

IMPACT OF ALTERNATIVE FUELS ON EMISSIONS IN PANAMA CANAL OPERATIONS

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Abstract

This study examines the emissions generated during vessel transit and waiting periods at the Panama Canal, as well as the potential of currently available alternative fuels to mitigate their environmental impact. Technical, operational, and environmental data are collected from two bulk carriers during Canal transits to construct operational profiles and evaluate fuel consumption for both propulsion and auxiliary systems. Emissions from conventional systems using marine diesel oil (MDO) are calculated as a baseline, and alternative scenarios using methanol and liquefied natural gas in dual-fuel engines are assessed. The analysis encompasses direct emissions from fuel use and indirect emissions from fuel production and transportation, providing a comprehensive life cycle perspective. The study also evaluates the energy production costs to compare the economic performance of each fuel option. Results show that liquefied natural gas (LNG) reduces life cycle carbon dioxide equivalent emissions by up to 19.03%, while methanol produced from fossil sources increases them by up to 17.42%. Methanol nearly eliminates sulphur oxides and particulate matter, whereas LNG achieves greater reductions in nitrogen oxides. The energy production cost ranges from \$0.1548 to \$0.2001 per kilowatt-hour for methanol, \$0.1157 to 0.1545 for LNG and 0.1167 to 0.1546 for MDO, highlighting the trade-offs between environmental performance and economic viability.

Keywords

Panama Canal, maritime decarbonisation, methanol, liquefied natural gas (LNG), dual-fuel engines.

1 Introduction

The maritime transport network is responsible for approximately 80% of the global volume of goods transported, underscoring its critical role in international trade. Despite its significant economic role, the maritime sector is a major emitter of greenhouse gases (GHGs) involving carbon dioxide (CO₂), methane (CH₄), and nitrous oxide (N₂O) (IMO, 2024). Other air pollutants, including nitrogen oxides (NO_x), sulphur oxides (SO_x), or particulate matter (PM), are also emitted during ship operations, posing significant threats to local environments and human health (Barberi et al., 2021; Murcia González, 2021). These emissions are primarily generated by the extensive use of fossil fuels in marine diesel engines, which serve as propulsion systems' main engines (MEs) and marine diesel generators (DGs) for onboard electricity generation (Kerbiriou et al., 2025; Skoko et al., 2024).

To mitigate the environmental impact of maritime vessels, the International Maritime Organization (IMO) established ambitious goals. These decarbonisation targets aim for a 20% reduction in emissions by 2030 and a 70% reduction by 2040 compared to 2008 levels, with the ultimate objective of achieving net-zero emissions by 2050 (IMO, 2023). One approach to meeting these reduction targets is retrofitting existing conventional systems to operate on alternative fuels. Dual-fuel (DF) engines can utilise both traditional liquid fuels, such as marine diesel oil (MDO) and heavy fuel oil (HFO), as well as alternative gas fuels, including liquefied natural gas (LNG) and methanol (MeOH) (Tadros et al., 2023). LNG and methanol (MeOH) are regarded as the most accessible and feasible marine fuels for achieving the 2030 targets, as manufacturers of DF engines have developed systems compatible with these fuels (Bilgili, 2023).

The Panama Canal is a key maritime passageway, facilitating 180 shipping routes that connect 1,920 ports and accounting for 9,904 transit passages in 2024 (PanamaCanalAuthority, 2024). However, this high volume of ship traffic contributes to significant air pollution during waiting and transit periods (Fuentes & Adland, 2023). In response, the Panama Canal Authority plans to closely monitor CO₂ emissions, particularly following the expansion with the third set of locks in 2006 (de Marucci, 2012). To address these environmental concerns, the use of LNG and MeOH DF engines in ship electrification and propulsion systems has the potential to substantially reduce GHG and other air pollutants emitted throughout the canal.

In this context, this study analyses emissions during the Panama Canal passage, utilising data collected from two sister bulk carriers. The data includes sensory measurements of engine parameters, such as power and fuel consumption (FC), encompassing the entire operations of the ships during their passage through the Canal, including waiting times. The analysis offers an environmental

benchmarking of the usage of MeOH and LNG DF engine systems, focusing on their environmental impact on canal operations. The analysis incorporates well-to-tank (WtT) and tank-to-wake (TtW) emissions related to Canal operations, illustrating the lifecycle environmental impact of the vessels.

The primary research contribution is to provide valuable insights to maritime authorities navigating the Panama Canal. It offers a detailed environmental benchmarking of MeOH and LNG DF engine systems, highlighting lifecycle emissions and their impact on canal operations. It also offers insights into the cost aspects of alternative fuels through the Canal operations, utilising the energy production cost (EPC) as a metric. This study can be essential for guiding future green corridors and investments in alternative fuels, promoting sustainable maritime practices.

2 Literature Review

Several research papers have examined the emissions related to Panama Canal transit operations. Especially with the expansion and its impacts on GHG emission changes, studies have been conducted in specific regions, such as the United States' East (Bittner et al., 2012) and West Coasts (Corbett et al., 2012), as well as on a global scale (de Marucci, 2012). A similar approach was undertaken to prepare port cities for the anticipated effects of the Canal expansion (Hricko, 2012). Moreover, Lindstad et al. (2013) highlighted the emphasis on emission and cost reductions in the Canal, particularly regarding the applicability of innovative bulk carrier designs for canal operations following its expansion..

