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Alternative marine fuels for sustainable and cost-efficient shipping

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ABSTRACT: With the global population projected to reach nearly 10 billion by 2050, the demand for animal products is expected to rise significantly. A less recognized source of emissions in this supply chain is livestock maritime transport, which moves millions of animals worldwide and emits large amounts of CO_2 and other pollutants. This study focuses on reducing the environmental impact of ships through cleaner fuels, efficient routing, and improved onboard power systems. Ship emissions pose a significant global challenge due to their detrimental impact on the environment, especially in terms of contributing to atmospheric global warming. To address this, the International Maritime Organization (IMO) has prioritized environmental protection, aiming to cut exhaust emissions by at least 50% by the year 2050. One of the key strategies proposed by the IMO is the adoption of alternative marine fuels, such as natural gas and methanol, in place of traditional fossil fuels. This paper presents a comparative analysis of converting conventional diesel engines into dual-fuel engines that run on either methanol or natural gas. The study focuses on the economic aspects of both the natural gas and methanol dual-fuel systems. According to the findings, the use of natural gas results in cost savings of \$275.546/ton for NOx, \$11,358.610/ton for SOx, \$29.0853/ton for CO_2, and \$8,518.962/ton for CO. In comparison, methanol offers cost reductions of \$362.687/ton for NOx, \$14,638.436/ton for SOx, \$12.736/ton for CO_2, and \$6,127.717/ton for CO. The study underscores the environmental and economic advantages of using natural gas and methanol as cleaner alternatives in the maritime sector. The results indicate that adopting these fuels could significantly lower emissions from ships and support broader global sustainability goals.

Keywords: dual-fuel engine; IMO regulations; methanol; natural gas; ship emission reduction.

Combustíveis marítimos alternativos para um transporte marítimo sustentável e economicamente eficiente

RESUMO: Com a projeção de que a população mundial alcance quase 10 bilhões de pessoas em 2050, a demanda por produtos de origem animal deverá aumentar significativamente. Uma fonte de emissões menos reconhecida nessa cadeia de suprimentos é o transporte marítimo de animais vivos, que movimenta milhões de animais em todo o mundo e emite grandes quantidades de CO_2 e outros poluentes. Este estudo concentra-se na redução do impacto ambiental dos navios por meio de combustíveis mais limpos, rotas mais eficientes e sistemas de energia a bordo aprimorados. As emissões dos navios representam um desafio global significativo devido ao seu impacto prejudicial ao meio ambiente, especialmente na contribuição para o aquecimento global atmosférico. Para lidar com isso, a Organização Marítima Internacional (OMI) priorizou a proteção ambiental, visando reduzir as emissões de gases de escape em pelo menos 50% até 2050. Uma das principais estratégias propostas pela OMI é a adoção de combustíveis marítimos alternativos, como gás natural e metanol, em substituição aos combustíveis fósseis tradicionais. Este artigo apresenta uma análise comparativa da conversão de motores a diesel convencionais em motores bicombustíveis, que funcionam com metanol ou gás natural. O estudo concentra-se nos aspectos econômicos dos sistemas bicombustíveis a gás natural e metanol. De acordo com as conclusões, o uso de gás natural resulta em uma economia de custos de US\$ 275,546/ton para NOx, US\$ 11.358,610/ton para SOx, US\$ 29,0853/ton para CO_2 e US\$ 8.518,962/ton para CO. Em comparação, o metanol oferece reduções de custos de US\$ 362,687/ton para NOx, US\$ 14.638,436/ton para SOx, US\$ 12,736/ton para CO_2 e US\$ 6.127,717/ton para CO. O estudo destaca as vantagens ambientais e econômicas do uso de gás natural e metanol como alternativas mais limpas no setor marítimo. Os resultados indicam que a adoção desses combustíveis poderia reduzir significativamente as emissões de navios e apoiar metas globais de sustentabilidade mais abrangentes.

Palavras-chave: motor bicombustível; regulamentações da IMO; metanol; gás natural; redução das emissões de navios.

