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Hybrid propulsion and alternative fuels in maritime transport: a Panama Canal-centred assessment

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ABSTRACT

This study presents a scenario-based environmental and economic assessment of hybrid propulsion systems and alternative marine fuels within Panama Canal-centred maritime operations. Dual-fuel (DF) engines configured in diesel-electric and mechanical propulsion systems, as well as fuel cell/battery electrification, were evaluated across two bulk carrier case studies. Cold ironing (CI) was assessed independently to quantify its contribution to port-side emission reductions. Ammonia DF systems achieved the highest tank-to-wake (TtW) greenhouse gas (GHG) reductions, up to 78.49% with CI, while green ammonia reduced well-to-wake (WtW) emissions by 66.03%. Liquefied Natural Gas (LNG) systems achieved GHG reductions aligned with 2030 targets. Methanol offered moderate benefits, while first- and second-generation biodiesel failed to meet GHG targets and showed limited environmental viability. Economically, grey ammonia yielded the lowest levelized cost of energy (\$140.61/MWh), while green ammonia reached \$469.01/MWh, indicating a trade-off between sustainability and cost. LNG and methanol remained competitive under both low- and average-price scenarios. The Panama Canal's strategic location makes it a key connection hub for low-energy-density alternative fuels, which require larger storage volumes and pose trade-offs between cargo capacity and refuelling frequency. As a mid-route chokepoint, the Canal enables reliable refuelling, supporting the operational viability of zero-carbon fuels in long-haul shipping.

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1. Introduction

Since maritime transportation is a significant contributor to greenhouse gas (GHG) emissions, the International Maritime Organization (IMO) has implemented ambitious decarbonisation targets to address the sector's environmental impact. These targets include reducing GHG emissions by 20% (aiming for 30%) by 2030 and 70% (striving for 80%) by 2040 relative to 2008 levels, ultimately aiming to achieve net-zero emissions by 2050 (IMO 2023).

International collaborative frameworks, such as green shipping corridors (GSCs), are increasingly viewed as crucial for achieving the IMO's goal of a low- to zero-emission shipping industry. They also promote collaboration among maritime stakeholders, including fuel producers, transport operators, and port facilities, to support the efficient supply of sustainable marine fuels (Wang et al. 2023; Ismail et al. 2024). Many GSCs also incorporate cold ironing (CI) infrastructure at ports, enabling vessels to access shore-side electricity and further reduce emissions during berthing (Alamouch et al. 2020; Alamouch et al. 2022).

CI is a promising decarbonisation strategy that enables ships to switch off auxiliary engines (AEs) while docked, drawing electricity from shore-based grids (Seyhan et al. 2023; Yuksel et al. 2024). This significantly reduces fuel consumption (FC) and emissions, including carbon dioxide (CO₂), nitrous oxide (N₂O), methane (CH₄), nitrogen oxides (NO_x), sulphur oxides (SO_x), and particulate matter (PM), thereby improving air quality and public health in port communities (Roberts et al. 2023).

Recent research on international collaborative frameworks like GSCs has advanced understanding across economic, infrastructural, and governance dimensions of maritime decarbonisation. Economic modelling approaches evaluated the viability of alternative fuels by analysing cost structures under varying carbon pricing schemes, bunkering fees, and vessel operating speeds (Jesus et al. 2024). Supply chain analyses, particularly those focused on ammonia, optimised global production and distribution networks to align with projected fuel demand (Wang et al. 2023). Stakeholder-driven frameworks underscored the complexities of port integration, identified financial and regulatory barriers, and proposed actionable solutions (Ismail et al. 2024).

Regional studies, such as those examining the Pacific North-west–Alaska corridor, assessed sustainability strategies and highlighted context-specific challenges in high-traffic maritime zones (Dolatabadi et al. 2025). Modelling methodologies, including game-theoretic approaches, revealed strategic interactions among governments, carriers, and cargo owners, offering insights into coordinated policy development (Zhang and Feng 2024). Complementary development frameworks provided phased implementation guidance, drawing on international case studies to support early fuel adoption and promote an equitable transition (Svendsen et al. 2023).

Recent studies on CI evaluated the emission reduction potential across specific geographic regions (Glavinović et al. 2023; Seyhan et al. 2023; Peddi et al. 2024), employed fleet-based approaches to assess decarbonisation strategies by ship type (Sevgili et al. 2025), conducted techno-economic analyses of renewable energy

integration into maritime operations (Rolán et al. 2019; Gülmez et al. 2024; Şenol and Seyhan 2024; Yuksel et al. 2024), and examined the effectiveness of green port technologies in supporting low-emission infrastructure (Twrdy et al. 2025).

Panama Canal studies have focused on emissions monitoring, operational efficiency, and vessel design improvements, identifying the Canal as a strategic maritime hub linking 180 shipping routes (Panama Canal Authority 2026). However, the high traffic volume contributes to considerable air pollution during waiting and transit periods (Fuentes and Adland 2023). In response, the Panama Canal Authority has enhanced CO₂ emissions monitoring, particularly following the 2006 expansion with the third set of locks (de Marucci 2012).

Several studies have investigated emissions associated with Panama Canal-centred operations, particularly following its expansion. Research has examined regional impacts on GHG emissions along the United States' East and West Coasts (Bittner et al. 2012; Corbett et al. 2012) and their global implications (de Marucci 2012). Similar assessments were conducted to help port cities prepare for the expansion's environmental effects (Hricko 2012).

Lindstad et al. (2013) explored emission and cost reductions through innovative bulk carrier designs tailored to post-expansion canal operations. Further studies examined hub-port selection (Tai 2015) and changes in trunk route deployment (Tai and Lin 2016) in relation to emissions. Carral et al. (2020) focused on the expansion's impact on both GHG and local air quality in Panama. More recently, Fuentes and (Fuentes and Adland 2023) estimated that operational efficiency improvements could reduce emissions by up to 1.8 million tonnes of CO₂ equivalent (CO₂e) annually between 2019 and 2021 through revised scheduling strategies.

The selection of the Panama Canal as the focal point of this study is driven by its status as a critical global chokepoint. Locally, the high concentration of maritime traffic within the Canal's confined geographical area creates significant environmental pressure, particularly during transit and waiting periods, which contribute to elevated local air pollution and GHG emissions. Unlike open-sea routes, the Canal's operational environment is characterised by frequent low-speed manoeuvring and lock transits. This provides a unique high-resolution testbed for evaluating the effectiveness of hybrid propulsion and CI technologies. By focusing on this strategic hub, the research can assess how localised decarbonisation strategies at a major maritime intersection can yield broader systemic benefits for international trade lanes.

In addition to shore power integration, retrofitting conventional systems to operate on alternative fuels is a key strategy for achieving emission reduction targets. Dual-fuel (DF) engines can use both liquid fuels, such as marine gas oil (MGO) and biodiesel, as well as gaseous alternatives, including liquefied natural gas (LNG), methanol (MEOH), and ammonia (Tadros et al. 2023). These engines can be used under Diesel-Electric Propulsion (DEP) or Mechanical Propulsion (MP) configurations combined with batteries or fuel cells, enabling further progress toward decarbonisation targets (Jimenez et al. 2022).

Recent studies offer a multi-dimensional evaluation of alternative marine fuels, covering engine performance, retrofitting, production, and environmental impact. LNG DF engines improved efficiency and regulatory compliance, though posed spatial challenges (Akman 2023; Akman et al. 2025). Retrofitting analyses showed LNG outperformed MeOH in IMO energy efficiency indexes, while MEOH achieved notable CO₂ reductions and favourable payback periods, with engine size as a key factor (Bayraktar and Yuksel 2023; Bayraktar, Yuksel, et al. 2023). MeOH's projected 70% market share by 2050 was supported by gains in biomass-based production (Panchuk et al. 2024). Carbon capture integration reduced GHG emissions, though

its effectiveness varied by fuel and method (Zincir and Arslanoglu 2024). Life-cycle assessments showed e-MeOH, e-ammonia, and biomass diesel could cut emissions by up to 92% but remained cost-prohibitive without higher carbon pricing (Lee et al. 2024).

The literature review demonstrates that studies on CI have primarily concentrated on regional emission reductions, fleet-level decarbonisation, and green port technologies. Research on alternative fuels has examined engine performance, retrofitting requirements, and life-cycle impacts. While Panama Canal studies have historically focused on emissions monitoring, operational efficiency, and vessel designs tailored to its locks, the integration of the Canal into broader decarbonisation frameworks remains underexplored. Specifically, there is a gap in understanding how the Canal's strategic location can facilitate multi-fuel bunkering and align with alternative-fuel transitions for deep-sea vessels. Given its role as a global hub connecting 180 shipping routes, the Panama Canal possesses the infrastructure to serve as a cornerstone of future maritime sustainability.

Building upon the established literature, this study addresses a critical research gap by evaluating the Panama Canal's role in maritime decarbonisation through a multifaceted lens of CI applications, hybrid propulsion architectures, and alternative fuel transitions. While previous research has focused on regional monitoring, this study provides a novel, high-resolution assessment of hybrid-electric retrofitting based on dual-fuel (DF) engine performance profiles and bunkering strategies at a strategic maritime chokepoint. By utilising real-world operational datasets, the analysis moves beyond generic modelling to examine the synergistic effects of shore power and hybrid energy management on decarbonisation feasibility. Furthermore, this research leverages the Panama Canal's strategic position as a global hub, evaluating the technical and economic viability of low-energy-density fuels in a unique geographical context along high-traffic maritime routes. Consequently, this study offers analytical precision that bridges theoretical decarbonisation planning with practical operational implementation. By establishing these findings, the research provides a foundation for future studies to explore how such localised assessments can be integrated into broader maritime frameworks and evolving international shipping networks.

2. Methodology

The analysis benchmarks the utilisation of alternative fuels in conjunction with hybrid energy systems across two sister vessels selected as case studies. Additionally, the impact of CI is evaluated along designated shipping routes, including transit through the Panama Canal, to assess the feasibility of establishing green corridors centred on this strategic maritime passage. Figure 1 presents the methodological framework employed in the study. The following sections elaborate on the key concepts and analytical stages, adhering to the sequence outlined in the flowchart.

2.1. Data collection and case study ships

The preliminary phase of this study focuses on data acquisition and preparation. Energy and FC data along the routes incorporating transit through the Panama Canal were recorded at one-minute intervals from two comparable vessels, referred to as Vessel A and Vessel B, which serve as the principal case studies in this research. The vessels selected for the case study are bulk carriers operated by Laskaridis Shipping Co. Ltd., an industry partner actively involved in the research project. Table 1 outlines the specifications of the vessels selected for the case study.

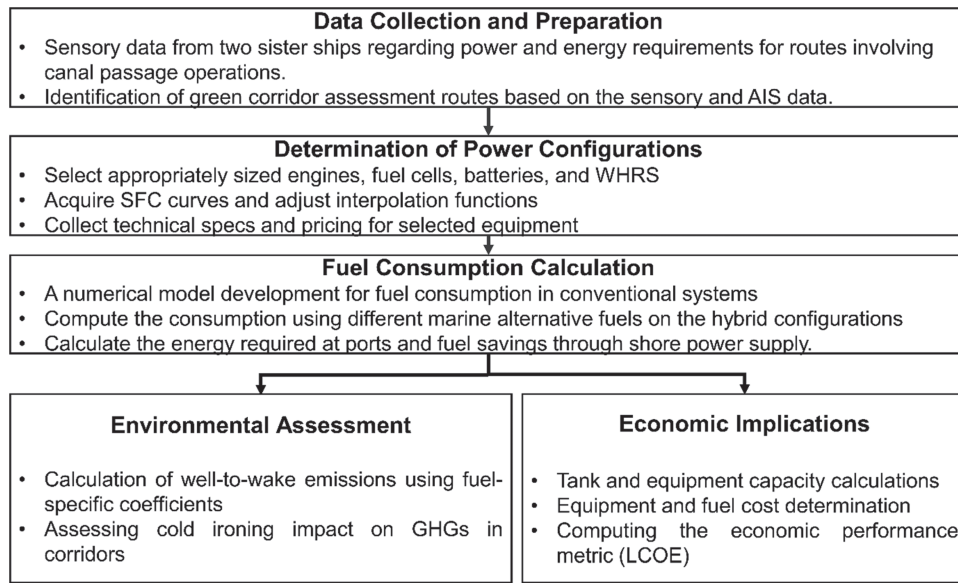


Figure 1. Methodology flowchart.

