e emissions · Specific fuel consumption

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Corresponding author: Kadir Mersin kmersin@gelisim.edu.tr

Introduction

Since the Industrial Revolution, the primary policy goal of institutions and nations has been financial growth. However, this rapid growth target has had a significant impact on the environment. With the increase in international trade, the reliance on carbon-intensive fossil fuels has also risen. Consequently, emissions originating from land-based industries and maritime transport have been the subject of research since 1850. To reduce negative impacts on the atmosphere, the ecosystem, and human health, policymakers are taking action by developing policies, making regulatory amendments, and reducing greenhouse gas emissions nationally and internationally.

Annual growth rate of seaborne trade between 2000 and 2024 is shown in Figure 1. Global maritime trade expanded by 2.4% in 2023, recovering from the decline in 2022. In 2023 the world's fleet moved over 12.3 billion tons of goods. Total growth for the sector for 2024 is estimated to be 2% and 2.4% annually through 2029. Ton-mile data is an indicator of total transport demand and provides a better measure than tonnage data alone, as it includes a factor for transport distance as well as cargo volume. As such, these data are important for establishing the magnitude of the world's maritime transport system and the increased demand for fossil fuels (Mersin et al., 2019; Al-Enazi et al., 2021; UNCTAD, 2024).

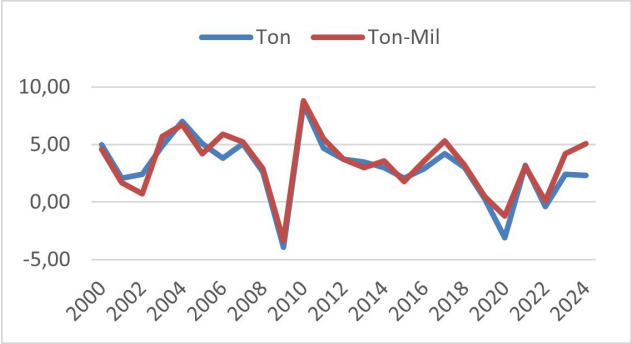


Figure 1. Annual growth rate of global seaborne trade (2000-2024) Source: UNCTAD (2024)

The blue line depicts an annual change in volume (tons) of the amount of cargo moved; while the orange line illustrates the annual changes in ton-miles which is an estimation of the volume of cargo moved multiplied by the miles moved. This second indicator reflects the total work performed by the shipping fleet and the transport demand. In 2018, the International Maritime Organization (IMO) adopted the goal of reducing greenhouse gas (GHG) emissions—such as carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O)—from international shipping by at least 50% by 2050 compared to 2008, in line with the Paris Agreement's target to control and reduce global warming.

Maritime transport remains an important source of greenhouse gas emissions, making fuel transition a central issue in shipping decarbonization. To achieve these goals, pathways for transitioning from traditional fuels to alternative fuels with zero or lower greenhouse gas emissions have begun to be investigated. While the greenhouse gases and toxic pollutants caused by fossil fuels (Heavy Fuel Oil – HFO and Marine Gas/Diesel Oil – MGO/MDO) are generally known, emissions associated with new fuel options are only now beginning to be measured and reported.

This study aims to compare major conventional and alternative marine fuels in terms of lower heating value, specific fuel consumption, and emission performance within a common analytical framework. In addition to reviewing the environmental characteristics of HFO, LNG, methanol, ammonia, hydrogen, and biofuels, the study presents a scenario-based quantitative comparison of daily fuel consumption and CO_2/CO_2e emissions for a representative large container vessel. The main contribution of the study lies in combining fuel-property comparison with operational emission calculations, thereby providing a clearer basis for evaluating fuel transition pathways in relation to maritime decarbonization targets and the IMO 2050 agenda.

Literature Review

According to Islam Rony et al. (2023), biofuels, specifically biomethanol and biodiesel, have the potential to be used as alternative fuel sources to assist in the decarbonization of maritime transportation and support UN Sustainable Development Goals. Their data indicated that the use of biofuels can decrease greenhouse gas emissions (GHGs) by 25% – 100% depending on the type of biofuel used; however, at this time, only approximately 15% of the world's demand for fuel can be met through the use of biofuels. Although they do have the ability to decrease emissions, many issues need to be addressed in order to gain widespread acceptance of biofuels, some of which include oxidation, availability of feedstocks, ecological issues, and operationally related issues.