1. INTRODUCTION

The pressing challenge of global environmental change demands a shift in how we produce and consume energy (ELMALLAH et al., 2023;2024a). As a vital part of global trade, the shipping industry plays a significant role in contributing to greenhouse gas emissions (ELMALLAH et al., 2024a,b,c; SHOUMAN et al., 2025). This study explores the long-term benefits of using alternative fuels in dual-fuel engines, focusing on their energy efficiency and environmental impact. It specifically evaluates the use of liquefied natural gas (LNG) and methanol as substitutes for conventional marine fuels. The research investigates how converting container ship engines to dual-fuel systems using LNG or methanol can lower emissions. Given that maritime transport handles over 80% of global trade, the industry's emissions have a considerable impact on global greenhouse gas levels. Ships are major sources of pollutants such as carbon dioxide (CO_2), nitrogen oxides (NO_x), sulfur oxides (SO_x), particulate matter (PM), and carbon monoxide (CO) (SAADELDIN et al., 2024). Reducing these emissions is essential for promoting environmental sustainability and protecting public health.

As the global population continues to rise, projected to reach nearly 10 billion by 2050-the demand for meat, milk, and other animal products is expected to increase substantially. An often-overlooked contributor to livestock-related emissions is the role of livestock ships and maritime transportation, which are responsible for moving millions of livestock globally. These vessels produce a high amount of CO_2 and other pollutants from fuel combustion. Greening the maritime transportation segment of the supply chain through cleaner fuels, optimized routing, and improved onboard systems can significantly reduce the overall environmental footprint. Cleaner innovations of power generation will take place in this study, according to a container ship.

According to recent data from the International Maritime Organization (IMO), shipping accounts for roughly 1.1 gigatons of CO_2 emissions annually-around 3% of total global greenhouse gas emissions (SAADELDIN et al., 2023a,b). The shipping sector is also responsible for about 13% of anthropogenic NO_x and 12% of SO_x emissions, in addition to producing 1.4 million tonnes of particulate matter and 936,000 tonnes of CO. As illustrated in Figure 1, there are approximately 54,743 merchant ships facilitating international transport, which collectively contribute to 55% of the industry's total CO_2 emissions (OLMER et al., 2017).

Among various vessel types, container ships are responsible for the highest share of CO_2 emissions. This is largely due to their rapid loading and unloading capabilities, which allow for more time spent at sea, resulting in greater fuel consumption and emissions. Several studies on containerization trends support this observation. According to the Fourth IMO GHG Study 2020, container ships spend approximately 70% of their operational time underway, compared to about 50-60% for bulk carriers and tankers. Additional findings from the ICCT report, Olmer et al. (2017), reinforce this, showing that container ships generally operate for more hours annually than other ship types, such as tankers and bulk carriers.

This extended operational time contributes directly to increased CO_2 emissions, as ships consume fuel continuously while underway. Furthermore, container ships typically operate at higher Froude numbers than crude oil tankers. The Froude number-a dimensionless value comparing a ship's speed to the wave speed-tends to be around 0.2–0.3 for container ships, while tankers operate at lower values of 0.1–0.15. Higher Froude numbers result in greater wave resistance, leading to increased fuel consumption and emissions.

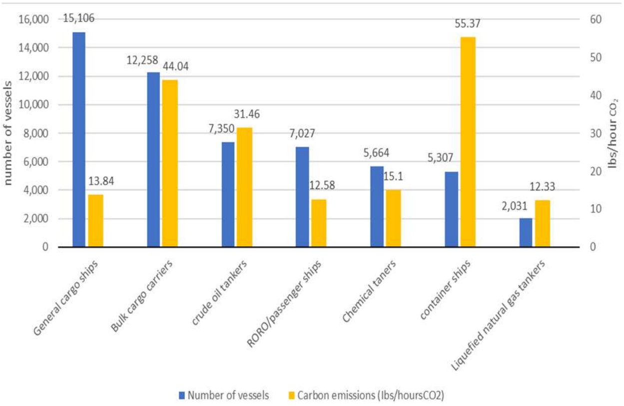

Figure 1. Number of merchant ships and their carbon emissions, by category in 2021.

Figura 1. Número de navios mercantes e respectivas emissões de carbono por categoria em 2021.