Table 1. Case study vessels' 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 5560ME-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 conventional configuration comprises an 8,050 kW two-stroke, very slow-speed engine dedicated to propulsion, supplemented by three marine diesel generator (DG) sets, each rated at 720 kW. A simplified schematic representation of this system is provided in Appendix A.

Ships are outfitted with an onboard monitoring system that integrates intelligent data logging units. These units collect harmonised and high-resolution inputs from a network of sensors, measurement devices, and control interfaces. Enabled by a secure wireless communication protocol, the system ensures uninterrupted and efficient data capture, thereby supporting precise performance tracking (LAROS 2024). The hardware has been certified by Bureau Veritas and complies with the European Declaration of Conformity, thereby ensuring adherence to stringent international safety and operational reliability standards. Figure 2 displays a filtered data sample for the Panama Canal transit operation of Vessel B.

After data cleaning and preprocessing, the dataset for Vessel A comprises 96,121 entries (66.75 days), whereas that for Vessel B includes 54,251 records (37.74 days). The route of Vessel A commenced with a port stay at the Port of Pecém, Brazil. Subsequently, the vessel proceeded to the Port of Los Angeles, United States, transiting through the Panama Canal. Following its call at Los Angeles, the ship continued to the Port of Vancouver, Canada. It then undertook a trans-Atlantic passage, once again navigating through the Panama Canal.

The voyage of Vessel B originated at the Port of Pascagoula, United States, with its initial destination being Puerto Quetzal, Guatemala, via a transit through the Panama Canal. Following this leg of the journey, the vessel returned to Myrtle Grove, United States, once again navigating through the Panama Canal.

2.2. Hybrid configurations

Four distinct hybrid configurations were evaluated by comparing DEP and MP systems. In MP systems, a single large DF engine is assumed to be retrofitted to match the propulsion power output of the conventional setup. In contrast, DEP configurations utilise four smaller DF engines that collectively share the load.

Electrification strategies were further examined by comparing DF engine-based systems with Proton Exchange Membrane Fuel Cell (PEMFC)/Battery configurations. In all cases, an Organic Rankine Cycle (ORC)-WHRS is integrated to support the electrification plant during navigation.

DEP1 and MP1 refer to the DF engine-based electrification and propulsion systems, while the more innovative PEMFC/Battery-based configurations are denoted as DEP2 and MP2. Figure 3 presents simplified layout diagrams for MP1 and DEP1.

MP1 represents a retrofitting scenario in which DF systems are integrated with propulsion and electrification units of equivalent size to the conventional configuration. DEP1 involves the implementation of a diesel-electric propulsion system comprising smaller DF engines coupled with electric motors. Figure 4 illustrates the configurations for MP2 and DEP2.

MP2 incorporates a 600 kW PEMFC plant and a 150-kWh battery system designed to meet the load demand of a single DF engine. In contrast, DEP2 integrates a 1,200 kW PEMFC plant and a 210-kWh battery system, capable of supporting the load of two generator sets, with additional power supplied by the main engines (MEs). Table 2 presents the technical specifications of the DF engines, PEMFC units, and battery cells employed in the analysis.

2.3. Fuel consumption calculation and alternative fuels

The specific FC (SFC) in liquid mode, specific pilot oil consumption (SPOC), and heat rates (HRs) for gas mode were sourced from

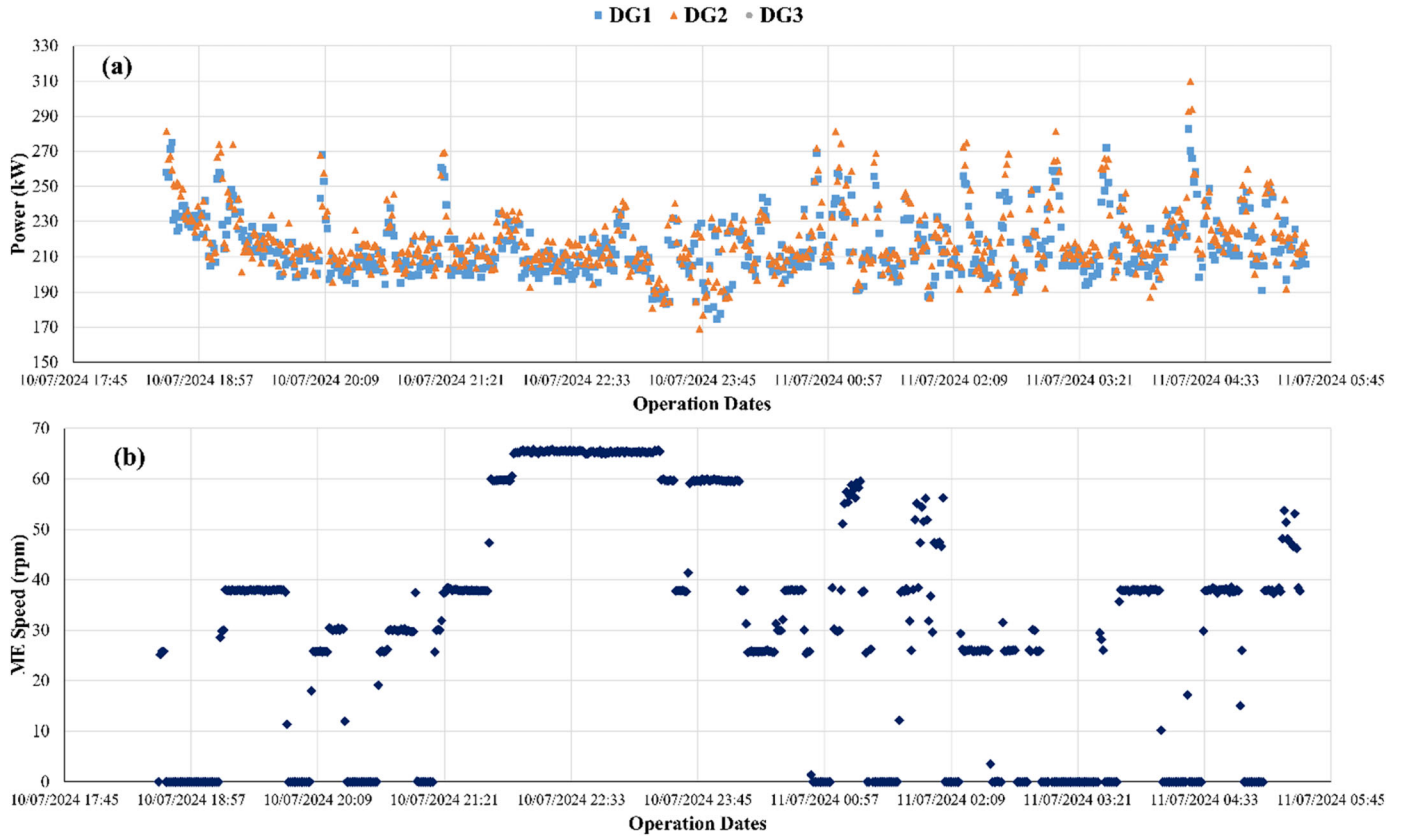


Figure 2. Representative datasets of (a) the electrical system and (b) the propulsion plant for Vessel B during transit through the Canal.

the manufacturers' datasheets corresponding to the selected engines. Curve interpolation was performed using the `interp1d` function from the SciPy library within the Python programming environment. The SFC, SPOC, and HR curves for the engines are provided in Appendix B, Table A1.

Based on the interpolation functions assigned to each piece of equipment, specific consumption values were determined as a function of the corresponding power output or load. The specific gas consumption (SGC), expressed in tonnes, was calculated using the HR values provided in kJ/kWh from the DF engine datasets, in conjunction with the lower heating value (LHV) of the respective fuels. The calculation methodology for SGC is illustrated in Equation (1) (MAN 2023).

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

All values were obtained and calculated under standard ISO conditions to ensure consistency and comparability across the analysis. The fuels evaluated in the paper are very low-sulphur fuel oil (VLSFO), MGO, LNG, MEOH, fatty acid methyl ester (FAME) biodiesel, ammonia, and hydrogen. Table 3 indicates the LHVs and densities of the marine fuels assessed in the analysis (IMO 2024; Bayramoğlu et al. 2025).

Ammonia is assumed to be combusted within a DF mixture characterised by an ammonia energy ratio (AER) of 90%, indicating that 90% of the total energy input is derived from ammonia, with the remaining 10% supplied by MGO. The AER metric quantifies the proportion of energy contributed by ammonia in DF combustion systems, with higher ratios reflecting greater reliance on ammonia as the primary energy source. AER is calculated as indicated in Equation

(2) (Ma et al. 2025).

$$AER = \frac{(m_{ammonia} \times LHV_{ammonia})}{(m_{ammonia} \times LHV_{ammonia}) + (m_{diesel} \times LHV_{diesel})} \quad (2)$$

To determine the specific mass ratio for the AER90 scenario, the energy balance is solved using the fuel-specific LHV constants provided in the study. By substituting these values into the AER equation, the relationship between the mass of ammonia ($m_{ammonia}$) and the mass of diesel (m_{diesel}) is established. Calculation shows that for every unit of diesel used, approximately 20.76 units of ammonia must be injected by mass to maintain the 90% energy threshold.

FC for both DF and conventional diesel engines, as well as gas consumption (GC) and pilot oil consumption (POC) specific to DF engines, were calculated using Equations (3) to (5).

$$FC(t) = SFC \left(\frac{g}{kWh} \right) \times E(kWh) \times 10^{-6} \quad (3)$$

$$GC(t) = SGC \left(\frac{g}{kWh} \right) \times E(kWh) \times 10^{-6} \quad (4)$$

$$POC(t) = SPOC \left(\frac{g}{kWh} \right) \times E(kWh) \times 10^{-6} \quad (5)$$

The energy in kWh is denoted as E in Equations (3) to (5). Hydrogen used in the PEMFC systems is assumed to be generated onboard via an integrated ammonia-cracking system. The analysis utilised a reactor model developed by Devkota et al. (2024) in Aspen Plus V1.2, in conjunction with a commercial cracker unit from Crystec (2024). The system processed an ammonia feed of 96.3 kg/h at 298 K and 10 bar. The thermal energy required for the endothermic reaction was supplied by the combustion of 9% of the ammonia input. The process yielded high-purity hydrogen ($> 99.999\%$) at a production rate of 16.7 kg/h, with associated NO_x emissions quantified at 0.021 kg-ammonia per kg-hydrogen produced (Yüksel et al. 2025).