The examination of hub-port selection (Tai, 2015) and the changes in trunk route deployment (Tai & Lin, 2016) with respect to emissions following the expansion was also conducted. Furthermore, Carral et al. (2020) investigated the implications of the Panama Canal expansion for maritime transport emissions, focusing on its effects on both GHGs and local air quality in the region of Panama. Lastly, Fuentes and Adland (2023) examined the impact of operational efficiency improvements on shipping emissions at the Panama Canal, estimating a potential reduction of up to 1.8 million tonnes of equivalent CO₂ (CO₂e) per year from 2019 to 2021 through various scheduling proposals.

Alternative fuels in marine DF engines have been extensively investigated recently, largely driven by the IMO's decarbonisation goals. In this context, life-cycle based techno-economic analyses of methanol (MeOH) and liquefied natural gas (LNG), considering both cost and environmental implications, have gained increasing attention.

Bilgili (2021) presented a comprehensive environmental evaluation of various marine fuels, including HFO, LNG, MeOH, ammonia, and hydrogen. The results indicated that while alternative

fuels can significantly reduce GHGs, their overall environmental benefits depend heavily on the production methods and energy sources used.

Akman (2023) reported that LNG-DF engines can enhance energy efficiency by up to 20% while significantly reducing emissions. However, these systems require additional space and equipment, which presents logistical challenges. Despite this, LNG remains a strong candidate for meeting IMO regulatory requirements.

Building on this, Bayraktar and Yuksel (2023) conducted a benchmarking study comparing LNG and MeOH by applying various retrofitting scenarios for DF engines based on a streamline fuel-focused life-cycle approach. Their findings improved the Energy Efficiency Existing Ship Index (EEXI) and Carbon Intensity Indicator (CII). Notably, LNG yielded better overall compliance outcomes, although engine size selection proved to be a critical determinant of performance. Further contributions by Bayraktar et al. (2023) evaluated the retrofitting of marine diesel engines to MeOH DF configurations having different size configurations. Outcomes highlighted significant reductions in CO₂ emissions and indicated attractive payback periods, especially considering expected advancements in MeOH technology.

Similarly, Panchuk et al. (2024) explored MeOH as a sustainable marine fuel. Their comparative assessment underscored its potential relative to other alternative fuels, emphasising necessary engine modifications. The study projected that MeOH could account for up to 70% of the low-carbon marine fuel market by 2050. Moreover, biomass-based production enhanced green MeOH output by 30% while reducing production costs, reinforcing its competitiveness in the maritime sector.

Zincir and Arslanoglu (2024) examined the life-cycle environmental impacts of various marine fuels when combined with carbon capture technologies. Results outlined that integrating carbon capture can significantly reduce GHGs. However, the overall benefits depend on the fuel, capture method, and energy source used in the capture process.

Lee et al. (2024) evaluated nine alternative marine fuel production pathways using life cycle assessments and economic analyses. Findings demonstrated that fuels such as biomass-based diesel, e-MeOH, and e-ammonia can reduce GHG emissions by up to 92%. However, they were not cost-competitive within the current circumstances unless carbon pricing increases significantly in the future.

Finally, Akman et al. (2025) introduced a conceptual design of a bulk carrier powered by LNG, MeOH, and hydrogen. Their findings revealed that the LNG-powered configuration achieved a 17.1%

lower Energy Efficiency Design Index (EEDI) compared to MDO, and a 13.7% reduction relative to MeOH.

The reviewed studies primarily focus on two interconnected themes: the environmental impacts of Panama Canal operations, particularly following its expansion, and the adoption of alternative fuels in marine dual-fuel engines. Research on the Panama Canal focuses on regional and global changes in GHG emissions, port preparedness, and operational efficiencies. Concurrently, studies on alternative fuels examine the techno-economic and environmental performance of LNG and MeOH, emphasising retrofitting potential, compliance with IMO regulations, and future fuel market projections.

A research gap has been identified in the investigation of emissions during the Panama Canal passage using a detailed load profile based on onboard data collection, which enables more accurate calculations. In addition, the analysis of DF engines operating on either LNG or MeOH for propulsion and electrification based on such detailed load profile data has not been addressed in the literature to the authors' knowledge.

The selection of LNG and MeOH as the focus fuels is based on their current availability in the marine fuel market and their compatibility with existing DF engine technologies, which are the only commercially viable options at present. Furthermore, the analysis prioritises fuels that can support a transitional pathway toward the IMO's 2050 decarbonisation targets, with a strategic emphasis on achieving meaningful progress by 2030. This approach also informs the evaluation of potential bunkering infrastructure developments in the Panama Canal region, aligning fuel choice with practical implementation and near-term climate goals.