These factors-longer time at sea and higher operational speeds-clearly show why container ships are major contributors to maritime CO_2 emissions. This underscores the importance of implementing targeted emission reduction strategies for container vessels, such as enhancing fuel efficiency and transitioning to cleaner alternative fuels.

To explore this further, the study uses the EVER A LOT - the world's largest container ship-as a case study. Currently equipped with a WinGD 11X92-B engine, the ship is proposed for conversion to a dual-fuel model (11X92DF). Its operational performance and cost-effectiveness are analyzed using the IMO's environmental assessment indicators.

The International Maritime Organization (IMO) has played a key role in advancing maritime energy efficiency and enforcing regulations aimed at reducing ship emissions (PERČIĆ et al., 2020). Under Annex VI of the International Convention for the Prevention of Pollution from Ships (MARPOL), the IMO has introduced a series of regulatory measures to curb emissions (ČAMPARA et al., 2018).

To address nitrogen oxide (NOx) emissions, the IMO implemented the NOx Technical Code, which took effect on October 10, 2008. This regulation applies to all ship diesel engines with an output exceeding 130 kW (HERDZIK, 2011). In the case of sulfur oxides (SOx) and particulate matter (PM), emissions are closely linked to the sulfur content in marine fuels. These pollutants are known to pose serious health risks, contributing to respiratory and pulmonary diseases.

In response, the IMO adopted Regulation 14 of MARPOL Annex VI in 2005, which limits the sulfur content in marine fuels. This regulation was further strengthened with the introduction of the "IMO 2020" mandate, which came into force in 2020. The regulation significantly lowers the allowable sulfur content in marine diesel fuel, aiming to improve air quality and protect environmental and human health (ZANNIS et al., 2022).

To regulate carbon dioxide (CO_2) emissions, the IMO has developed two key indicators: the Energy Efficiency Design Index (EEDI) and the Energy Efficiency Operational Indicator (EEOI) (REHMATULLA et al., 2017). The EEDI sets performance-based efficiency benchmarks for different vessel types and sizes, measuring CO_2 emissions per ton-mile. It provides a standardized metric to evaluate and compare the energy efficiency of ships, helping to establish minimum efficiency requirements across vessel categories. The mandatory application of the EEDI is a major step in accelerating efforts to improve energy efficiency and reduce greenhouse gas emissions in the shipping sector.

As illustrated in Table 1, there are several strategies and technologies available to meet EEDI targets and reduce maritime emissions.

Table 1. Several techniques for reducing gas emissions in maritime transport.
Tabela 1. Diversas técnicas para reduzir as emissões de gases de efeito estufa no transporte marítimo.

Emissions	Type of operation	
SOx emissions	scrubbers' system, sulfur-free alternative fuel, and Marine diesel oil (0.1S%)	
NOx emissions	Pre-combustion	Alternative fuels, Water injection into the air system or fuel system, and engine modification
	Combustion	Water injection into the cylinder, and the Exhaust Gas Recirculation system (EGR)
	After treatment	Selective Catalytic Reduction system (SCR)
CO_2 emissions	Concerning Design	Ship weight reduction, propeller redesign, and improving the aft body, and ideal for bulb and bow
	Engine modifications	Waste heat recovery, engine modifications, and auxiliary system modifications, such as improving pump efficiency
	Operational measures	The hull is cleaned and coated, ballast and trim optimization, and the speed of the ship.
	New technologies	Carbon Capture and Storage system (CCS), alternative fuels, renewable energy, and an air lubrication system

Among the various technical and operational strategies for decarbonizing the maritime industry, replacing conventional fossil fuels with environmentally friendly alternatives presents one of the most promising solutions. Many of these alternative fuels contain minimal amounts of nitrogen and sulfur, making them especially suitable for use in Emission Control Areas (ECAs), where emission standards are significantly stricter than global regulations (SADEK; ELGOHARY, 2020).

Alternative marine fuels are generally categorized into two groups: liquid fuels (such as methanol, biodiesel, and ethanol) and gaseous fuels (such as natural gas, hydrogen, and propane). Biodiesel is a renewable fuel that produces lower emissions of particulate matter (PM), unburned hydrocarbons, carbon monoxide, and sulfur dioxide. However, it suffers from reduced performance in low-temperature conditions and raises concerns about food security, as its increased production competes with food crops. This competition can exacerbate food shortages, inflate prices, and heighten food insecurity in vulnerable regions. Additionally, biodiesel is associated with higher nitrogen oxide (NOx) emissions (KESIEME et al., 2019).