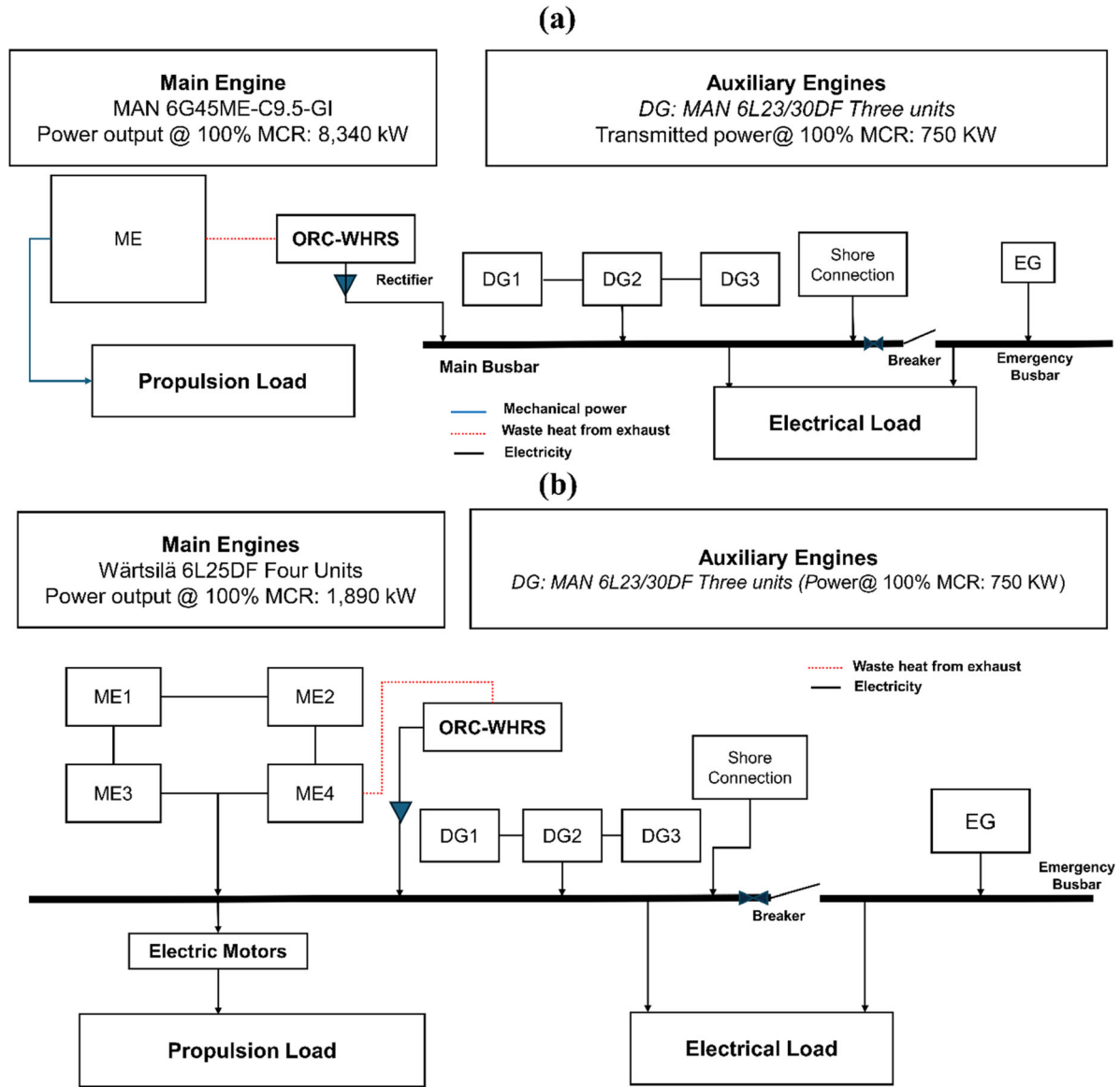


Figure 3. Simplified layout schemes of (a) MP1 and (b) DEP1.

While this model provides a robust thermodynamic baseline, it is acknowledged that the transition from localised reactor modelling to full-scale maritime integration involves significant techno-economic complexities. Challenges regarding dynamic load response, thermal management of the cracking unit during transient operations, and the volumetric constraints of large-scale purification systems introduce inherent scale-up uncertainties. Consequently, while the current results demonstrate a high theoretical potential, further empirical validation at a pilot-scale maritime level is required to mitigate risks associated with system-wide integration and long-term operational reliability.

Hydrogen consumption (HC) within the PEMFC system was quantified using Equation (6), supported by manufacturer-provided performance data, including efficiency and specific FC curves (PowerCellGroup 2024). The hydrogen storage system was sized to ensure operational autonomy for up to 2 days, accounting for potential contingencies, including emergency scenarios and scheduled maintenance of the ammonia decomposition unit (Yuksel et al. 2025).

$$HC(t) = SFC_{PEMFC} \times P_{PEMFC} \times \eta_{PEMFC} \times t \quad (6)$$

The operational duration, denoted by t (in hours), is used in conjunction with interpolated SFC values for hydrogen derived from performance curves given in Appendix B, Figure A2. The variables P_{PEMFC} and η_{PEMFC} represent the rated power and quantity of PEMFC units, respectively.

The energy required at each port was calculated based on ship-specific operational data, focusing on energy consumption during berthing. In CI scenarios, it is assumed that ships do not use onboard electrification systems; instead, all energy is supplied directly from the shore-side grid. Consequently, FC values were adjusted to reflect zero onboard fuel use during port stays, with equivalent electrical energy demand allocated to the grid. This approach enables a clear assessment of the impact of CI on port energy requirements and fuel-related emissions.

2.4. Battery model

In hybrid power system configurations, battery packs are integrated as auxiliary energy sources to support PEMFCs, particularly during transient load conditions or when the PEMFC output is insufficient. Lithium-ion batteries have been selected for these scenarios due to

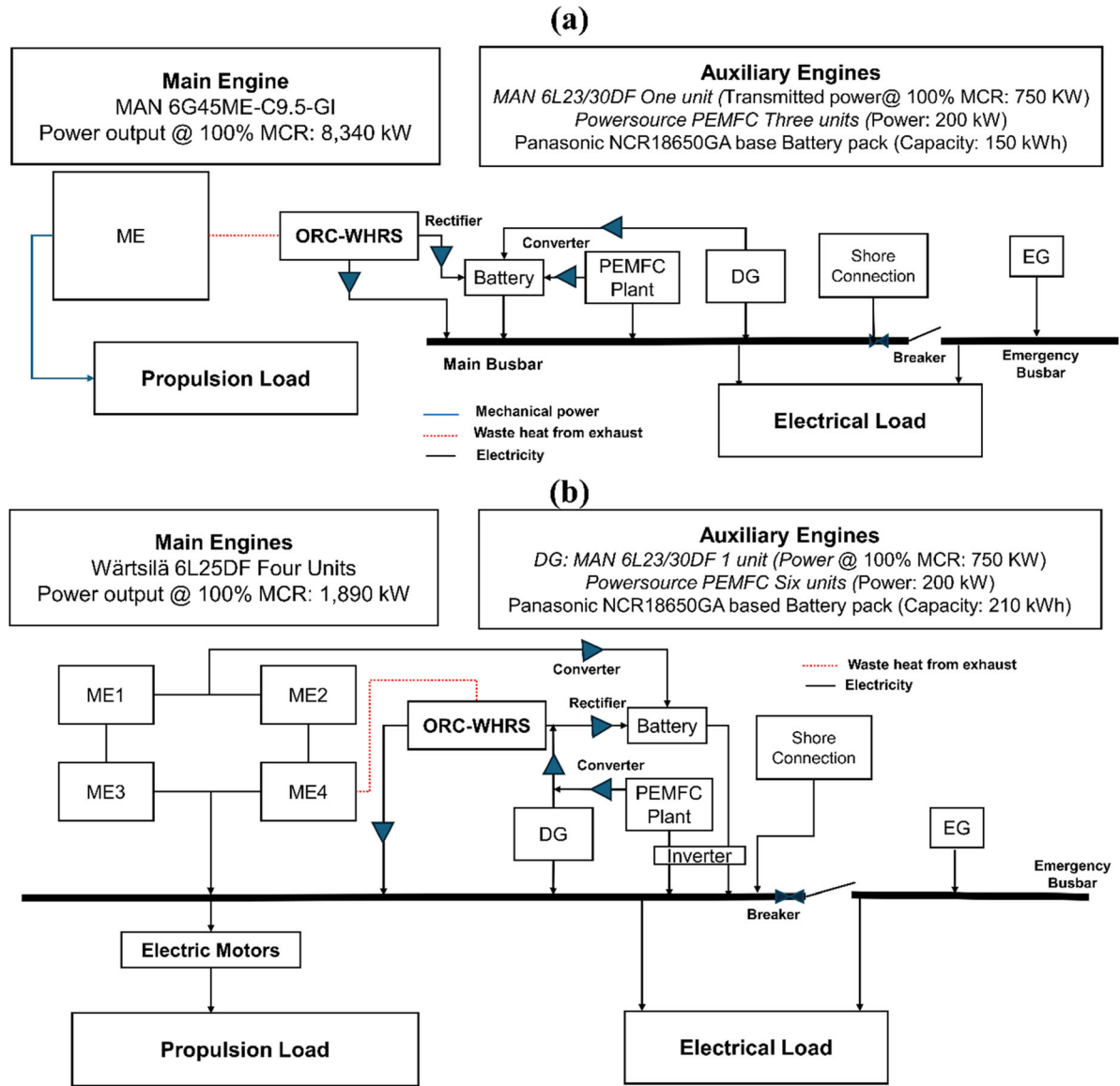


Figure 4. Simplified layout schemes of (a) MP2 and (b) DEP2.

their superior specific energy and negligible memory effect (Sepasi et al. 2015).

Battery degradation, quantified through the State of Health (SoH), was derived from manufacturer datasheets. An energy management strategy governs battery operation based on the available State of Charge (SoC), which evolves over time. The temporal variation of SoC was calculated using the Coulomb counting method, as expressed in Equation (7) (Saxena et al. 2016).

$$SoC(t) = SoC(0) - \int_0^t \frac{I(t) \times \eta_C}{C_B (Ah)} dt \quad (7)$$

The initial State of Charge (SoC (0)) denotes the battery's charge level at the onset of the simulation, while SoC(t) reflects its updated value at time t. To preserve battery integrity and minimise internal resistance, the energy management strategy maintains the SoC within an operational window of 20% to 80%. This controlled range contributes to improved battery longevity and performance stability. The Coulomb counting method, employed to compute the time-dependent SoC, assumes a coulombic efficiency (η_C) of 1. In this formulation, I(t) represent the instantaneous charging or discharging

current, and C_B denotes the nominal battery capacity in Ah (Sepasi et al. 2015).

The progressive decline in battery capacity over its operational lifespan is quantified by accounting for the influence of charge/discharge rate. The SoH is evaluated using Equation (8), which defines SoH as the ratio of the degraded or actual capacity (C_a) to the initial nominal capacity (C_i) at the commencement of operation.

$$SoH(t) = \frac{C_a (Ah)}{C_i (Ah)} \quad (8)$$

The SMA Sunny SCS2900 inverter converts direct current (DC) from the battery system into alternating current (AC) for integration with the ship's electrical grid. This inverter achieves a conversion efficiency of 98.4% when operating between an input of 800 V DC and an output of 450 V AC (SMA 2021).

It should be noted that the battery modelling framework adopted in this study is intended for comparative system-level assessment rather than detailed lifetime prediction. This approach assumes ideal coulombic efficiency and does not explicitly account for temperature-dependent degradation, depth-of-discharge sensitivity,

Table 2. Technical specifications of DF engines, PEMFC Units, and battery cells.

Electrification Plant – DF			
Parameter	Value	Unit	Reference
Model	MAN 6L23/30 DF	–	(MAN 2023)
Bore	225	mm	
Stroke	300	mm	
Cylinders	6	–	
Rated Power	750 @ 720 rpm	kW	
Transmitted Power	710	kW	
Engine Speed	720	rpm	
Electrification Plant – PEMFC			
Parameter	Value	Unit	Reference
Model	PowerCell Marine System 200	–	(PowerCellGroup 2024)
Gross Output DC Voltage	580	V	
Gross Output Current	400	A	
Electrical Efficiency (Peak)	54%	–	
Fuel Quality	Pure H ₂ ISO 14687:2019 (ISO 2019)	–	
Electrification Plant – Battery Cell			
Parameter	Value	Unit	Reference
Model	Panasonic NCR18650GA	–	(Panasonic 2022)
Chemistry	Lithium-ion	–	
Capacity	3.45 (typical), 3.35 (minimum)	Ah	
Charging Method	Constant Current-Constant Voltage	–	
Nominal Voltage	3.6	V	
Propulsion Plant – MP			
Parameter	Value	Unit	Reference
Model	6G45ME-C9.5-GI	–	(MAN 2025)
Bore	450	mm	
Stroke	2250	mm	
Cylinders	6	–	
Rated Power	8340 @ 111 rpm	kW	
Engine Speed	111	rpm	
Propulsion Plant – DEP			
Parameter	Value	Unit	Reference
Model	Wärtsilä 6L25DF	–	(Wärtsilä 2024)
Bore	250	mm	
Stroke	340	mm	
Cylinders	6	–	
Rated Power	1890	kW	
Engine Speed	900	rpm	

Table 3. Densities and LHV of the marine fuels.

Fuel	Density (kg/m ³)	LHV (kJ/kg)
VLSFO	932	41,200
MGO	890	42,900
LNG	480	48,000
MEOH	792	19,900
FAME	885	38,000
Ammonia	730	18,600
Hydrogen	89	120,000

or calendar ageing effects. These simplifications are considered acceptable given the objective of comparing alternative propulsion configurations under consistent operational conditions.