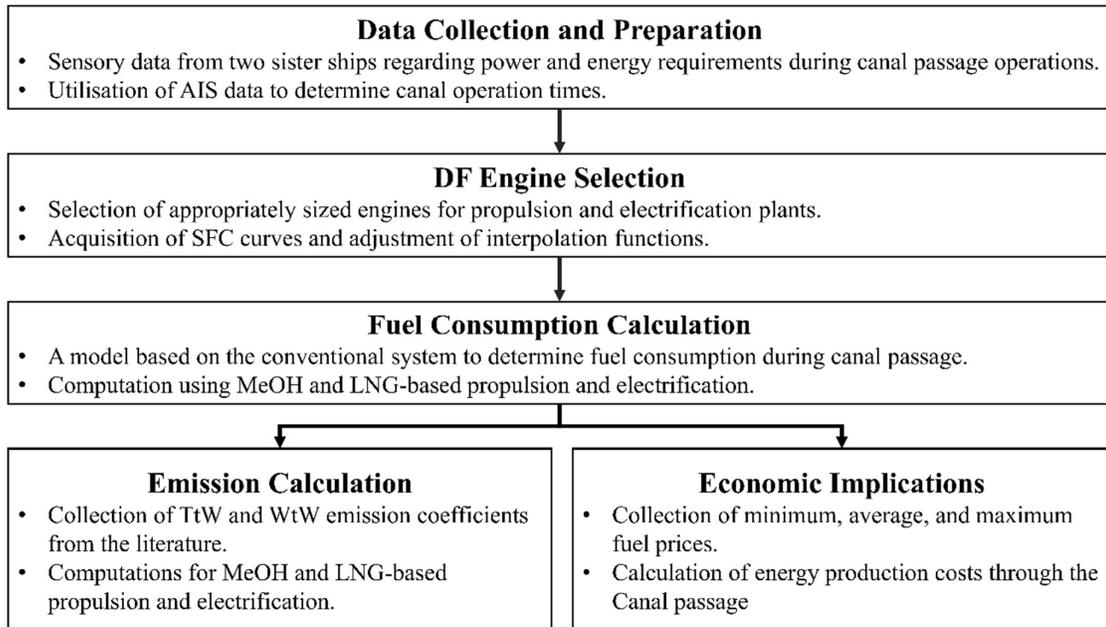
This study distinguishes itself by addressing these under-explored dimensions through the integration of high-resolution operational data, with a specific focus on real-world DF engine performance and associated emissions. As a result, it provides a level of analytical precision and contextual relevance that has not been previously demonstrated in the literature concerning Panama Canal passage operations.

3 Methodology

The analysis employed a comparative approach to assess the utilisation of LNG and MeOH in DF engines for propulsion and electrification of two sister ships during their Panama Canal passage operations. These operations encompass both waiting times and transit passages through the canal. The stages used in the analysis are depicted in Figure 1.

Figure 1

Methodology flowchart



The initial stage of the analysis involves collecting and preparing the data. Power and energy requirements during the Canal passage were gathered from two sister ships (denoted as Vessel A and Vessel B in the study) serving as case studies. An advanced onboard hardware system with smart data collectors is integrated into the case study vessels to acquire synchronised and reliable inputs from sensors, instruments, and control systems. Functioning over a stable wireless network, this system enables continuous and efficient data acquisition for accurate monitoring (LAROS, 2024). The equipment is certified by Bureau Veritas and conforms to the European Declaration of Conformity standards, ensuring compliance with high safety and quality requirements.

Subsequently, data obtained from the Automatic Identification System (AIS) was utilised to ascertain the Canal passage dates for the case study ships. Vessel A transited the Canal twice in 2024, with operational durations of 9 hours and 32 minutes and 27 hours and 32 minutes, respectively. Similarly, Vessel B completed two operations during the same year, recording durations of 10 hours and 52 minutes and 28 hours and 12 minutes. Table 1 presents the particulars of the case study ships.

Table 1

Case study ships' particulars

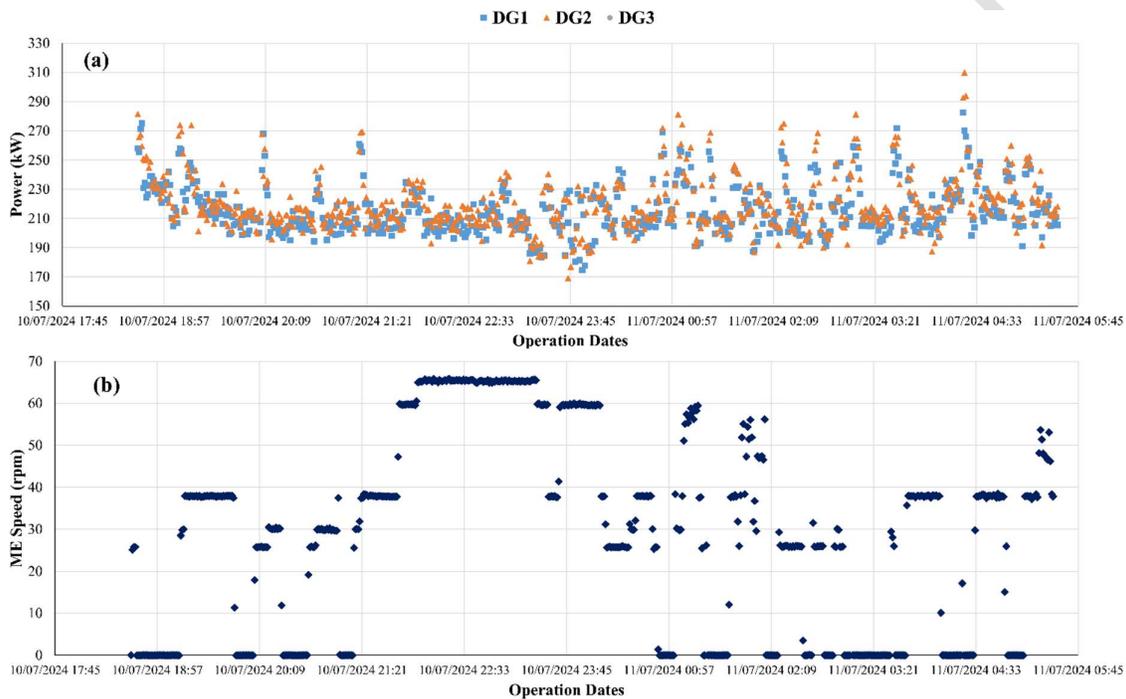
Parameter	Value	Unit
Deadweight Tonnage	63,519	t
Built Year	2016	-
Length Overall	199,9	m

Summer draft	13.3	m
Beam	32	M
ME Model	MAN B&W 5S60ME-C8.2	-
ME Power Capacity	8,050	kW
DG Model	YANMAR 6EY22LW	-
DG Power Capacity	3 × 720	kW
DG Frequency	60	Hz
Fuel Capacity	2,441	m ³

The case study vessels are bulk carriers owned by Laskaridis Shipping Co. Ltd., a collaborator in the project. Figure 2 illustrates the sample data corresponding to a passage for Vessel B.