Ethanol is another viable alternative fuel for marine applications. It burns cleanly, producing mainly carbon dioxide and water, but faces challenges such as poor cold-start performance and significant land requirements for production, which can raise sustainability concerns (BILGILI, 2020). Methanol has also been widely studied, with the Stena Germanica becoming the first ferry to operate on methanol and marine gas oil in 2015 (PAULAUSKIENE et al., 2019). A Life Cycle Analysis (LCA) study by the IMO revealed that methanol has a smaller greenhouse gas (GHG) footprint over its lifecycle compared to traditional marine fuels. Despite its promise, methanol presents issues including aldehyde emissions, cold-start difficulties, and cost-effectiveness concerns.

Natural gas is typically used in maritime transport as either liquefied natural gas (LNG) or compressed natural gas (CNG). However, certain regulatory bodies, such as the United States, currently prohibit the storage of CNG for propulsion due to safety concerns. In contrast, LNG is widely adopted in the shipping industry due to its low sulfur, carbon, and nitrogen content, making it particularly suitable for operations within ECAs (SPOOF-TUOMI; NIEMI, 2020). Research has shown that LNG is a cost-effective and powerful option for long-distance transport, with a favorable environmental profile (SAADELDIN et al., 2023a). Nonetheless, the widespread use of LNG faces hurdles such as high initial investment costs, limited LNG bunkering infrastructure at ports, and strict safety regulations. Another challenge is methane slip, the release of unburned methane during combustion, but this issue has been largely mitigated in advanced two-stroke engine designs.

While extensive research has been conducted on the environmental benefits of alternative marine fuels, many studies have neglected to fully address other critical factors, such as technical feasibility, alignment with IMO regulations, and economic viability, including cost-effectiveness. A more holistic approach is necessary to evaluate the true potential of these fuels for sustainable implementation in the maritime sector.

2. METHODOLOGY

This study presents a detailed methodology for converting a vessel's propulsion system to operate on alternative fuels, aiming to determine whether the project qualifies as a rough order of magnitude estimate, a feasibility assessment, or a functional design. A key focus is placed on evaluating fuel storage options, including precise power requirements for storage systems and the energy demands associated with safety protocols. Multiple storage configurations are explored to ensure seamless integration with the ship's existing layout while maintaining operational efficiency. Additionally, the necessary auxiliary systems, such as cooling and safety infrastructure, are identified and specified. The study incorporates a robust economic and environmental evaluation framework, applying defined environmental indicators such as CO_2 and NO_x emissions. Advanced life cycle assessment (LCA) tools are used to accurately measure the economic and environmental impact of the proposed fuel conversion.

The economic analysis evaluates the cost-effectiveness of the conversion using key financial metrics such as return on investment and payback period, considering all relevant cost components and applying financial models and tools. This thorough approach provides a clear and comprehensive evaluation of the technical, environmental, and economic feasibility of converting the ship's propulsion system to alternative fuels, ensuring that the study is detailed and rigorous.

In general, NG could be stored on board vessels in either compressed (CNG) or liquefied form (LNG), but due to the larger quantity of NG used throughout this case study trip, it will not be workable to hold it in compressed form (AYMELEK et al., 2014). The only appropriate storage form here is a liquefied gas, which already has the advantage of being lighter and taking up less space than CNG. The specifications of LNG ISO tank containers that can be used for this purpose are shown in Table 2. Because of its liquid state, one of the major benefits of methanol fuel is that it is very comparable to marine diesel fuels. Because of its low flashpoint, the current diesel fuel facilities can be used for methanol fuel with minor modifications (AMMAR, 2019). Regulations about the safety of fuel tanks, location, and venting have requirements for the storage of methanol or LNG. Fuel should not be kept in machinery or accommodation spaces, and at least a horizontal distance of 760 mm shall exist between the fuel tank side and the ship's shell. Each tank must be able to support the propulsion system's continuous rating and the generator plant's typical operating load for at least eight hours while at sea.