2.5. Waste heat recovery system

An ORC-based WHRS has been employed to convert the ME's exhaust heat into electrical power. The thermal-to-electric conversion efficiency of the ORC system (η_{ORC}) has been adopted as 13.2%, based on the findings reported by Konur et al. (2022) and Konur et al. (2023). The exhaust gas temperature following steam generation (T_{in} , in °C) and the corresponding exhaust mass flow rate ($\dot{m}_{\text{ex}}$, in kg/s) associated with the ME are presented in Appendix B, Table A1.

Equation (9) computes the power produced by the WHRS ($\dot{W}_{\text{WHRS}}$) in kW (Konur et al. 2020).

$$\dot{W}_{\text{WHRS}} = \dot{m}_{\text{ex}} \times (T_{\text{in}} - T_{\text{out}}) \times C_p \times \eta_{\text{ORC}} \quad (9)$$

The exit temperature from the ORC, denoted as T_{out} , is set at 100 °C. The specific heat capacity of the exhaust gas at constant pressure, represented by C_p , is taken as 1.089 kJ/kg·K. This value characterises the amount of thermal energy transferred per unit mass of exhaust gas for each degree of temperature variation (Lyu et al. 2023).

2.6. Model logic and structure

The equations outlined in the preceding sections were applied to estimate the FC across various engine configurations operating with different alternative fuels in both gaseous and liquid modes. A computational model was developed to iteratively process the input data and compute the FC for both propulsion and electrification systems. The logical structure of this model is illustrated in Figure 5.

The initial step involves reading input data, initialising empty lists, and constructing interpolation functions. For the propulsion unit, iterations are performed over ME rpm data for each vessel to determine the required power using the conventional engine's rpm–power curve. ORC power output is then calculated by extracting exhaust

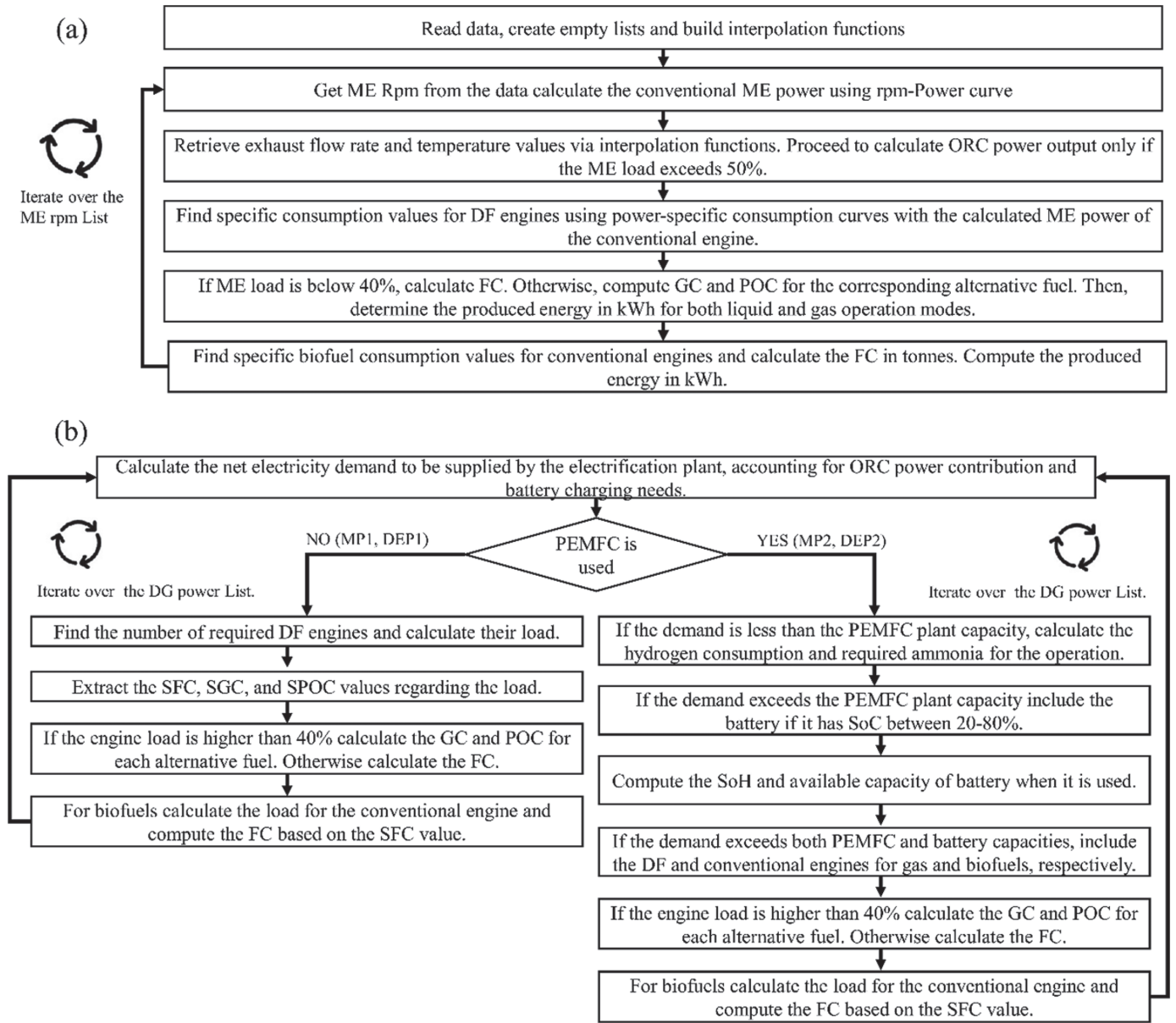


Figure 5. FC calculation stages for propulsion (a) and electrification (b) plants.

flow rate and temperature values from the interpolation functions based on the power demand. ORC operation is assumed only above 50% load; below this threshold, its output is set to zero. For DF engines, gas mode is activated above 40% load, as recommended by the manufacturer (MAN 2025), while MGO is used at lower loads. Biofuels are assumed to operate exclusively in liquid mode.

For the electrification plant, the vessel's electricity demand is calculated by accounting for ORC power contribution and battery charging requirements. Depending on the plant configuration, if PEMFC is included, load sharing is computed accordingly. For MP1 and DEP1 configurations, the load distribution among DF generators is determined, and the load of each engine is computed. Based on the resulting load, SFC, SGC, and SPOC are determined. Applying the 40% load threshold described above, FC, GC, and POC are subsequently calculated.

In MP2 and DEP2 configurations, the electrical load is primarily supplied by PEMFCs. If the demand exceeds the PEMFC plant capacity, batteries and DF engines are engaged sequentially to meet the remaining load. The same methodology is applied to calculate

PEMFC hydrogen consumption. If DF engines are utilised, their FC is computed using the same approach as in MP1 and DEP1. For DEP configurations, the propulsion plant engines also contribute to meeting the electrical load during navigation.

2.7. Environmental model

After determining the FC for each configuration using the selected marine fuels, both tank-to-wake (TtW) and well-to-tank (WtT) emissions are calculated for scenarios with and without shore power supply. TtW emissions include CO₂, CH₄, and N₂O as GHGs, along with SO_x, NO_x, and PM as other pollutants. WtT emissions are expressed as CO₂e for GHGs, while SO_x, NO_x, and PM are reported using the same notation as in the TtW assessment. Table 4 indicates the emission factors (EFs) used in the analysis.

In Table 4, MEOH is assumed to be produced via the Fischer-Tropsch process using a grey production methodology. Ammonia is classified by colour codes as green, blue, and grey, while FAME is distinguished by first- and second-generation (feedstock is

Table 4. Emission factors.

Fuel	TtW						Reference
	CO ₂ (g/g-fuel)	CH ₄ (g/g-fuel)	N ₂ O (g/g-fuel)	SO _x (g/kWh)	NO _x (g/kWh)	PM (g/kWh)	
VLSFO	3.151	0.00005	0.00018	3.23*	15.80*	0.72*	(Gilbert et al. 2018; Kuzu et al. 2021)
MGO	3.206	0.00005	0.00018	0.32*	14.80*	0.16*	(Gilbert et al. 2018; Kuzu et al. 2021)
LNG	2.75	0.00148	0.00011	0.003*	1.17*	0.027*	(Gilbert et al. 2018; IMO 2024)
MEOH	1.375	0.0000	0.0000	0	1.44*	0	(Gilbert et al. 2018; IMO 2024)
Ammonia	0.00	0.00	0.31*	0	3.78*	0	(Ma et al. 2025)
FAME	2.74	0.0061*	0.013*	0.37*	17.10*	0.19*	(Gilbert et al. 2018; Bayramoğlu et al. 2025)

**Units are expressed as g/kWh for these factors.

Fuel	WtT					Reference
	CO ₂ e (g CO ₂ e / g Fuel)	SO _x	NO _x	PM	Unit	
VLSFO	0.7149	0.13	0.07	0	g WtT/ g TtW	(Gilbert et al. 2018; Climaq 2024)
MGO	0.7438	0.14	0.19	0	g WtT/ g TtW	(Gilbert et al. 2018; Climaq 2024)
LNG	0.4232	0.16	0.14	0	g WtT/ g TtW	(Gilbert et al. 2018; Climaq 2024)
MEOH	0.7299	0.16	0.20	0	g/kWh	(Gilbert et al. 2018; Climaq 2024)
Grey Ammonia	0.177	0.002	0	0	g/kWh	(Hatzell 2024)
Blue Ammonia	1.23	0.004	0	0	g/kWh	(Hatzell 2024)
Green Ammonia	1.88	0.004	0	0	g/kWh	(Hatzell 2024)
FAME- 2nd gen	0.4348	1.72	0.04	1.00	g WtT/ g TtW	(Gilbert et al. 2018; Climaq 2024)
FAME 1st gen	0.5405	1.62	0.06	0.83	g WtT/ g TtW	(Gilbert et al. 2018; Climaq 2024)

The unit column represents units for SO_x, NO_x and PM emissions.

repressed oil) production methods. Equations (10) to (12) demonstrate the calculation of total emissions (E_{total}) described in Table 4, depending on the emissions unit (Kuzu et al. 2021; Yuksel 2023).

$$E_{total,i,j}(t) = \sum EF_{i,j} \left(\frac{g}{g_{fuel}} \right) \times FC_j(t) \quad (10)$$

$$E_{total,i,j}(t) = \sum EF_{i,j} \left(\frac{g}{kWh} \right) \times E(kWh) \times 10^{-6} \quad (11)$$

$$WtT E_{total,i,j}(t) = \sum EF_{i,j} \left(\frac{g}{g_{TtW}} \right) \times TtW E_{total,i,j}(t) \quad (12)$$

Equation (10) defines the total emissions generated during the whole operation for a specific pollutant (i) and fuel type (j). It is calculated by taking the FC and multiplying it by the corresponding EF, which represents the mass of pollutant emitted per unit of fuel consumed. Equation (11) indicates the calculation of emissions having the unit of g/kWh and Equation (12) indicates the computation of WtT emissions with the unit of g-WtT/g-TtW.

This study applies a simplified well-to-wake (WtW) framework, focusing on the fuel production and operational stages, while excluding the energy use and carbon emissions associated with the manufacturing of PEMFCs and battery systems. This approach supports consistent comparison across fuel pathways but introduces limitations, especially for battery technologies, which typically entail substantial embodied energy and emissions during production. Excluding the manufacturing phase may underestimate total lifecycle emissions, as production-related impacts for FCs and batteries can result in approximately 20–30 per cent higher emissions than those from the operational stage alone (Dulău 2023). The calculation of TtW CO₂e incorporates the global warming potential over a 100-year time horizon (GWP100), as represented in Equation (13) (IMO 2024).

$$TtW CO_2e(t) = TtW CO_2(t) + 265 \times TtW N_2O(t) + 28 \times TtW CH_4(t) \quad (13)$$

Equation 12 outlines the method used to estimate the GWP100. Given that the GWP values for N₂O and CH₄ are approximately 260–273 times and 27–30 times greater than those of CO₂, respectively, the coefficients applied in the equation reflect these relative

Table 5. Specific CO₂e emissions from the grid electricity for each country involved in the analysis.