Figure 2

Sample data of (a) electrification and (b) propulsion plants for Vessel B during the Canal passage.



The subsequent stage entails the selection of DF engines and acquiring specific FC (SFC) curves for both DF and conventional diesel engines. In the selection process for the DF engines, a thorough examination was conducted of engines that closely matched the required power output and those for which relevant data were available. For the electrification plant, the MAN 6L23/30DF was identified, while the propulsion plant was determined to be the MAN 6G45ME-C9.5-GI. Table 2 presents the technical specifications of the selected DF engines.

Table 2

DF engines' specifications

Parameter	Electrification Plant	
	Value	Unit

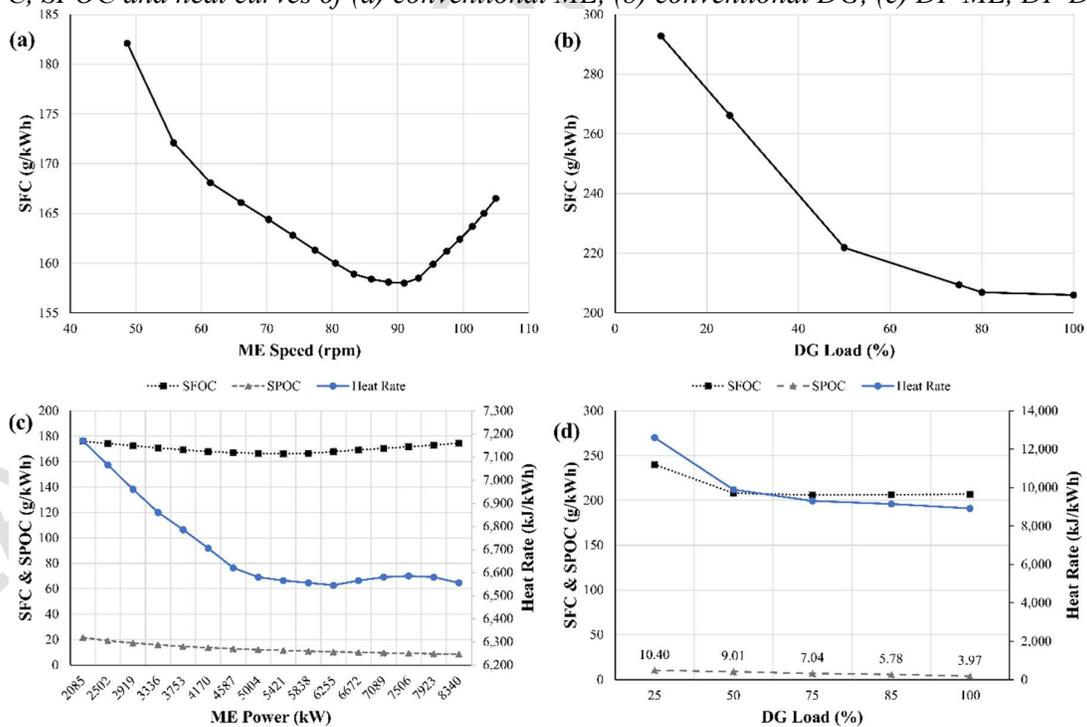
Model	MAN 6L23/30 DF	-
Bore	225	mm
Stroke	300	mm
Cylinders	6	-
Rated Power	750 @ 720 rpm	kW
Transmitted Power	710	kW
Engine Speed	720	rpm
Propulsion Plant		
Parameter	Value	Unit
Model	6G45ME-C9.5-GI	-
Bore	450	mm
Stroke	2250	mm
Cylinders	6	-
Rated Power	8340 @ 111 rpm	kW
Engine Speed	111	rpm

Source: (MAN, 2023, 2025)

The SFC, specific pilot oil consumption (SPOC), and heat rates in gas modes were obtained from the manufacturers' datasheets for the specified engines. Figure 3 illustrates the curves used in the analysis for both conventional and DF engines. The interpolation of the curves was ensured using the `interp1d` function in the SciPy library in Python programming environment.

Figure 3

SFC, SPOC and heat curves of (a) conventional ME, (b) conventional DG, (c) DF ME, DF DG.



Source: (MAN, 2023, 2025)

Based on the interpolation functions associated with each piece of equipment, the specific consumptions were determined regarding the corresponding power or load. The specific gas consumption (SGC) in tonnes is calculated using the heat rates (HR) provided in kJ/kWh from the DF engines data sets, along with the lower heating value (LHV) of the fuels. Equation 1 illustrates the calculation of SGC (MAN, 2023).

$$SGC \left(\frac{g}{kWh} \right) = \frac{HR \left(\frac{kJ}{kWh} \right)}{LHV \left(\frac{kJ}{kg} \right)} \times 1000 \quad (1)$$

The values were obtained and calculated under ISO conditions. Table 3 demonstrates the LHV of the analysed fuels in the study.

Table 2

LHV of fuels.