Fuel tanks must be equipped with a system for gas freeing and secure inert gas purging. When there is no full access from the open deck, fuel tanks must have enough ventilation entrances and outlets to ensure full gas-freeing, but no fewer than two inlets and two outlets per tank. To reduce any fire risks near the fuel tanks on the weather deck, special care must be taken. Depending on the circumstances, a fire safety assessment may be required to determine how to protect the low-flashpoint liquid (LFL) fuel tanks from potential fires on board.

The economic factor has a large influence on the comparative study to determine the best option.

Table 2. Specifications of the LNG containers.

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Model	Pressure (bar)	Weight (kg)	Length (m)	Height (m)	Width (m)	Capacity (Gross)
ISO VAC 40-LNG	10	12,670	12.19	2.591	2.438	43,500 Ltr
ISO VAC 20-LNG	17	7875	6.058	2.591	2.438	20,000 Ltr

In this study, the economic assessment is based on evaluating the benefit of using dual-fuel instead of marine diesel oil, then calculating the annual savings cost, and finally calculating the annual cost-effectiveness of reducing ship emissions. For switching from diesel fuel to a dual-fuel engine, the annual saving cost (ASC) is evaluated according to equation 01, where OSC and MSC are the operation and maintenance cost savings from using dual-fuel instead of diesel. FSC is the fuel saving cost and can be calculated by using equation 02, where P is the power of the main engine kW, t is the annual time of operation, and FC.D and $F_{C.AF}$ is the fuel cost for diesel and other alternative fuels in USD. C_b is is the capital recovery cost for the conversion process, which can be calculated by using equation 03. C inferior à linha A is the capital cost of changing from the main diesel engine to the dual-fuel engine. N is the time of ship operation after using a dual-fuel engine, and i is the annual interest rate.

$$ASC = FSC + OSC + MSC \tag{01}$$

$$FSC = P * t * [(SFC_D * F_{C.D}) - (SFC_{AF} * F_{C.AF})] \tag{02}$$

$$C_b = C_A * \left(\frac{i(1+i)^N}{(1+i)^N - 1}\right) \tag{03}$$

The reduction of ship emissions annual cost-effectiveness EAC_{CE} can be evaluated by using Eq. (4). This includes the annual capital cost reduction (ACC) of using alternative fuels onboard and the conversion process in \$/ton. The maintenance and operation costs (AMC), and the amount of emission reduction (RE) in tons/year:

$$EAC_{CE} = \frac{ACC + AMC}{RE} \tag{04}$$

The total emission for ships during a voyage per tonne can be calculated by using equation 05. The ship emission (EM) depends on the main engine power (P_w) in kW, the running time in hours, the load factor of the engine (L_f) and the fuel pollution factor $P_{f,i}$ in g/kWh; (i) is the type of emission, (f) is the type of fuel, (t) is the operating time, and (SFC_{ME}) is the specific fuel consumption.

$$\text{à}EM_{trip,i,f} = \sum[t(P_w . L_f . P_{f,i} . SFC_{ME})] \tag{05}$$

As a case study, the container ship EVER ALOT was chosen, for which it was proposed to convert its diesel engine into a dual-fuel engine running on alternative fuels. Therefore, it is crucial to study the environmental and economic consequences of using dual-fuel. The study was based on a comparison of methanol and liquefied natural gas as alternative fuels. The container vessel EVER ALOT, which is owned by a Taiwanese ship operator, Evergreen Marine, and primarily serves trade routes connecting the Far

East and Europe, was built in 2022 with a 24,000 TEU capacity and is sailing under the Panamanian flag. Table 3 depicts the ship's critical data.