Country	gCO ₂ e/kWh	Reference
The United States	384	(Ember 2025)
Brazil	103	
Panama	259	
Guatemala	273	
Canada	175	

impacts. In scenarios involving a CI application, the TtW CO₂e emissions derived from shore-side electricity consumption are integrated into the vessel's cumulative emission profile. Table 5 presents the CO₂e emissions associated with grid electricity usage during CI, differentiated by the country in which each port is located.

The values in Table 5 are applied to the total energy consumption during the port stay, as derived from the simulation to compute the TtW CO₂e due to CI. WtT CO₂e is calculated using Equation (14). Finally, WtW emissions are computed employing Equation (15) (IMO 2024).

$$WtT CO_{2e,i,j}(t) = \sum EF_{i,j} \left(\frac{g}{g_{fuel}} \right) \times FC_j(t) \quad (14)$$

$$WtW CO_{2e,i,j}(t) = \sum WtT CO_{2e,i,j}(t) + TtW CO_{2e,i,j}(t) \quad (15)$$

TtW and WtT emissions were assessed for each case-study vessel across various fuel types, based on FC and energy output. This evaluation aims to quantify the environmental footprint across the fuel life cycle. By employing a simplified analytical framework, the methodology enhances the transparency and interpretability of emissions data for maritime stakeholders.

2.8. Economic analysis

To manage uncertainty, a scenario-based strategy was used to estimate the Levelized Cost of Energy (LCOE) for 2025 and 2040. This approach incorporated anticipated energy and carbon prices from dependable sources, including limited-use systems such as the Emissions Trading Scheme (ETS) and academic studies. The objective was

Table 6. C_{plant} and C_{om} .

Equipment	C_{plant}	C_{om}	Unit	Reference
PEMFC	2,540.46	1.5%	USD/kW	(Gianni et al. 2022; Wang et al. 2022)
Battery	11.86	1.0%	USD/cell	(Korkmaz et al. 2023)
Inverter	200.00	1.0%	USD/kW	
Diesel Engine	400.00	1.5%	USD/kW	(Lagouvardou et al. 2023)
LNG DF Engine	800.00	1.5%	USD/kW	
MEOH DF Engine	600.00	1.5%	USD/kW	
Ammonia DF Engine	800.00	1.5%	USD/kW	
ORC-WHRS	1,348,578.56	1.5%	USD	(Konur et al. 2022; Konur et al. 2023)
Ammonia Decomposition Unit	2,067,840.21	6.0%	USD	(Jackson et al. 2020; Richard et al. 2024)
Ammonia Catalyst/Adsorber	N/A	32,718.81	USD	(Richard et al. 2024)
Ammonia Tank & Add-ons	600.00	1.5%	USD/kW	(Lagouvardou et al. 2023)
Hydrogen Tank & Add-ons	1200.00	1.5%	USD/kW	
LNG Tank & Add-ons	600.00	1.5%	USD/kW	
MEOH Tank & Add-ons	200.00	1.0%	USD/kW	
Conventional Fuel and Biodiesel Handling	300.00	1.0%	USD/kW	
Selective Catalytic Reduction (SCR)	56.35	940 USD/t-NO _x	USD/kW	(Ammar and Seddiek 2021; Zhang et al. 2021)

to explore how price fluctuations affect system outcomes, with particular attention to identifying the carbon price point where renewable energy becomes economically viable.

LCOE was selected from various assessment tools for its ability to offer a unified measure of financial performance across different energy sources and technologies. It includes all essential costs, investment, operation, maintenance, and fuel, over the system's lifespan, enabling straightforward comparisons between generation methods. Its broad acceptance in both research and industry enhances the analysis's relevance and clarity (Shen et al. 2020). Equation (16) demonstrates the calculation process of LCOE (Hansen 2019).

$$LCOE \left(\frac{\$}{MWh} \right) = \frac{\sum_{n=1}^{LT} \frac{(C_{\text{plant}} + C_{\text{fuel}} + C_{\text{om}}) (\$)}{(1+r)^n}}{\sum_{n=1}^{LT} \frac{P_{\text{gen}} (MW) \times t(h)}{(1+r)^n}} \quad (16)$$

The capital investment required for retrofitting the engine and fuel systems is denoted as C_{plant} , while C_{fuel} represents expenditures related to FC and carbon taxes. C_{om} indicates operational and maintenance costs. The system's annual energy output is expressed as P_{gen} , and the total annual operating hours are denoted by t . A moderate discount rate of 7% is applied, and the system's operational lifespan (LT) is assumed to be 20 years (Shu et al. 2017; IEA 2020). Table 6 depicts the C_{plant} and C_{om} for the assessed fuel configurations.

C_{om} is derived by applying the specified ratio to the C_{plant} within the corresponding tariff-defined rows. The operational lifespan of PEMFCs is assumed to be 40,000 h per unit. The longevity of battery systems depends on usage patterns and is determined by the manufacturer-provided SoH degradation curves. The SCR system is assumed to be implemented on configurations that do not meet the IMO Tier III emission standards. Tank capacities are determined to ensure equivalent bunkering intervals to those of conventional fuel systems, thereby maintaining operational consistency across different fuel types. Table 7 outlines the fuel and carbon price assumptions corresponding to the low, medium, and high pricing scenarios.

Although the two vessels are sister ships with identical technical specifications, the price differences observed in Table 7 are attributable to distinct operational timelines. The vessels navigated the Panama Canal on different dates, subjecting each to unique market conditions. Consequently, the low, average, and high price values were calculated based on the specific operational windows unique to each vessel, rather than a synchronised timeframe. Low, average, and high operational time values are considered for each vessel to capture variability in usage patterns.

Table 7. Fuel and carbon tax prices in USD/t for case study vessels.

Item	Low	Average	High	Reference
Carbon Tax	54.34	86.96	104.52	(Tiseo 2024)
Ammonia	229.00	372.00	1,055.00	(Cesaro et al. 2021)
MGO	Low	Average	High	
Vessel A	838.50	861.50	893.50	
Vessel B	876.50	894.50	934.00	
VLSFO	Low	Average	High	
Vessel A	660.50	684.50	707.00	
Vessel B	650.00	668.50	705.50	
FAME	Low	Average	High	(ShipandBunker 2026)
Vessel A	651.50	713.50	760.00	
Vessel B	723.00	776.50	813.50	
MEOH	Low	Average	High	
Vessel A	360.00	389.00	416.00	
Vessel B	367.00	360.50	367.00	
LNG	Low	Average	High	
Vessel A	725.00	779.00	816.00	
Vessel B	652.00	685.00	788.00	

Carbon tax rates are based on the 2024 annual average price reported under the European Union ETS, amounting to \$86.96 per metric ton of CO₂ (Tiseo 2024). For ammonia, pricing scenarios are differentiated by production pathways: the low scenario reflects grey ammonia, the medium scenario corresponds to blue ammonia, and the high scenario represents green ammonia. These distinctions are taken regarding the production pathway due to the absence of an established marine fuel market for ammonia. Due to the absence of a standardised approach to CI tariffs across countries, a representative value of \$248.25 per MWh has been adopted, based on the findings of Sevgili et al. (Sevgili et al. 2025).

3. Findings

When the model was executed with conventional engines operating on MGO and VLSFO, the error rates compared to reference data were 1.16% for Vessel A and 2.30% for Vessel B, indicating strong model fidelity. FC values were computed based on the operational durations of each vessel under various configurations and fuel types.

The route of Vessel A took 66.75 days, equivalent to 0.18 years, including port stays. The ME working hours were 996.02, and the AE working hours were 1,847.02. The operational duration of Vessel B is 37.74 days, equivalent to roughly 0.10 years. ME working time was 354.01 h, and AE working hours were 1,078.97 h. The port stay

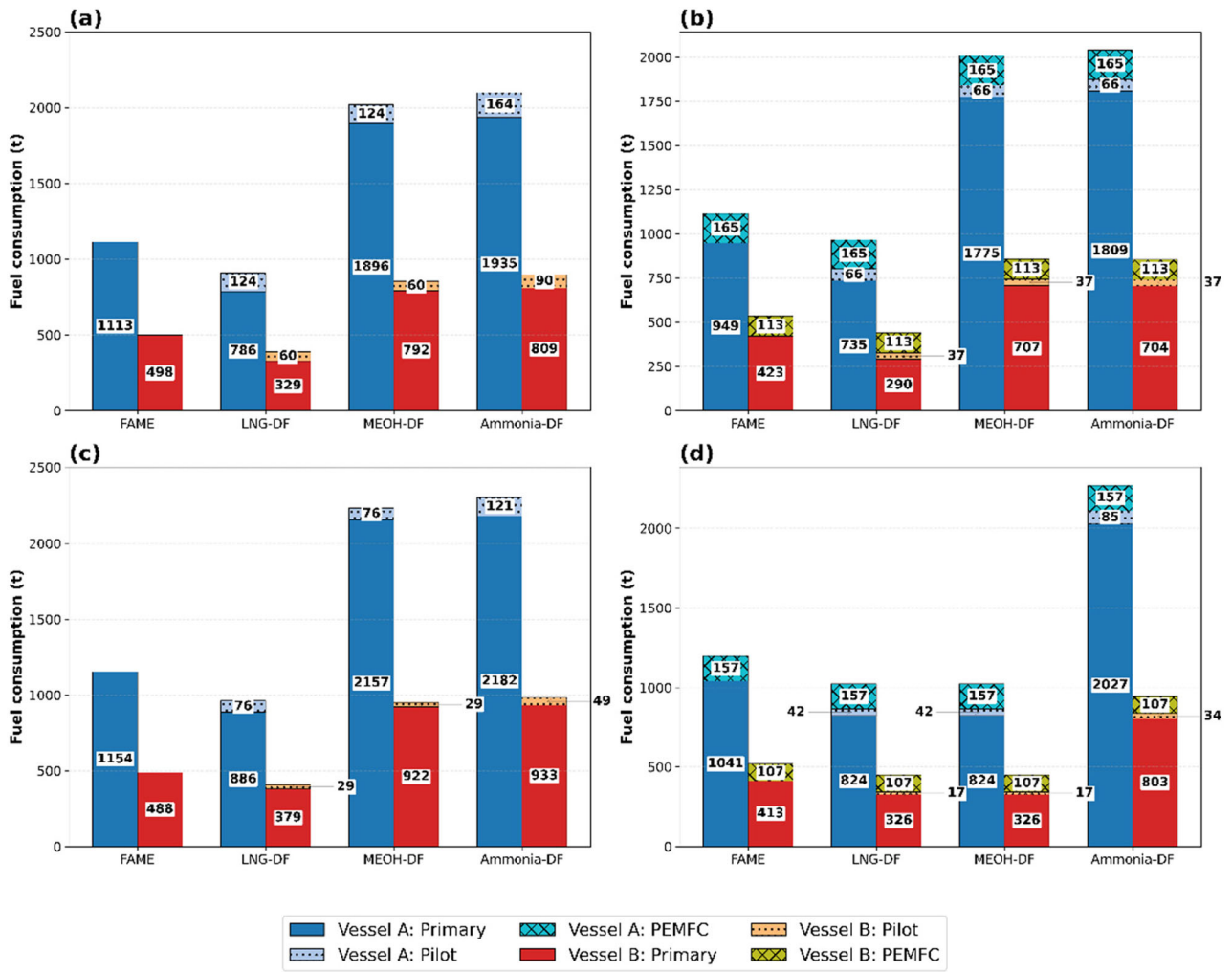


Figure 6. FC with alternative fuels with configurations MP1 (a), DEP1 (b), MP2 (c), and DEP2 (d).

of Vessel B was longer, while Vessel A was at sea longer. Figure 6 illustrates the total FC of ME and AEs throughout the operational routes of each vessel. Additional details on FC, including separate values for ME and AEs, are provided in Appendix C, Table A2.

During its voyages centred around the Panama Canal, Vessel A consumed 838.36 t of MGO in ME and 147.90 tonnes in AEs. Vessel B recorded a total ME FC of 266.07 t of MGO and 87.94 t of HFO, while its AEs consumed 87.51 t of MGO. These figures reflect the operational fuel demands across different engine types and fuel configurations for each vessel.