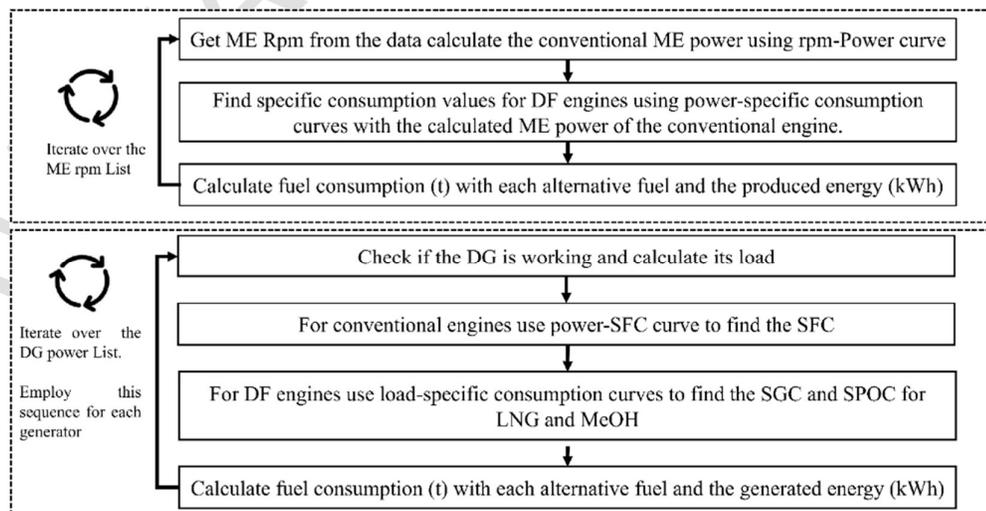
MDO	LNG	MeOH
42,700 kJ/kg	48,00 kJ/kg	19,900 kJ/kg

Source: (IMO, 2018)

After completing the specific consumption calculations and building the interpolation functions, the third stage involves calculating the FC resulting from the electrification and propulsion operation of the case study ships during the canal passage. Figure 4 illustrates the logic of the FC calculation methodology and the sequence of using the interpolation functions.

Figure 4

FC calculation stages for ME (upper) and DGs (lower)



The calculation process begins by iterating through the conventional ME (ME_C) RPM data to calculate the required power in the Canal operation. Using the required power, the SPOC and SGC values for the DF ME for LNG and MeOH are determined from the curves provided in Figure 3. Finally, the FC values of the propulsion unit were calculated throughout the entire operation for each case study vessel, along with the energy produced (E).

A separate function (shown in the lower figure) calculates the load of DG and SFC for the conventional DG (DG_C) based on the power-SFC curves described in Figure 3. For DF engines in the electrification plant, SGC and SPOC are computed using the load-SGC and load-SPOC curves. FC and energy generation were calculated for each DG during the Canal operations of the case study vessels. Equation 2 demonstrates the employed for the computation of FC (Yuksel et al., 2025).

$$FC(t) = SFC \left(\frac{g}{kWh} \right) \times E(kWh) \times 10^6 \quad (2)$$

The final stages of the methodology involve calculating emissions and determining the EPC for each case study vessel that utilises various fuels during transit through the Panama Canal. The emissions were calculated using the emission coefficients provided in Table 3.

Table 3

Emission coefficients for fuels.

Fuel	TtW (g-E/g-fuel)					
	CO ₂	CH ₄	N ₂ O	SO _x	NO _x	PM
MDO	3.206	0.0001	0.0002	*0.3200	*14.800	*0.160
LNG	2.75	0.0015	0.0002	*0.0030	*1.088	*0.027
MeOH	1.375	0	0	0	3.350	0
Fuel	WtT (g-WtT /g-TtW)					
	CO _{2e}	SO _x	NO _x	PM		
MDO	0.1504	*0.3482	*0.1896	0		
LNG	0.1270	*0.1600	*0.1418	0		
MeOH	0.3470	0	*0.3783	0		

*The unit is g/kWh, Source: (Comer & Osipova, 2021; Gilbert et al., 2018; IMO, 2016)

The coefficients for MeOH were derived based on grey production methodologies. Depending on the coefficient unit, the coefficient was either multiplied by the FC for the TtW calculation, or by the TtW emissions in the case of the WtW emission calculation, or by the generated energy. The CO_{2e} is computed employing Equation 3 for each fuel (IMO, 2024).

$$CO_{2e}(t) = CO_2(t) + 265 \times N_2O(t) + 28 \times CH_4(t) \quad (3)$$

The formula described in Equation 3, computes the global warming (GWP) potential based on 100 years. Since the GWP is larger for N₂O and CH₄ around 260 to 273 times and 27 to 30 times greater than that of CO₂, respectively the coefficients reflect this phenomenon.

The TtW and WtT emissions were evaluated for each case study vessel utilising different fuels, based on FC and generated energy. This assessment aims to determine the overall environmental impact throughout the life cycle. By adopting a streamlined methodology, this approach simplifies the evaluation process, enhancing the clarity of these parameters for maritime stakeholders (Yuksel et al., 2025).

The EPC values regarding each fuel utilised in the case study vessels were calculated employing Equation 4 (Shu et al., 2017).

$$EPC \left(\frac{\$}{kWh} \right) = \frac{C_{fuel}(\$)}{E (kWh)} \quad (4)$$

EPC represents the cost per unit of energy produced, excluding factors like interest rates, installation costs, or equipment lifespan. While it lacks comprehensiveness in these areas, the EPC is particularly relevant for the Canal Passage, where the operational duration is limited. Thus, it offers a more suitable benchmark for this analysis. In the formula, C_{fuel} represents the fuel cost calculated using the fuel prices provided by ShipandBunker (2024) for the specified operation range as depicted in Table 4.

Table 4

High, average, and low fuel prices (\$/t).

Fuel	High	Avg	Low
MeOH	445.5	383.5	359.5
LNG	834	746	652
MDO	782	677	609.5

The fuel prices in the table were gathered from the Rotterdam port, encompassing all examined fuels. Given the fluctuations in fuel prices, high, average, and low values between the operation dates were considered to establish the range of EPC values.