The ship track should be selected to assess the environmental impact of ship operation. The ship's liner service is depicted in Fig. 5, and for this study, the route from Hamburg, Felixstowe, Rotterdam, Colombo, Tanjung Pelepas, Kaohsiung, and Qingdao via the Suez Canal was chosen, and the total distance is 11004 nautical miles. The ship is currently operated with a low-speed diesel engine (CMD-WinGD 11X92-B), at 70 rpm and 11 cylinders. The length and height of the engine are 21.215 m and 16.12 m; the bore is 920 mm, and the stroke is 3468 mm. The engine weight is 1960 MT. The engine uses marine diesel (0.1 S%) to move cargo between several ports with a maximum continuous rating of 66,440 kW. The relation between specific fuel consumption and maximum continuous rating (MCR) can be evaluated according to engine data. The SFC for the low-speed engine is 162.3 (g/kWh). For NOx emissions, after January 2016, the IMO applied new NOx emission limits of around 3.4 g/kWh for ships operating in an existing NOx Emission Control Area (ECA) or built and operating on or after the date of acceptance of a new ECA. Furthermore, for SOx emissions, IMO 2020 established a new sulfur limit of 0.5%.

Therefore, it is suggested to convert the main engine into an 11X92DF engine with the same speed and power, which will run on liquid natural gas as fuel. Since no major structural elements need to be changed, DF-capable engines can be converted to dual-fuel engines. Another proposal is to transfer the 11X92-B to a MAN B&W ME-LGI engine with the same speed and power that can run on methanol as a dual-fuel. The ability of dual-fuel engines to maintain safe gas operation and perform accurate fuel oil and gas switching even in difficult weather conditions gives them an advantage. The combustion process for the ME-LGI engine occurs at 1300 °C to avoid methane slip and N_2O. The study aims to evaluate the economic impact of using LNG and methanol as a dual-fuel instead of conventional fuel.

Table 3. Main data of the EVER ALOT ship.
Tabela 3. Dados principais do navio EVER ALOT.

Type	Container ship
Ship’s Name	EVER ALOT
Year built	2022
IMO No.	9893955
Flag	Panama
Length over all (m)	400
Breadth over all (m)	61.5
Draught (Avg / Min / Max) (m)	13.2 / 3.5 / 25.5
Speed (kn)	20.1
Power (kW)	60,400 at 70 rpm
TEU	24000
Deadweight (tons)	241000
Gross Tonnage (GRT)	236228
Main engine	CMD - WinGD 11X92-B
Generators (kW)	5 x 4,300

3. RESULTS

The total emission per trip and annual emission were calculated to assess the environmental effect from using a dual-fuel engine (Table 4). The annual costs of dual-fuel systems for diesel versus dual-fuel systems and natural gas versus methanol are presented in Tables 5 and 6, respectively.

Figure 2 depicts the annual expense for capital cost recovery along with the payback periods. Figure 3 shows the annual cost-effectiveness of the proposed dual-fuel engine in reducing ship emissions for the container ship.

Table 4. Total emissions achieved by using a dual-fuel engine.
Tabela 4. Emissões totais obtidas com o uso de um motor bicombustível.

	Type of emission	Emission factor (g/kwh)	Emission rate during operation (kg/hr.)	Emission rate during maneuvering (kg/hr.)	Emission rate during standby (kg/hr.)
89% (NG) dual-fuel	NOx	3.7924	264.0079	62.11951	15.52988
	SOx	0.0396	2.756754	0.648648	0.162162
	CO_2	563.6649	39239.53	9232.831	2308.208
	PM	0.0209	1.454954	0.342342	0.085586
	CO	0.9728	67.72147	15.93446	3.983616
	HC	1.312	91.33488	21.49056	5.37264
91% Methanol (ME) dual-fuel	NOx	3.7777	262.9846	61.87873	15.46968
	SOx	0.0324	2.255526	0.530712	0.132678
	CO_2	312.2411	21736.66	5114.509	1278.627
	PM	0.0171	1.190417	0.280098	0.070025
	CO	0.6174	42.9803	10.11301	2.528253
	HC	0.891655	62.07256	14.60531	3.651327

Table 5. Fuel consumption with various percentages of alternative fuels.
Tabela 5. Consumo de combustível com diferentes percentagens de combustíveis alternativos.

Fuel consumption (m^3)	Diesel engine (ton)	Dual-fuel engine with 89% Natural gas (ton)		Dual-fuel engine with 91% Methanol (ton)	
	MDO	Natural gas	Pilot fuel	Methanol	Pilot fuel
per trip	7062.4512	6227.4816	312.765696	6426.830592	635.620608
per year	56499.61	49819.85	2502.13	51414.64	5084.96

Table 6. Annual fuel cost for NG and ME as a dual-fuel.
Tabela 6. Custo anual de combustível para GN e ME, considerando combustível duplo.