Huang and Duan (2023) provide an extensive review of all the available technologies that have the potential to contribute to the decarbonization of the shipping industry, including alternative fuels and hybrid power systems. They found that LNG was a transitional fuel that had a great deal of potential to contribute to the decarbonization of the shipping industry, but also suggested that when alternative fuels were integrated into hybrid propulsion systems, it could potentially increase the overall effectiveness of the ship's ability to

decrease its carbon emissions. They employ a comparative analysis to assess the environmental efficiency and economic viability of various emerging clean technologies for shipping decarbonisation.

An integrated method combining Multi-Criteria Decision Analysis (MCDA) employing the Simple Multi-Attribute Rating Technique (SMART) and a Discounted Cash Flow (DCF)-based economic model was employed by Kouzelis, Frouws, and van Hassel (2022) to evaluate the decarbonisation potential of alternative marine fuels. Their results demonstrated that upgraded bio-oil, Fischer-Tropsch diesel and liquefied bio-methane have the lowest environmental impacts compared to their fossil-based counterparts. Additionally, the authors' findings indicated that the application of alternative fuels to replace conventional fuels in ships would likely lead to reduced optimal cruising speeds, resulting in additional emission savings under changed regulatory and market conditions.

A Systematic Review of 103 studies assessing the capability of alternative fuels to support the decarbonisation of maritime transportation was conducted by Santos, da Silva, and Serrano (2022). Santos, da Silva, and Serrano (2022) identified LNG, Hydrogen and Biodiesel as the top three most effective alternatives to achieve maritime decarbonisation, with LNG being able to reduce GHG and SOx emissions between 20–30% when compared to conventional fossil fuels. Apart from identifying the best options for maritime decarbonisation, Santos, da Silva, and Serrano (2022) identified barriers to the application of alternative fuels to include lack of infrastructure, cost and operational constraints; they utilised Bibliometric and Descriptive Statistical Analyses to identify trends in Research in Maritime Decarbonisation and Regional Contributions to the Field.

Ultimately, Ramsay, Fridell and Michan (2023) utilized Life Cycle Assessments (LCAs) to measure the Greenhouse Gas (GHG) emissions savings potential of different alternative marine fuels. They found that hydrogen and ammonia generated from renewable energy sources have the greatest GHG emissions savings potential at 79.9% and 71.0% respectively; they also reported that liquefied petroleum gas (LPG), liquid natural gas (LNG) have smaller GHG emissions savings potential at 17.2% and 8.8% and, importantly, methane-based fuels (methanol) could potentially generate greater levels of greenhouse gas emissions compared to traditional fuels. They highlighted significant barriers to implementation that include technical maturity, onboard storage capacity and bunkering infrastructure; therefore, their results demonstrated that the environmental benefits of hydrogen and ammonia depend largely upon the renewability of their production source.

Law et al., (2022) utilize techno-economic modeling, along with data from actual ship designs to model how the adoption of alternative marine fuels would affect the decarbonization of various ship types, cargo types and voyage lengths. They indicated that biodiesel offers the largest level of emissions reduction for deep-sea container vessels, and that ammonia, hydrogen, biomethanol and carbon capture and storage (CCS) each have lower levels of emissions reduction; further, they emphasized that the relative effectiveness of these alternative fuels varies significantly based upon both the type of cargo being transported and the distance of the voyage. More importantly, according to Law et al., while each of the alternative fuels studied has the potential to lower emissions, specific strategies will need to be developed to fully optimize de-carbonization of various ship types.