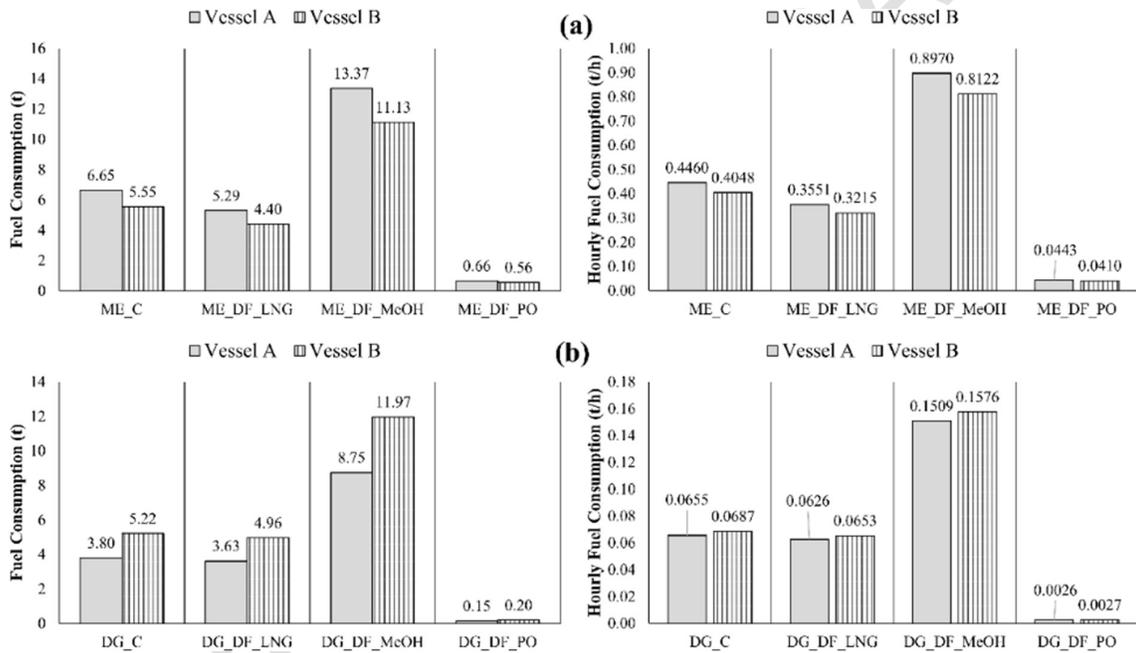
4 Findings

Table 5 presents a summary of the utilisation hours and energy consumption of the propulsion and electrification systems through the Panama Canal passage.

Table 5*Operation durations and energy generated in the case study vessels.*

Vessel	ME Time (h)	Operation Time (h)	DGs Time (h)	Operation Time (h)	Total Operation (h)	Canal	ME Energy (kWh)	DG Energy (kWh)
A	14.90		58.00		37.17		38,692.25	15,855.88
B	13.70		75.95		52.52		32,291.07	22,135.65

The DG operation times vary with respect to the total operational duration, depending on the number of generators running in parallel. Vessel B employed parallel DGs more frequently than Vessel A as a precautionary measure, which is also evident in the DG energy data. Figure 5 illustrates the FC of the case study vessels' propulsion and electrification plants during Canal passage operations.

Figure 5*FC values for propulsion (a) and electrification (b) plants.*

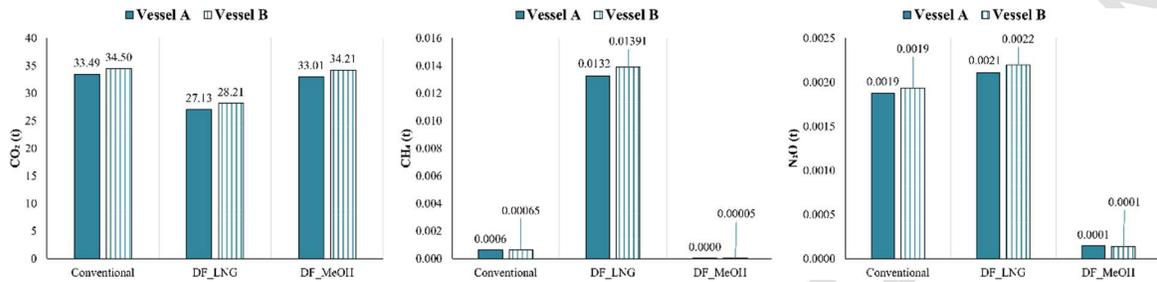
In Figure 5a, the conventional ME is denoted as ME_C, while the DF ME is represented as ME_DF. Additionally, the specific fuel type used in the DF ME is indicated by an appended abbreviation. For example, a DF ME operating with MeOH is labelled as ME_DF_MeOH in the figure. The pilot oil (PO) is shown separately as ME_DF_PO, which remains constant for both LNG and MeOH usage during the analysed operation. In Figure 5b, the same notation convention is applied to represent DG operations. This notation is consistently applied throughout the remaining results figures as well.

MeOH usage leads to a pronounced increase in FC across both ME and DG systems, attributable to its lower energy density and mass-based efficiency. Consequently, vessels operating on MeOH

necessitate a substantially greater quantity of fuel to achieve equivalent energy output, potentially impacting fuel storage capacity and operational range. Figure 6 presents the GHG emissions of the case study vessels.

Figure 6

FC values for propulsion (a) and electrification (b) plants.