In the MP1 DF engine configurations, 97.94% and 94.49% of the operational profiles for Vessels A and B, respectively, were compatible with the use of alternative gas fuels. In gas fuel mode, ME operations accounted for 60.16 and 27.17 t of MGO consumption for Vessels A and B, respectively, while AEs consumed 2.17 and 1.79 t of MGO under the same mode. The remaining MGO usage was predominantly associated with AE operations in liquid mode. The adoption of alternative fuels in AEs was comparatively lower, with usage ratios of 39.53% for Vessel A and 50.80% for Vessel B. This resulted in liquid mode MGO consumption of 56.31 and 27.47 t in AEs, respectively. In MEs, liquid mode operation accounted for only 5.02 and 5.75 t of MGO for Vessels A and B, respectively.

The implementation of the DEP configuration enhanced the utilisation of alternative fuels through improved load distribution. However, this was accompanied by a slight increase in overall FC in gas mode, primarily due to the reduced efficiency associated with

smaller engine units. In the DEP1 configuration, ME consumption of MGO in liquid mode was reduced to 0.43 and 0.61 t for Vessels A and B, respectively. These reductions reflect improved fuel allocation efficiency under DEP1 compared to MP1 in ME operations. The corresponding POC values for gas fuel mode in ME were 43.17 and 19.50 t. In AEs, alternative fuel usage ratios were 66.02% for Vessel A and 83.88% for Vessel B. This resulted in liquid mode MGO consumption of 30.22 and 7.77 t, respectively. The corresponding POC values for gas fuel mode in AEs were 1.96 t for Vessel A and 1.60 t for Vessel B. These figures highlight the increased adoption of alternative fuels in electrification operations under the DEP1 configuration.

Hydrogen consumption in PEMFCs in the MP2 configuration amounted to 28.70 and 19.64 t for Vessels A and B, respectively. In the DEP2 configuration, these values decreased slightly to 27.16 t for Vessel A and 18.53 t for Vessel B. Ammonia usage for hydrogen cracking is 165.48 and 113.24 t for Vessels A and B in the MP2 configuration. In DEP2, these values were 156.59 and 106.83 t, respectively.

In the MP2 configuration, reliance on DF engines in the electrification system was reduced compared to MP1, with the PEMFC plant carrying most of the operational load. In this configuration, MGO consumption in AE-DFs operating in liquid mode was reduced to 0.78 t for Vessel A and 6.25 t for Vessel B. Corresponding POC values for gas fuel mode in AEs were 0.02 and 0.18 t, respectively.

Table 8. Required tank capacities and bunkering frequency of configurations.

Configuration	LNG Tank (m ³)	MEOH Tank (m ³)	MGO Tank (m ³)	Ammonia Tank (m ³)	Hydrogen Tank (m ³)	FAME Tank (m ³)	Total Required Capacity (m ³)	Bunkering Frequency (months)
MP1-LNG	4,477.23	N/A	379.84	N/A	N/A	N/A	4,857.06	3.02
MP1-MEOH	N/A	6,545.05	379.84	N/A	N/A	N/A	6,924.89	2.11
MP1-Ammonia	N/A	N/A	497.59	6,871.26	N/A	N/A	7,368.85	1.99
MP1-FAME	N/A	N/A	N/A	N/A	N/A	3,439.77	3,439.77	4.26
DEP1-LNG	5,047.59	N/A	232.68	N/A	N/A	N/A	5,280.27	2.77
DEP1-MEOH	N/A	7,446.93	232.68	N/A	N/A	N/A	7,679.61	1.91
DEP1-Ammonia	N/A	N/A	366.92	7,746.59	N/A	N/A	8,113.51	1.81
DEP1-FAME	N/A	N/A	N/A	N/A	N/A	3,564.94	3,564.94	4.11
MP2-LNG	4,188.83	N/A	202.70	587.58	9.66	N/A	4,988.78	2.94
MP2-MEOH	N/A	6,126.23	202.70	587.58	9.66	N/A	6,926.18	2.11
MP2-Ammonia	N/A	N/A	318.98	7,016.24	9.66	N/A	7,344.88	1.99
MP2-FAME	N/A	N/A	N/A	587.58	9.66	2,931.20	3,528.44	4.15
DEP2-LNG	4,690.74	N/A	129.87	556.01	9.14	N/A	5,385.76	2.72
DEP2-MEOH	N/A	6,857.18	129.87	556.01	9.14	N/A	7,552.20	1.94
DEP2-Ammonia	7,754.95	N/A	260.08	7,754.95	9.14	6,930.92	22,710.04	1.83
DEP2-FAME	N/A	N/A	N/A	556.01	9.14	3,215.07	3,780.23	3.87

Under the DEP2 configuration, which incorporates a larger PEMFC plant, DF fuel use in electrification operations was eliminated, indicating a full transition to fuel-cell-based power generation in that subsystem.

Based on the calculated FC values, the required tank capacities were determined to maintain the same bunkering frequency as the conventional configuration. The reference system features a tank capacity sufficient for six months of operation, as derived from operational data. Additionally, the bunkering frequency was assessed under the condition that the tank capacity remains the same as in the conventional setup. Table 8 presents both the required tank capacities for six-month maximum endurance and the corresponding bunkering frequencies when the conventional tank capacity is retained.

The required tank capacity increases substantially when employing low-energy-density fuels such as ammonia and MEOH, posing significant spatial and operational challenges. These configurations result in markedly reduced bunkering frequencies, thereby limiting their feasibility for most deep-sea voyages. LNG presents a more moderate spatial requirement, offering comparatively achievable bunkering intervals. In contrast, FAME demonstrates bunkering frequencies more closely aligned with those of conventional marine fuels, making it a more practical alternative for operational continuity.

The Panama Canal occupies a strategically vital position within the global maritime network, functioning as a key transit point for transoceanic shipping routes. The findings underscore its potential as an optimal location for establishing green corridors and deploying alternative marine fuels. By designating the canal as a central bunkering hub for low-carbon and zero-emission fuels, stakeholders can accelerate the transition toward sustainable maritime operations across major international trade lanes. This approach not only supports the decarbonisation of long-haul voyages but also strengthens the operational feasibility of emerging fuel technologies by ensuring reliable access to refuelling infrastructure along high-traffic shipping routes. Figure 7 presents the energy output across different configurations, disaggregated by each power generation component.

In the conventional configuration, the propulsion unit of Vessel A generated 5,337.28 MWh, whereas electrification via AEs accounted for 655.12 MWh. For Vessel B, the corresponding values were 2,115.48 and 390.56 MWh, respectively. In the MP1 configuration, the WHRS unit partially supported the electrification demand, thereby reducing the energy contribution required from the AEs.

Additionally, the DEP configurations improved the utilisation efficiency of the WHRS, resulting in increased energy output through more effective load distribution under low-load operating conditions. In the DEP1 configuration, the MEs met the electrification demand alongside the WHRS, further reducing energy production from the AEs. In the DEP2 configuration, the PEMFC plant is prioritised for its ability to provide a cleaner energy supply, aligning with the system's emphasis on environmental sustainability. Figure 8 illustrates the FC reductions achieved in the MEP1/DEP1 and MP2 configurations through the application of CI at ports along the vessel routes.

In the CI scenarios, shore-based electricity supply was assumed to contribute 214.47 MWh for Vessel A and 202.28 MWh for Vessel B. Under the conventional configuration, this substitution resulted in a reduction of MGO consumption by 50.13 and 46.05 t for the DGs of Vessels A and B, respectively.

In the DEP2 configuration, the use of shore-based electricity reduced hydrogen consumption in the PEMFC plant by 12.84 and 12.10 t for Vessels A and B, respectively. This reduction corresponded to ammonia savings of 74.05 and 69.39 t, which would otherwise be required for hydrogen production via cracking. The remaining fuel types remained unchanged in this configuration, as DF engines were fully eliminated. Consequently, the fuel savings of DEP2 were not represented in Figure 8.

In the MP2 configuration, most fuel savings were attributed to reduced ammonia consumption, primarily for hydrogen production, because DF engine operation was limited. DEP1 and MP1 configurations exhibited identical DF engine profiles during port operations. As a result, the fuel savings achieved through the CI application were equivalent in these two configurations.

Vessel A's port energy usage across different port states showed a distribution of 53.65 MWh in Brazil, 30.60 MWh in the United States, 31.27 MWh in Panama, and the highest consumption of 98.95 MWh in Canada. In comparison, Vessel B recorded energy usage of 79.29 MWh in the United States, 37.62 MWh in Panama, and 85.37 MWh in Guatemala.

The conventional configuration of Vessel A resulted in GHG emissions of 3,107.71 tonnes of CO₂, 0.05 tonnes of CH₄, and 0.18 tonnes of N₂O over the course of its route. In comparison, Vessel B operating with the diesel setup emitted 1,407.44 tonnes of CO₂, 0.02 tonnes of CH₄, and 0.08 tonnes of N₂O during its voyage.

For both case-study vessels, the use of ammonia in DF engines yielded the largest reduction in CO₂ emissions across all configurations. In DEP2, ammonia-fuelled DF engine configurations achieved

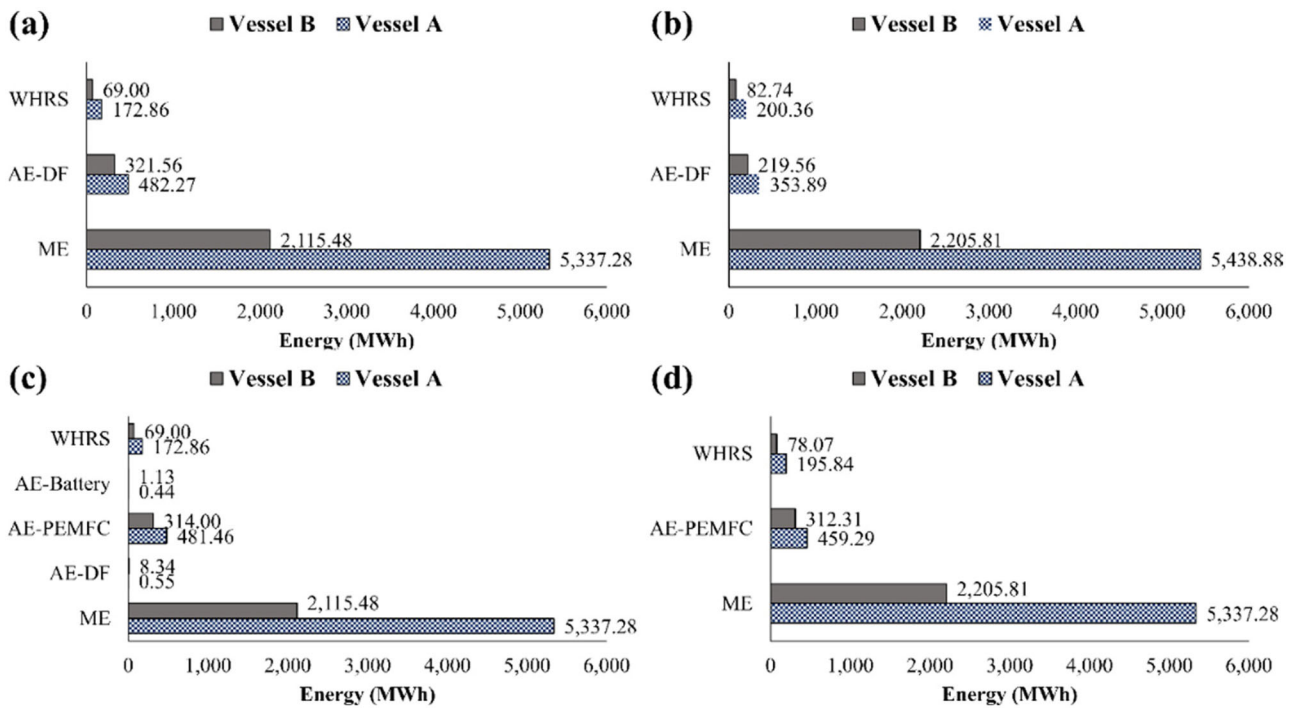


Figure 7. Energy generated with configurations MP1 (a), DEP1 (b), MP2 (c), and DEP2 (d).