Although many studies examine the technologies needed for the maritime industry to make the transition to more environmentally friendly fuel options, there are also broader environmental governance frameworks including the Blue Economy and Coastal Resource Restructuring that should be taken into consideration when assessing the sustainability of the maritime industry. In this larger context, Bayırhan (2025), identified the strategic value of carbon credits in coastal and maritime transportation and evaluated the role of alternative marine fuels for reducing the emission of greenhouse gases from traditional fossil-fuel based marine fuels; however, Bayırhan (2025) concluded that simply replacing one marine fuel with another is insufficient; rather, alternative marine fuels must be accompanied by a combination of other mitigation approaches to realize overall net positive environmental impacts including but not limited to, deployment of portside electric charging infrastructure, coastal ecosystem-based blue carbon management practices and blue carbon management practices. In order to realize the desired reduction in ship-based CO2 emissions, the substitution of fuel must be supported by the development of economically viable incentives for using alternative fuels (i.e. carbon credits, compensation programs, etc.) and/or taxing fuel use based upon its consumption rate. This approach aligns with the literature trend suggesting that the environmental benefits of alternative fuels like LNG, methanol, and biofuels must be reinforced through policy design. Thus, the current study situates fuel-based emission analysis within a broad sustainability framework, integrating the carbon governance logic proposed by Bayırhan with an operational fuel comparison, thereby contributing

to establishing the technical-political link missing in the literature.

Overview of Ship Types and Current Fuels

Approximately 3% of global greenhouse gas (GHG) emissions are caused by maritime transport. Despite an increasing number of regulatory and market pressures, the world's aging maritime fleet is being replaced at a slow rate because of the high cost of replacing vessels, uncertainty regarding future fuel choices, and the very low rate of ship scrapping.

In 2023, the global shipping fleet exhibited a capacity increase of 3.4%, reaching a total cargo capacity of 2.4 billion tons. While this growth exceeds general trade growth, it remains behind historical averages. The segments leading this growth were container ships and LNG carriers, while bulk carriers and oil tankers traditionally maintain the largest share of the fleet (UNCTAD, 2024).

Figure 2 comparatively shows the distribution of the World fleet's total carrying capacity (DWT) by ship type between 1980 and 2024.

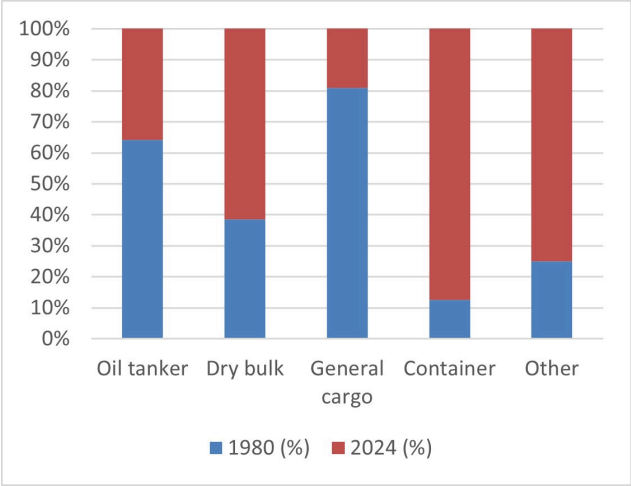


Figure 2. Evolution of Global Shipping Fleet Capacity (1980–2024) Source: UNCTAD (2024)

The main problem in the maritime sector's ability to decarbonize is the low readiness of the sector to adopt alternative fuels: at the beginning of 2024, only 14% of the new build tonnage was completely suitable for alternative fuel use, while 50% were able to be adapted for use of alternative fuels. If the rate of decarbonization of the sector does not increase, the sector will face severe challenges – such as the inability to compete effectively in the global market, which is increasingly prioritizing sustainability; and financial risks due to high operational costs, and fines resulting from non-compliance with regulations that require the sector to take measures to mitigate the greenhouse gas emissions from shipping.

Based on the current fleet renewal rates and the amount of fossil fuel currently used, the most effective method of reducing emissions in maritime transport is through the adoption of alternative fuels and the assessment of their greenhouse gas (GHG) footprints.

The Role of Emission Reduction Strategies

The International Maritime Organization (IMO) has set a goal to reduce GHG emissions from shipping by 50% by 2050 (IMO, 2020). To achieve this goal, the IMO believes that the integration of alternative fuels and emission reduction technologies is crucial. Together, the two allow for the maximum amount of environmental benefits to be realized while ensuring the economic sustainability of the sector.