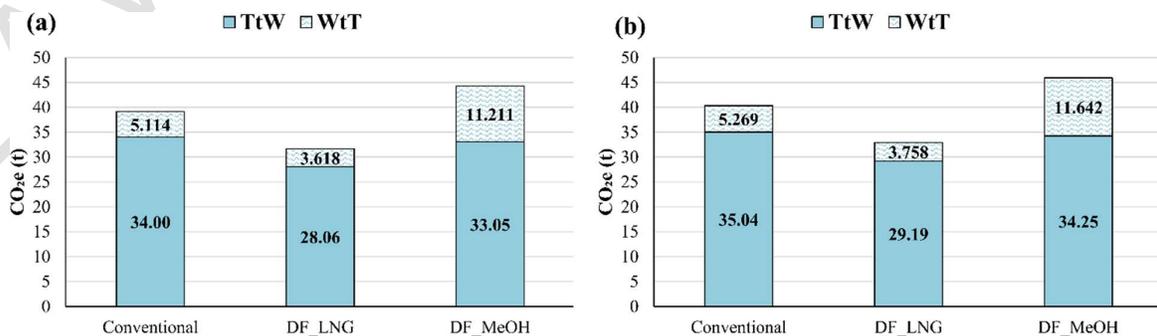
TtW CO₂ emissions were reduced by 18.99% and 18.23% for Vessels A and B, respectively, using DF_LNG configurations in both propulsion and electrification systems. In comparison, MeOH usage resulted in more modest reductions of 1.42% and 0.85% for the respective vessels.

Operational CH₄ emissions were nearly eliminated through MeOH usage, with reductions of 92.23% and 92.89% for Vessels A and B, respectively. In contrast, LNG usage led to a substantial increase in CH₄ emissions, with rise rates reaching 2013.92% and 2054.01% for the respective vessels. However, it is important to note that the maximum CH₄ emission recorded during the Canal passage was only 0.0014 t with LNG DFs.

N₂O emissions increased by 12.13% and 13.14% with LNG-DF configurations, while MeOH-DF configurations led to reductions of 92.23% and 92.89% for Vessels A and B, respectively. The observed N₂O and CH₄ emissions in the MeOH configurations are attributed to PO use of PO. Figure 7 illustrates the CO₂e calculated based on TtW and WtT coefficients given in Table 3.

Figure 7

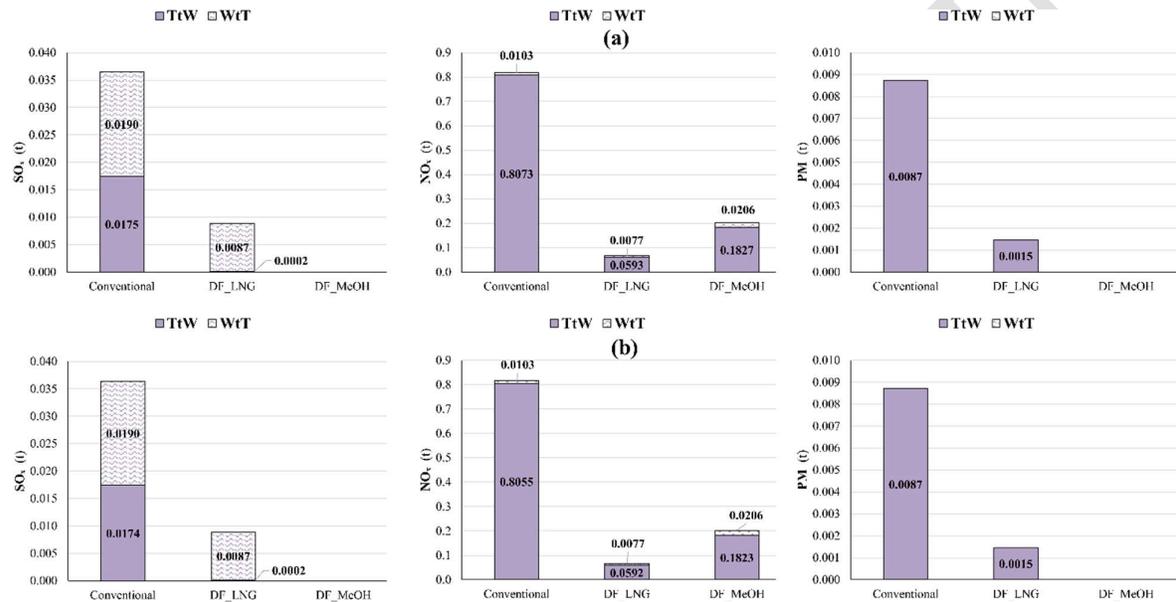
CO₂e emissions of Vessel A (a) and B (b).