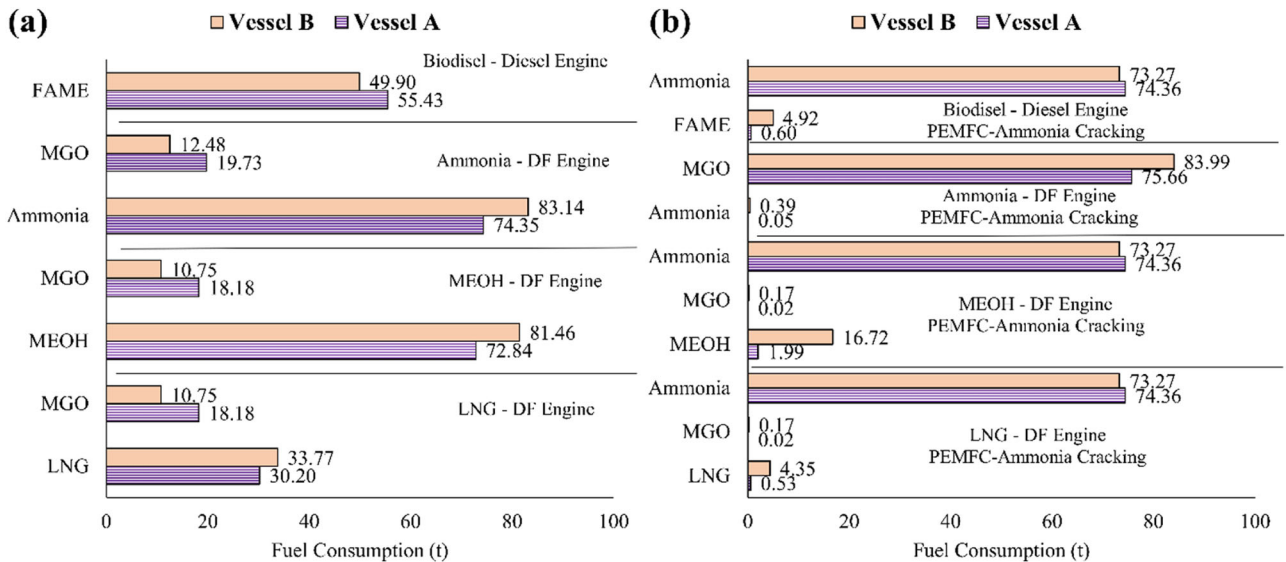


Figure 8. FC reductions using CI under MEP1/DEP1 (a) and MP2 (b).

the lowest CO₂ emissions, with CH₄ emissions eliminated. However, ammonia combustion increases N₂O emissions, which add to the overall global warming potential. In this configuration, ammonia consumption was higher compared to MP2, while MGO usage was substantially reduced, contributing to lower CO₂ emissions.

The utilisation of LNG in DF engines also reduced CO₂ emissions, despite elevated CH₄ emissions. MEOH nearly eliminated both N₂O and CH₄ emissions, though its impact on CO₂ reduction was less pronounced compared to LNG. FAME usage resulted in a slight increase in both N₂O and CH₄ emissions, while still contributing to a decrease in CO₂. Among carbon-containing alternative fuels, the MP2 configuration achieved the lowest CO₂ emissions due to the higher efficiency of the large DF engine. Although alternative fuel use in the propulsion system was marginally higher in DEP2 than in

MP2, it led to higher CO₂ emissions. A similar trend was observed when comparing MP1 and DEP1 configurations.

Energy consumption during berthing and the resulting WtT CO₂e emissions from CI using grid electricity were calculated based on collected operational data. Berthing durations and energy demand of ship electrification systems were determined, and the corresponding energy values were multiplied by the specific grid electricity CO₂e factors provided in Table 5.

Although Vessel A had a longer overall operational duration, Vessel B spent more time berthed. As a result, the energy consumption values for CI are relatively similar between the two vessels. In the WtT CO₂e calculations, the emissions associated with grid electricity usage during berthing, as presented in Table A3 (Appendix C),

Well-to-Wake GHG Emissions – Base Scenario (MP1 / DEP1)

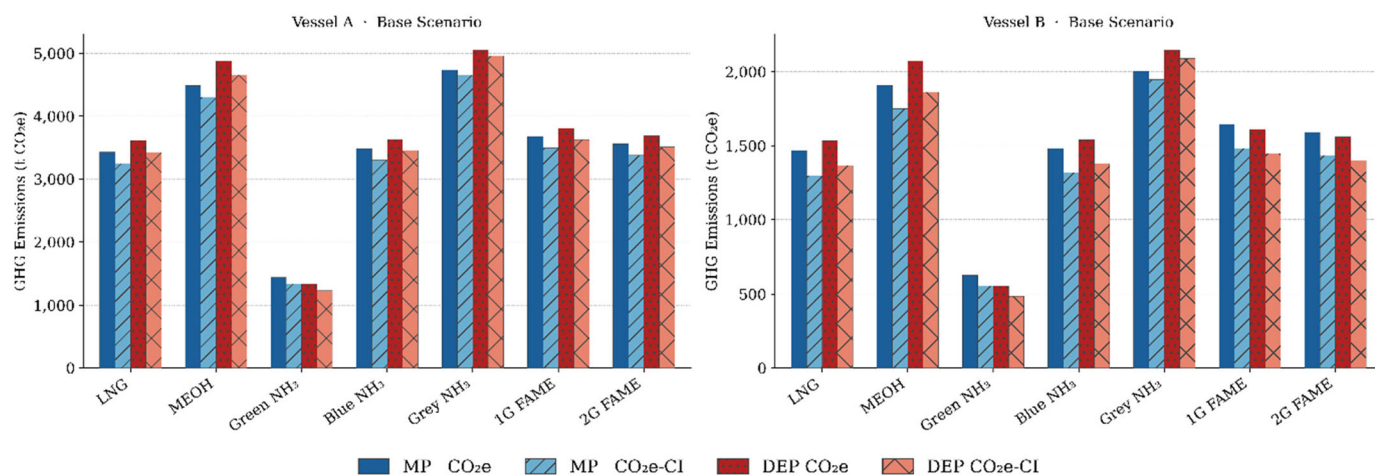


Figure 9. WtW CO₂e of MP1 and DEP1.

were incorporated into the total emissions of the case study vessels in CI-applied scenarios.

In the conventional configuration, both TtW and WtT CO₂e emissions were calculated for Vessel A and Vessel B, and the impact of CI was assessed. For Vessel A, TtW CO₂e emissions decreased from 3,155.95 tonnes to 2,992.78 tonnes with CI, representing a 5.17% reduction. WtT CO₂e emissions similarly declined from 733.58 tonnes to 696.29 tonnes, representing a 5.08% reduction.

Due to longer port stays and the usage of two generators in most electrification operations, Vessel B exhibited a more pronounced response to CI. TtW CO₂e emissions dropped from 1,429.04 tonnes to 1,279.17 tonnes, corresponding to a 10.49% reduction. WtT CO₂e emissions fell significantly from 325.87 tonnes to 228.75 tonnes, yielding a 29.80% reduction. These results demonstrate that CI is particularly effective in reducing upstream emissions for Vessel B.

Figure 9 presents the WtW CO₂e emissions for the MP1 and DEP1 configurations, with and without CI. Table A4 (Appendix C) details the TtW emissions of CO₂, CH₄, N₂O and CO₂e providing a comparative analysis of configurations with and without the application of CI. Similarly, Table A5 (Appendix C) provides the WtT CO₂e details of the configurations with or without CI.

Under the MP1 configuration, the use of LNG resulted in a reduction in TtW CO₂e emissions by 17.00% for Vessel A and 21.49% for Vessel B compared to the base conventional scenario. When CI was applied in conjunction with this configuration, the reductions further increased to 21.57% and 30.61% for Vessels A and B, respectively. Compared to LNG, the reductions in TtW CO₂e emissions achieved with MEOH were comparatively lower. Without the application of CI, MEOH yielded reductions of 4.64% for Vessel A and 10.09% for Vessel B. When CI is implemented, the reductions reached to 9.69% and 20.37% for Vessels A and B, respectively.

With the MP1 configuration, FAME yielded the lowest reductions in TtW CO₂e emissions, with values of 2.65% for Vessel A and 3.80% for Vessel B. When CI is applied, these reductions increased to 7.48% and 13.41%, respectively. In contrast, ammonia utilisation in DF engines provides the most substantial reductions in TtW CO₂e emissions, achieving 69.01% for Vessel A and 70.09% for Vessel B. With the integration of CI, the reductions increased to 71.33% and 73.52%, respectively.

By considering the WtT CO₂e, the total or WtW CO₂e reductions under MP1 using LNG DF were 3.54% and 8.64%, respectively, while CI enhanced reductions to 8.95% and 19.31%, respectively,

for Vessels A and B. When production emissions were considered, grey ammonia and MEOH led to an overall increase in total CO₂e emissions. Similarly, first- and second-generation biodiesel, as well as blue ammonia, led to a slight increase in CO₂e emissions. In contrast, green ammonia demonstrated a substantial reduction in total CO₂e emissions, achieving decreases of 54.29% for Vessel A and 56.07% for Vessel B. These reductions were further enhanced with the application of CI, reaching 57.49% and 61.18%, respectively.

Under the DEP1 configuration, TtW CO₂e reductions achieved with carbon-containing fuels were slightly lower compared to those observed in MP1. For example, LNG-DF reduced TtW CO₂e emissions by 12.99% for Vessel A and 18.47% for Vessel B. With the application of CI at berth, these reductions increased to 17.56% and 27.45%, respectively. In contrast, ammonia utilisation in DF engines resulted in greater TtW CO₂e reductions than in MP1, achieving 72.80% for Vessel A and 75.20% for Vessel B. When CI was applied, these reductions were further enhanced to 75.12% and 78.49%, respectively. These findings highlight the superior emissions mitigation potential of ammonia under DEP1, particularly when combined with CI.

When WtT CO₂e emissions are included in the analysis, the results under the DEP1 configuration closely resemble those observed in MP1. Among the evaluated fuels, only LNG and green ammonia contribute to a net reduction in total CO₂e emissions. With the application of CI, LNG achieves reductions of 4.73% for Vessel A and 16.21% for Vessel B. Green ammonia demonstrates significantly greater mitigation potential, reducing total CO₂e emissions by 57.71% and 61.09% for Vessels A and B, respectively. These reductions are further enhanced by CI, reaching 60.91% and 66.03%, respectively.

The findings presented in Figure 9 reinforce the importance of considering upstream emissions and berth-side electrification when evaluating the environmental performance of alternative marine fuels. Figure 10 illustrates WtW CO₂e emissions for the MP2 and DEP2 configurations, both with and without the application of CI.

WtT emissions for the MP2 and DEP2 configurations were assessed based on ammonia colour codes, as both configurations employ ammonia cracking systems to generate hydrogen for use in PEMFCs across all fuel types. Due to the extensive number of data columns, Figure 11 is presented separately for Vessels A and B to ensure clarity and readability.