Alternative Fuels and Emissions

The use of eco-friendly alternative fuels to replace fossil fuels in maritime transport contributes to a significant reduction in GHG emissions. HFO remains the conventional benchmark fuel in maritime transport due to its widespread availability, established infrastructure, and relatively high energy density. However, it is also associated with high CO_2, SO_X, NO_X, and particulate emissions, which makes it the baseline fuel against which alternative fuel options are evaluated. Biofuels are regarded as promising transitional marine fuels because they can often be used with limited engine modification and may reduce life-cycle carbon emissions depending on feedstock and production pathway. However, their environmental benefit is not uniform and depends on factors such as feedstock sustainability, land use effects, blending ratio, and supply availability. Fossil fuels are replaced by alternative fuels that have characteristics such as biofuels, natural gas, ammonia, hydrogen, and methanol that are carbon neutral or low carbon. Alternative fuels increase energy efficiency and represent a major step towards environmental sustainability. They are also a key component in reducing the carbon footprint of the international maritime sector as part of overall strategies to achieve this goal.

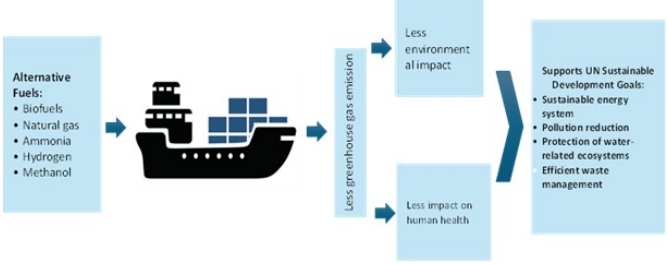


Figure 3. Schematic diagram of sustainable alternative fuel production and analytical assessment Source: Rony et al., (2023)

Liquefied Natural Gas (LNG)

LNG reduces CO_2 emissions by ~20-25% compared to conventional fuels, eliminates SOX, and reduces NOX. However, since methane is a potent greenhouse gas (28 times that of CO_2), methane leakage during use remains a source of concern (Balcombe et al., 2019). Typical emissions from LNG:

- CO_2 : 201.96 g/kWh
- NO_X: 3.6-10.8 g/kWh
- SO_X : 0

Methanol

Methanol reduces NOx emissions by ~60%, produces no SO_X, and can achieve carbon neutrality if bio-methanol is used (Anderson et al., 2021). Typical emissions from Methanol:

- NO_X : 2.16-5.4 g/kWh
- CO_2: 250.56 g/kWh
- SO_X: 0

Hydrogen

Hydrogen produces only water vapor during combustion, eliminating CO_2

and SOx emissions. However, NOx emissions may occur in some engine

types (IRENA, 2022).

Typical emissions from Hydrogen:

- NO_X : 0.5-1 g/kWh
- SO_X : 0
- CO_2: 0 (TTW: Tank to Wake)

Ammonia

Ammonia is a zero-CO_2 fuel but can lead to NOx emissions without proper controls (Ash & Scarbrough, 2023). Typical emissions from Ammonia:

- NO_X: 2-4 g/kWh
- SO_X : 0
- CO_2: 0 (TTW: Tank to Wake)

Fuels usable in ships and their characteristics are provided in Table 1.

As seen in Table 1, the fuel with the highest LHV (Lower Heating Value) is hydrogen, while the lowest is ammonia. LHV refers to the amount of usable energy released by the complete combustion of 1 kg of fuel. As this value increases, less fuel is consumed to obtain the same energy output. Examining SFC values, hydrogen again appears to be the most efficient. This means hydrogen is the fuel where the engine consumes the least amount to produce 1 kWh of mechanical power.

Table 1. Comparison of Energy and Emission Characteristics of Alternative Marine Fuels

Fuel Type	SFC (g/kWh)	LHV (MJ/kg)	Methane Slip	Source
HFO	159–170	40–41	None	CIMAC Marine Fuel Guideline (2024) (MAN Energy Solutions, 2024)
LNG	120–140	48–50	Yes (%1–3 CH_4 slip)	SEA-LNG & DNV GL, *Alternative Marine Fuels Study*
Methanol	190–220	~19.7	None	SEA-LNG & DNV GL
Hydrogen	50–70	120–142	None	World Nuclear Association, fuel heat table
Ammonia	210–240	18.6	None	SEA-LNG & DNV GL

Sample Scenario

In this section, a CO_2 emission analysis will be conducted using a container ship, one of the most used vessel types in maritime transport. A Maersk Triple-E class container ship will be used in the scenario. This ship was inspired by the Maersk Mc-Kinney Moller. The characteristics of this ship are given in Table 2.