	Prices in (millions of US$/year)		
	Diesel engine	89% NG-dual-fuel engine	91% ME-dual-fuel engine
Diesel fuel	87.79374631	3.888008765	7.901437167
Diesel bunkering	0.531761032	0.023549417	0.047858493
Natural gas	0	72.52498571	0
Natural gas bunkering	0	0.084799749	0
Methanol	0	0	34.38533342
Methanol bunkering	0	0	0.052065463
Total fuel cost	88.32550734	76.52134365	42.38669454

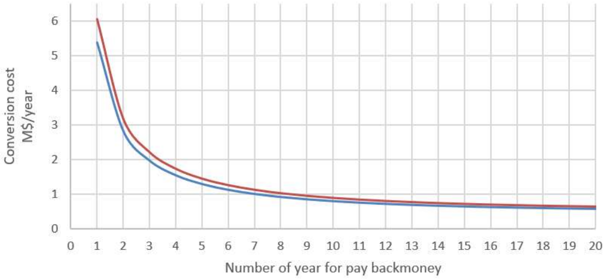

Figure 2. Annual savings cost and cost recovery using capital recovery.
Figura 2. Economia anual de custos e recuperação de custos por meio da recuperação de capital.

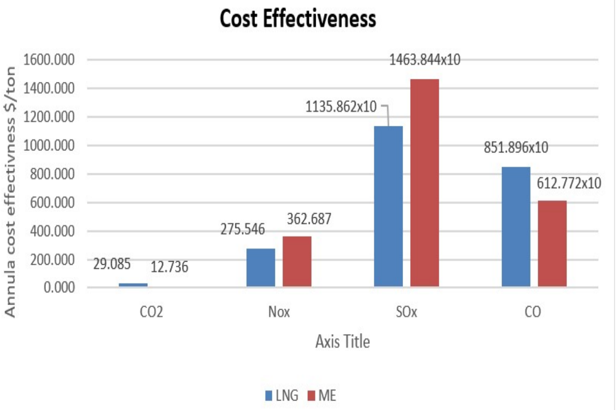

Figure 3. Annual cost-effectiveness for dual-fuel.
Figura 3. Relação custo-benefício anual para combustível duplo.

4. DISCUSSION

The study compared the use of methanol and NG as alternative fuels in dual-fuel engines. Firstly, the emission rates (Sox, NOx, CO_2, PM, CO, and HC) per trip were evaluated to assess the environmental performance of using methanol and natural gas. The emission rates are compared based on IMO limitations. Finally, the impact of using natural gas and methanol on cost-effectiveness is measured. The total emission per trip and annual emission were calculated to assess the environmental effect of using a dual-fuel engine.

The economic factor has a large influence on the comparative study to determine the best option. This section is based on an economic analysis that compares the use of 11X92DF and MAN B&W ME-LGI engines that run on NG and methanol as dual-fuel, respectively, versus the 11X92-B engine that runs on diesel fuel onboard, for the same power and efficiency. The fuel-saving cost of using dual-fuel instead of diesel is first evaluated, followed by an analysis of the annual saving cost for dual-fuel engines. Finally, the cost-effectiveness of reducing ship NOx, SOx, CO_2, and CO emissions by using natural gas and methanol was assessed. In terms of fuel-saving cost, to calculate the annual fuel cost, it is important to evaluate the total fuel consumption in the case of using diesel fuel and dual-fuel, as shown in Table 4.

The total fuel consumption for LNG dual-fuel is 52321.98 tons per year, while methanol consumption is 56499.61 tons per year. It is noted that the pilot fuel consumed for natural gas (2502.13 tons/year) is significantly lower than for methanol (5084.96 tons/year), despite the pilot fuel amounts being 11% and 9%, and the total tons consumed of natural gas and methanol being 49819.85 tons and 51414.64 tons, respectively. This discrepancy can be attributed to the difference in energy content and combustion efficiency between the two fuels.