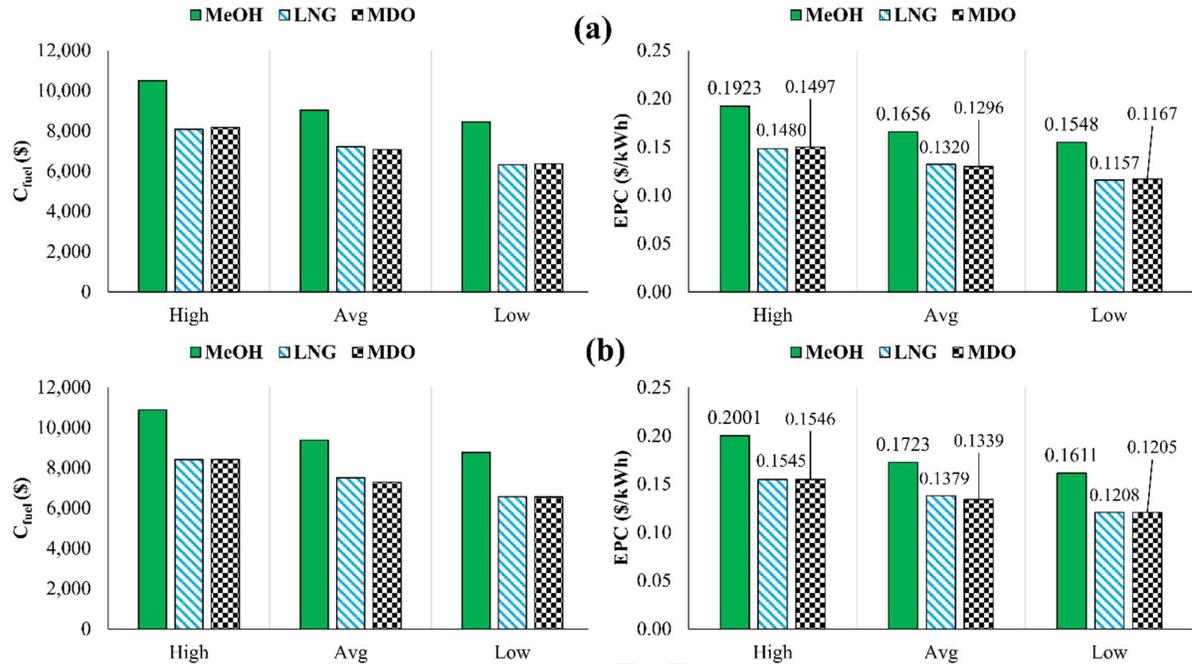
LNG usage during Canal operations resulted in a reduction of total CO_{2e} emissions by 19.03% and 15.78% for Vessels A and B, respectively. In contrast, MeOH usage led to an increase in CO_{2e} emissions by 13.15% and 17.32%. This increase is primarily attributed to the high WtT emissions associated with grey MeOH, underscoring the critical importance of adopting green production methodologies. Figure 8 presents the emissions of other air pollutants released by the case study vessels during Canal passage operations.

Figure 8

Other emissions of Vessel A (a) and B (b).



Total SO_x and PM emissions were eliminated using MeOH in DF configurations, while NO_x emissions were reduced by 75.13% and 75.18% for Vessels A and B, respectively. In comparison, LNG utilisation in DF systems resulted in SO_x reductions of 75.61% and 75.66%, and PM reductions of 83.13% and 83.16%. Additionally, NO_x emissions were reduced by 91.82% and 91.80% for the respective vessels. Figure 9 illustrates the C_{fuel} and EPC of the case study vessels during Canal operations.

Figure 9*C_{fuel} and EPC of Vessel A (a) and B (b).*

Depending on the prevailing fuel price scenario, MeOH operational costs ranged from \$8,446 to \$10,488 for Vessel A and from \$8,770 to \$10,888 for Vessel B. When LNG was utilised in DF engines, the corresponding costs varied between \$6,310 and \$8,073 for Vessel A, and between \$6,574 and \$8,441 for Vessel B. In comparison, the MDO usage in conventional engines resulted in costs ranging from \$6,366 to \$8,168 for Vessel A, and from \$6,660 to \$8,416 for Vessel B.

Corresponding to these C_{fuel} values, the EPC of MeOH ranged from \$0.1548 to \$0.2001 per kWh, while LNG exhibited a range of \$0.1157 to \$0.1545 per kWh, and MDO ranged from \$0.1167 to \$0.1546 per kWh.

5 Conclusion

This study provided environmental and economic assessments of alternative fuel usage during Panama Canal operations, based on empirical data collected from two sister bulk carriers. By integrating sensory engine data with WtT and TtW emission analysis, the research benchmarked the environmental performance of MeOH and LNG DF engine systems.

The findings demonstrated that MeOH consumption was considerably higher due to its low density, which required greater storage capacity on board the vessels. LNG usage resulted in a more pronounced reduction in CO₂ emissions, although this was accompanied by a significant increase in

CH₄ and a slight rise in N₂O. In contrast, MeOH achieved a more modest reduction in CO₂ emissions while substantially decreasing CH₄ and N₂O.

When evaluated in terms of CO₂e, LNG contributed to a meaningful overall decrease. However, grey MeOH led to an increase in CO₂e emissions due to elevated WtT values. Given MeOH's effectiveness in reducing other emissions, the significance of adopting green or blue production methods becomes evident for improving its CO₂e performance.

MeOH operation nearly eliminated SO_x and PM emissions and achieved a notable reduction in NO_x. Similarly, the use of LNG resulted in a considerable decrease in NO_x, along with substantial reductions in SO_x and PM.

Although the results highlighted the environmental advantages of green and blue MeOH, it exhibited the highest EPC values due to increased fuel consumption. LNG and MDO demonstrated comparable EPC performance, indicating the economic competitiveness of LNG as a marine fuel.

Future studies will aim to extend this research by broadening the temporal scope, which can be achieved by applying this methodology to selected potential green corridors involving the Panama Canal. This will include a detailed assessment of hydrogen and ammonia as potential marine fuels, with a focus on their viability for meeting the IMO 2040 and 2050 decarbonisation targets. The study will consider upstream production pathways, infrastructure readiness, and lifecycle emissions to support long-term strategic planning for sustainable maritime operations in this critical global transit route.

The economic analysis can be further developed by incorporating investment costs and calculating additional financial metrics to provide a more comprehensive evaluation. Moreover, the inclusion of fuel price uncertainty within an extended operational timeframe will enhance the robustness and applicability of the findings. Additionally, the incorporation of cold ironing systems or renewable energy systems onboard can further enhance the analysis by mitigating emissions during port stays and improving overall energy efficiency.

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