Table 2. Triple-E Vessel — Engine & Fuel Consumption Technical Data

Feature / Parameter	Value / Description
Main Engine	Twin MAN 8S80ME-C9.2, two low-speed two-stroke diesel engines (Shipspotting,2026)
Engine (each) Power	~ 29.7 MW (≈ 43,000 hp) (Shipspotting,2026)
Total power of two engines	~ 59–60 MW (≈ 86,000 hp total) (Shipspotting,2026)
Specific fuel consumption (SFC) / fuel type	168 g/kWh (bunker oil / HFO) (MAN Energy Solutions, 2024)
Daily fuel consumption (typical, IFO)	~164 tons/day (Westbound routes, excluding bunker) (MarineLink, 2026)

Note: Principal particulars of the sample vessel were compiled from publicly available ship databases such as Shipspotting, whereas the representative HFO-specific fuel consumption value was based on MAN Energy Solutions (2024). The engine load factor and daily operating time were adopted as assumptions of the present study for comparative calculations.

To improve transparency, the calculation framework used in this study is presented step by step. The sample vessel is assumed to have a total installed main engine power of 60 MW. The MCR utilization rate is taken as 80%, and the

operating time is assumed to be 24 h/day. Accordingly, the daily mechanical energy output is calculated as

$$E_{day} = Power \times Load\ Factor \times hour \quad (1)$$

.

Therefore, the ship's daily energy production is:

E= 60 MW×80%×24 hour=1,152,000 kWh/day

Daily fuel consumption values are calculated in Table 3.

Table 3. Daily fuel consumption of the ship

Fuel	Daily Fuel Consumption (tons)
HFO	195.84
LNG	149.76
Methanol	230.4
Ammonia	241.92
Hydrogen	69.12

Fuel consumption values are directly proportional to CO_2 emissions. Therefore, daily CO_2 emissions can be calculated by multiplying each fuel by its CO_2 emission factor. Table 4 presents daily CO_2 emissions by fuel type.

Table 4. Daily CO_2 emissions by fuel type

Fuel	Emission Factor (ton/ton)	Source	Emission (ton)
HFO	3.1144	(Czerma, Cirella, Oniszczuk-Jastrzabek, Pawłowska, & Notteboom, 2021; Bilsback et al., 2020).	≈610
LNG	2.75	(Czerma, Cirella, Oniszczuk-Jastrzabek, Pawłowska, & Notteboom, 2021; Bilsback et al., 2020).	411.84
Methanol	1.38	(Czerma, Cirella, Oniszczuk-Jastrzabek, Pawłowska, & Notteboom, 2021; Bilsback et al., 2020).	≈318
Ammonia	0	Carbon-free.	0
Hydrogen	0	Carbon-free.	0

While calculating values in Table 4, methane slip was neglected; however, methane slip is one of the biggest risks of LNG. If we assume a methane slip of 1%, the leakage amount is:

Since the GWP_{100} value for methane is 27.2 (CH_4, IPCC AR6), the equivalent CO_2 emission for LNG is:

Consequently, the total LNG emission would be 411.84+40.7≈452.54 tCO_2e/day.

For LNG, methane slip sensitivity was assessed at 1%, 2%, and 3%. Under these scenarios, total LNG emissions increase to approximately 452.54, 493.31, and 534.04 tCO_2e/day, respectively.

Similarly, methanol and hydrogen have equivalent CO_2 emissions generated during production, but these values are neglected in this study. Table 5 below includes the equivalent emission values.

Table 5. Emission values

Fuel	Emission (tCO_2e/day)
HFO	≈610
LNG (1%)	≈452.54
LNG (2%)	≈493.31
LNG (3%)	≈534.04
Methanol	≈318
Ammonia	0
Hydrogen	0

These comparative CO_2e emission values are also illustrated in Figure 4.