Natural gas, being a more energy-dense fuel compared to methanol, requires less pilot fuel to initiate and sustain combustion effectively. Additionally, the combustion characteristics of natural gas allow for a more efficient use of pilot fuel, resulting in lower overall pilot fuel consumption. These factors contribute to the observed difference in pilot fuel consumption between natural gas and methanol. The calculations are based on diesel, natural gas, and methanol fuel costs of 1320.8 $/m^3, 684.2 $/m^3, and 528.34 $/m^3, in addition to 8.0 $/m^3 for the bunkering prices, depending on the current fuel prices. Using methanol as a dual fuel resulted in a significant reduction in fuel costs of approximately 52% when compared to LNG, which saved approximately 11.8 million dollars per year.

The benefit of converting a diesel engine to a dual-fuel engine must be calculated in order to calculate the annual savings cost (ASC). Capital and operating costs for the engine are included in the costs. The capital cost of the alternative fuel systems includes system elements, engine retrofits, and engine room improvements. The majority of the NG conversion cost is considered to be the storage tanks and their security. In contrast, the costs for methanol consist of engine conversion costs and engine compartment safety modifications. The capital expenditure (CAPEX) cost for the ME-GL engines is about 5.5 million USD and 4.9 million USD for the X-DF engines. Maintenance, consumables, and fuel prices are all part of the operational costs. When compared to diesel fuel operation, using NG as a fuel in diesel engines increases maintenance costs three to fourfold.

For the NG dual-fuel engine, the X92-B engines are constructed to be converted later to an X92DF. Because no significant structural elements need to be changed, the DF-ready engines can be transformed to dual-fuel. All the components that will be changed during the conversion are either standard wear parts or particular X-DF systems and components. According to previous research, the total savings in maintenance and operation costs for using a dual-fuel engine instead of a diesel engine are US$49.86/kW.

For the case study, the ship is operated by 60400 kW; the total savings cost will reach US$3,011,544/year. The total annual fuel savings cost for using an NG dual-fuel engine is 14.816 million US dollars, while the total annual savings cost for methanol is 48.95 million US dollars. The time required for pay recovery is important in the statistical assessment of the transfer process from diesel engines to dual-fuel engines. The payment cost for the conversion process was calculated using the mentioned equations. These times should be compared to the expected working years for the ship after the conversion process, assuming a ship life cycle of 20 years from the start date of construction. Now, the total cost-effectiveness is calculated for each emission type based on the added annual cost of the conversion process, as discussed. The most cost-effective advantage of utilizing a dual-fuel engine is the reduction of CO_2 emissions.

Using LNG dual-fuel reduces CO_2 emissions by 64929.717 tons per year at a cost-effectiveness of 29.085 dollars per ton, while using methanol dual-fuel reduces CO_2 emissions by 195398.153 tons per year at a cost-effectiveness of 12.736 dollars per ton.

5. CONCLUSIONS

The International Maritime Organization (IMO) has proposed a range of strategies to minimize ship emissions and enhance energy efficiency in the maritime sector, focusing on both operational practices and technical upgrades. One of the most promising long-term approaches examined in this study involves replacing conventional diesel engines with dual-fuel engines capable of operating on alternative fuels. Among the options considered, natural gas and methanol stand out due to their lower environmental impact compared to traditional marine diesel oil (MDO).

This research presents a comparative assessment of methanol and natural gas usage in dual-fuel engines, analyzing their effectiveness in reducing emissions and their economic viability. The results indicate that a dual-fuel configuration using 89% natural gas and 11% MDO can significantly cut emissions and lower costs, with savings of $275.55/ton for nitrogen oxides (NOx), $11,358.62/ton for sulfur oxides (SOx), $29.09/ton for carbon dioxide (CO_2), and $8,518.96/ton for carbon monoxide (CO). Similarly, using 91% methanol and 9% MDO in a dual-fuel setup yields emission reductions with respective savings of $362.69/ton for NOx, $14,638.44/ton for SOx, $12.73/ton for CO_2, and $6,127.72/ton for CO.

These findings underscore the environmental and economic advantages of adopting alternative fuels in dual-fuel marine engines, offering a practical solution for reducing the carbon footprint of maritime transport, including livestock shipping.

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