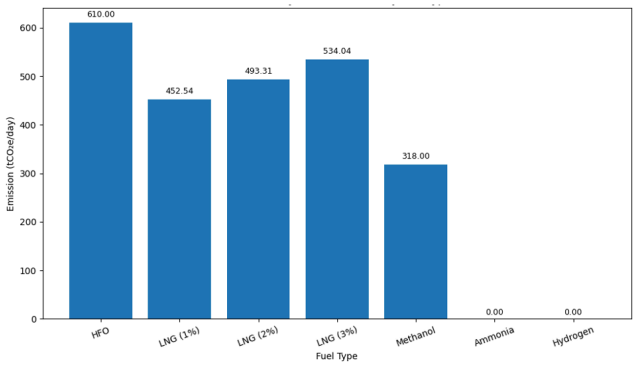


Figure 4. Daily CO_2e emissions by fuel type under alternative methane slip scenarios

Broader Emission Reduction Methods

In addition to fuel switching, maritime emission reduction can be supported by a broader set of technical, operational, and infrastructure-based measures. Decarbonization in shipping is unlikely to be achieved through a single solution; instead, it requires a combination of cleaner fuels, energy-efficiency technologies, improved operational practices, and supportive port infrastructure.

One of the most widely used technical solutions is the exhaust gas cleaning system, commonly known as the scrubber. Scrubbers are effective in reducing sulphur oxide emissions and enabling compliance with sulphur regulations when conventional high-sulphur fuels are used. However, they do not eliminate carbon dioxide emissions and may create additional environmental concerns. Open-loop scrubbers discharge washwater into the sea, while closed-loop systems avoid direct discharge but generate sludge that must be treated on land. Therefore, scrubbers reduce air pollution but

may shift part of the environmental burden to the marine or terrestrial environment.

Another important pathway is the use of energy-efficiency technologies. Measures such as hull-form optimization, improved propeller systems, air lubrication, and waste heat recovery can reduce fuel consumption directly by improving propulsion and engine performance. These technologies are particularly valuable because they can lower emissions without requiring a complete change in fuel type.

Renewable energy integration also offers supplementary benefits. Wind-assisted propulsion systems, such as rotor sails and towing kites, can reduce fuel demand under suitable operating conditions. Similarly, onboard solar systems may help supply auxiliary electrical loads. Although these technologies cannot fully replace conventional propulsion in large commercial vessels, they can contribute to hybrid decarbonization strategies.

Operational measures are among the most practical short-term solutions. Slow steaming, route optimization, weather routing, trim optimization, and just-in-time arrival can significantly reduce fuel consumption and associated emissions. Compared with major retrofitting investments, these practices are often easier to implement and can provide immediate environmental benefits.

Port-based measures also play an important role. Shore power allows ships at berth to connect to onshore electricity instead of using auxiliary engines, thereby reducing emissions in port areas. Its environmental effectiveness depends on the electricity generation mix of the local grid, with greater benefits achieved where cleaner electricity is available.

Finally, emerging technologies such as onboard carbon capture and advanced dual-fuel or electronically controlled engines may contribute to long-term maritime decarbonization. Although these technologies still face economic and technical limitations, they may become increasingly relevant during the transition to low-carbon and zero-carbon shipping.

Overall, broader emission reduction methods show that maritime decarbonization should be approached as a multi-dimensional process. Fuel transition remains essential, but its effectiveness can be significantly enhanced when combined with energy-efficiency improvements, operational optimization, and port-based environmental strategies.

Conclusion

The maritime sector is faced with a dual challenge: meeting the increasing demand for trade while minimizing its environmental impact. The sector can dramatically reduce its carbon footprint by adopting alternative fuels and using advanced methods to reduce emissions. For a sustainable future, promoting the use of LNG, methanol, biofuels, hydrogen, and ammonia, along with energy efficiency technologies and operational improvements, is critical.

Using energy carriers (fuels) with a low or zero greenhouse gas (GHG) footprint is one of the most effective paths to reducing carbon emissions in maritime transport. Zero-carbon fuels produced from renewable sources, including hydrogen and ammonia, are among the most promising – and possibly the only – options for achieving the desired reductions in GHG emissions for the shipping industry (Lindstad et al., 2021). Although not the focus of this review, it should be noted that Well-to-Tank (WtT) emissions for all fuels can vary greatly (European Parliament, Council of the European Union, 2018).

Currently, Liquefied Natural Gas (LNG) is the most well-known low-carbon alternative available to many ships in maritime transport. LNG can also significantly reduce other pollutants such as SOx, NOx, and PM; however, methane leakage is a significant disadvantage due to its high GHG potential. While Bio-LNG is a potential option, production volumes are not at a level to meet high sector demand. For Hydrogen, while Tank-to-Wheel analysis shows zero GHG emissions for fossil-sourced H_2, its carbon intensity can be high when analyzed from a well-to-wheel perspective. Renewable or green hydrogen is widely discussed for the medium to long term, but current usage and development levels in maritime transport remain low. Biodiesel, along with Hydrotreated Vegetable Oil (HVO) (%3.8) and Straight Vegetable Oil (SVO) (%3.4), can be blended into existing marine engines without additional modification. However, since the primary feedstock comes from food/feed sources and deforested areas, it may raise other environmental issues. The biggest obstacle to methanol use is that production is still based on fossil sources and the number of ships using this fuel is limited. Fossil or renewable-sourced Ammonia can be used in internal combustion engines or fuel cells. However, as it is still in the research phase, it is seen as a promising option for the future. While Pyrolysis oil and Fischer–Tropsch diesel are effective in reducing GHG emissions, low technology readiness levels, lack of standards, and high production costs are significant disadvantages.

In general, these clean fuels are not yet widely enough adopted in the maritime transport sector; the reason for this is mainly the lack of production incentives and structural resistance within the sector. The review highlights that low technology development, cost and accessibility issues, acceptance by the maritime industry, and regulatory differences in international waters impede the development

of new fuel sources. Some alternatives, however, such as LNG, biodiesel, and methanol can be used by blending them with existing fuels. Trends in the literature indicate that LNG is the most researched alternative fuel source, since it is abundant, is accepted as clean fuel, and is competitive in terms of production, transport, storage, and usage costs. However, new research trends are emerging regarding methanol, ammonia, and hydrogen. Experts note that implementation will be difficult due to high costs. However, considering that fossil fuels are still heavily subsidized globally and the maritime sector uses the cheapest fuel, the question of the real cost to be paid in the future gains importance. The study reveals a lack of in-depth studies on clean fuel options in the maritime transport sector and emphasizes that the private sector and governments must begin to incentivize R&D.

In this study, the greenhouse gas emissions of alternative fuels used in maritime transport were examined comparatively. While Scrubber systems significantly reduce sulfur oxide (SOx) emissions, they lead to an increase in carbon dioxide (CO_2) emissions due to parasitic energy load. Therefore, scrubbers offer a short-term solution for air quality but provide limited benefit in combating climate change.

Findings obtained after correcting for the methane slip (CH_4 slip) calculation show that LNG's climatic advantage is significantly reduced compared to previous work. According to corrected calculations, even with a relatively low methane slip rate of 1%, the total CO_2 equivalent emissions of a ship using LNG reaches about 453 tCO_2e/day. As such, the total CO_2 emissions of a ship using LNG are comparable to those of traditional fuels (HFO and VLSFO), and in some cases may result in a greater climate impact. These findings demonstrate that evaluating LNG as a long-term decarbonization strategy is dependent upon the methane slip being reduced to negligible levels. Therefore, to achieve climate goals in the maritime sector, it is important to implement strategies that not only include fuel switching but also methane emission control, increased energy efficiency, and lifecycle-based CO_2e assessments.

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Author Details

Şeyma Özekinci
[1] Istanbul Gelisim University, Department of Logistics Management, İstanbul, Türkiye
0009-0006-6189-5436

Kadir Mersin
[1] Istanbul Gelisim University, Department of Logistics Management, İstanbul, Türkiye
0000-0003-3999-6960 kmersin@gelisim.edu.tr

Biray Koçak
[1] Istanbul Gelisim University, Department of Logistics Management, İstanbul, Türkiye
0000-0002-0297-2976

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