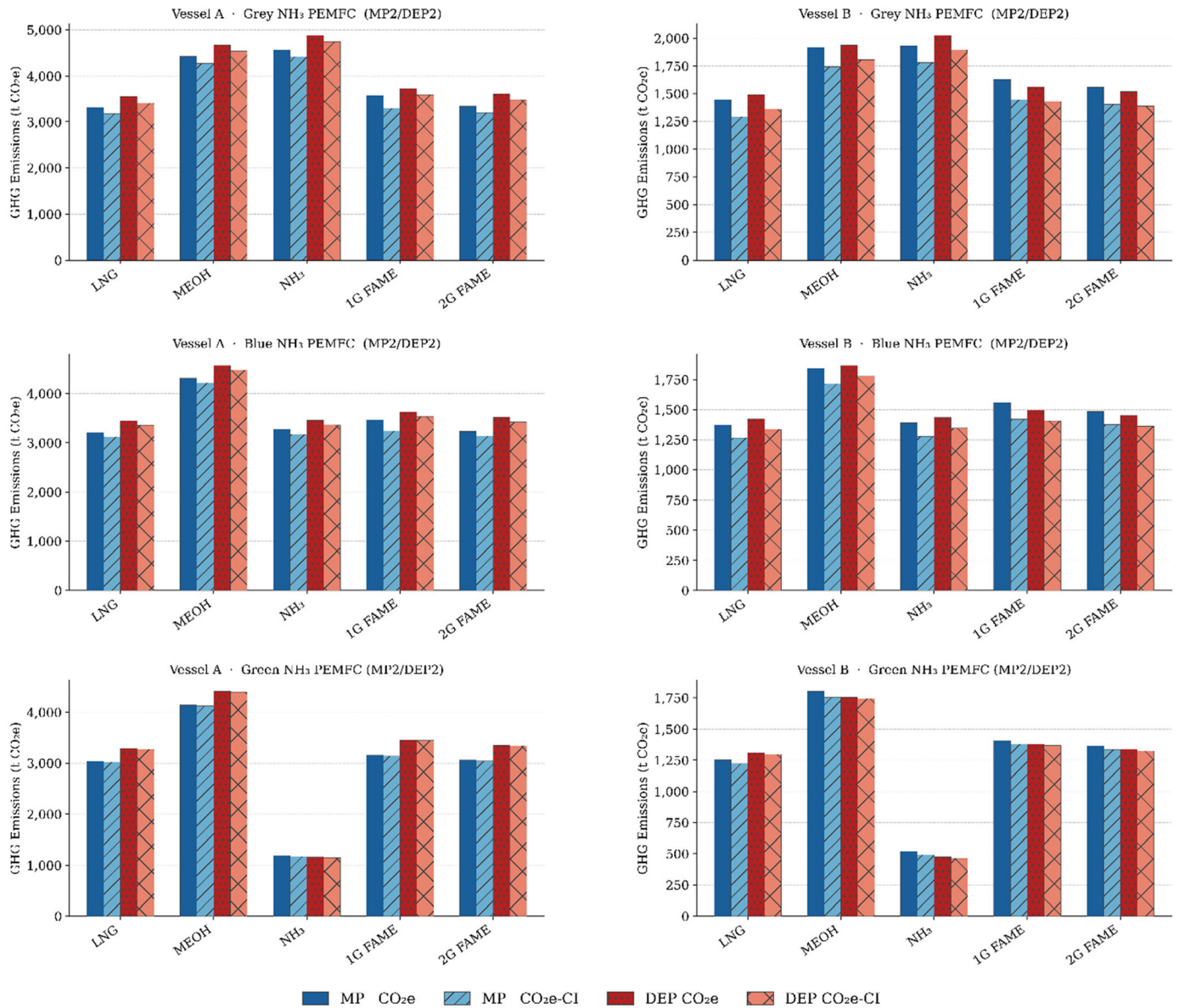
Well-to-Wake GHG Emissions — NH₃ PEMFC Scenarios (MP2 / DEP2)

Figure 10. WtW CO₂e of MP2 and DEP2-Vessel B.

CI applications in these configurations largely meet the PEMFC plant's load; therefore, when green ammonia is assumed as the hydrogen source, the benefit of CI remains minimal. Under MP2, the TtW CO₂e was reduced by 27.47% with LNG, 15.88% with MEOH, 75.72% with ammonia, and 17.01% with biodiesel for Vessel A compared to the conventional setup. For Vessel B, the reductions were 34.20% with LNG, 23.52% with MEOH, 76.64% with ammonia, and 18.36% with biodiesel.

WtW CO₂e emission calculations under MP2 indicate that the greatest reductions were achieved with green ammonia, amounting to 62.19% and 63.67% for Vessels A and B, respectively. CI application at ports further reduced these to 62.90% and 65.44%. The LNG-DF configuration using green ammonia for cracking resulted in reductions of 15.13% and 22.26% without CI, and 15.60% and 24.20% with CI, for Vessels A and B, respectively. In contrast, the combination of MEOH and green ammonia cracking led to increases in CO₂e emissions of 30.56% and 22.66%, respectively, when CI

was applied. First-generation biodiesel yielded minimal WtW CO₂e reductions of 0.37% and 3.53% with CI, while second-generation biodiesel improved these values to 3.54% and 6.53%.

When blue ammonia is used for hydrogen production under MP2, only LNG provided a meaningful WtW CO₂e reduction with CI, with values of 9.61% and 13.91% for Vessels A and B, respectively. If the carbon capture ratio in blue ammonia production is improved, these reductions could reach levels comparable to those achieved with green ammonia. When grey ammonia is used for cracking, LNG-DF resulted in modest reductions of 6.20% and 8.76%. However, when combined with MEOH and ammonia, WtW CO₂e emissions increased significantly.

TtW CO₂e reductions with DEP2, compared to the conventional setup, were 22.04% and 31.77% with LNG, 9.10% and 20.45% with MEOH, 77.45% and 79.74% with ammonia (the highest among all configurations), and 9.04% and 20.31% with biodiesel for Vessels

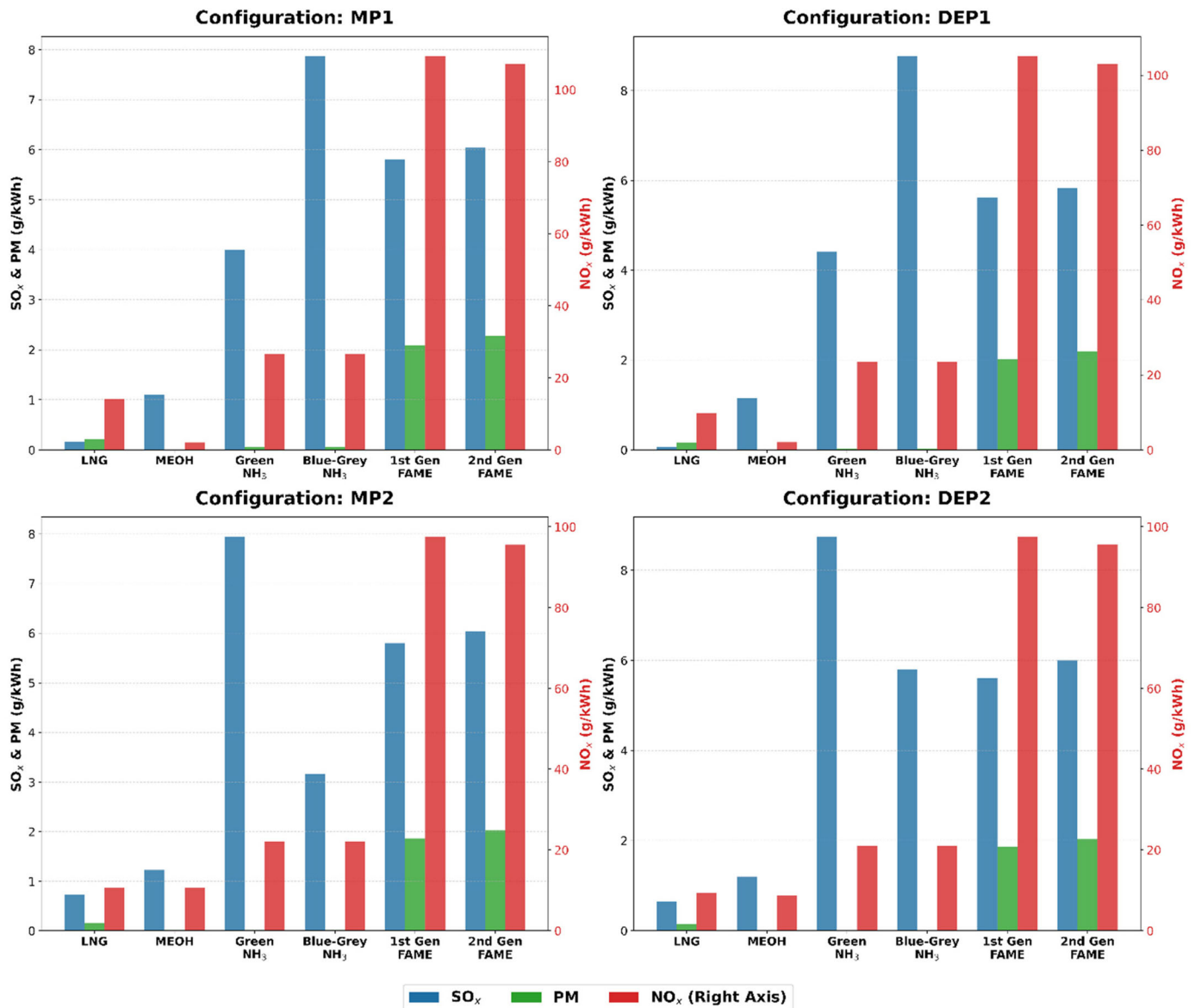


Figure 11. Other WtW emissions for the assessed configurations.

A and B, respectively. In this configuration, CI offers no additional benefit in terms of TtW CO₂e reduction.

Green ammonia used for hydrogen production and propulsion under DEP2, without CI applied, yielded the largest WtW CO₂e reductions at 63.21% and 66.72% for Vessels A and B, respectively. CI application enhanced these values to 63.62% and 67.59%. Without CI, LNG reduced emissions by 8.69% and 19.46%, while CI improved these reductions to 9.11% and 20.32%. Like MP2, MEOH increased CO₂e emissions even with green ammonia utilisation, and biodiesels did not provide satisfactory reductions under these conditions.

When blue ammonia is used for hydrogen production under DEP2, LNG provided WtW CO₂e reductions of 6.35% and 17.61% for Vessels A and B, respectively. With grey ammonia used for cracking, LNG-DF resulted in reductions of 4.65% and 15.93%. Like MP2, combinations involving MEOH and ammonia led to significant increases in WtW CO₂e emissions.

Based on the results shown in Figures 9 and 10, the CI application combined with alternative-fuelled DF engines, represented by DEP1 and MP1, is as effective as hydrogen PEMFCs in DEP2 and MP2 in terms of WtW CO₂e reductions. This finding is particularly

significant given the reliance on green ammonia and the technical challenges associated with onboard hydrogen storage and handling. It highlights the relevance of these configurations for meeting 2030 decarbonisation targets and underscores the strategic importance of potential green corridors centred on the Panama Canal.

The baseline TtW emissions for the conventional configuration reveal relatively high pollutant levels across both vessels. For Vessel A, TtW SO_x, PM, and NO_x emissions were 1.92, 0.96, and 88.69 t, respectively, while Vessel B recorded 2.33, 0.70, and 37.61 t for the same pollutants. Following the implementation of CI, reductions were observed across all emission categories. For Vessel A, SO_x decreased to 1.85 t, PM to 0.92 t, and NO_x to 85.51 t. Similarly, Vessel B showed reductions in SO_x to 2.27 t, PM to 0.66 t, and NO_x to 34.61 t. These results demonstrate the effectiveness of CI in mitigating local air pollutants, particularly SO_x and NO_x, during port operations. Figure 11 presents WtW emissions of SO_x, NO_x, and PM for the assessed configurations using various fuels for Vessel A. Figure A3 in Appendix C illustrates the same comparison for Vessel B. Similarly, TtW and WtT emissions of SO_x, NO_x, and PM for the assessed configurations using various fuels, alongside a comparative analysis

of the impact of CI application, are presented in Figures A4 and A5 (Appendix C).

SO_x emissions were significantly reduced in DF engines using alternative fuels. Greater reductions were observed in DEP configurations due to decreased reliance on MGO and improved load distribution. The most substantial reductions occurred in DEP2 configurations using MEOH and ammonia DF engines, achieving near-complete elimination of SO_x emissions by 99.72% and 99.87%, respectively. With the application of CI, DEP1 configurations also demonstrated strong performance, reducing SO_x emissions by 98.90% and 99.84% for Vessels A and B, approaching the levels observed in DEP2. FAME contributed to SO_x reduction in Vessel B, which operated partially on fuel oil. In contrast, Vessel A, which utilised MGO throughout its operations, experienced a slight increase in SO_x emissions as demonstrated in Figures A3 to A5 in Appendix C.

Comparable trends were observed for PM emissions. In DEP2 configurations, MEOH and ammonia DF engines achieved the highest reductions, with PM emissions decreasing by 99.73% and 99.78%, respectively, representing the maximum values without CI. DEP1 configurations also demonstrated strong performance, reducing PM emissions by 98.90% and 99.71% for Vessels A and B, closely approaching the levels achieved in DEP2. FAME contributed to PM reduction in Vessel B, while Vessel A experienced a slight increase in PM emissions.

FAME did not contribute to NO_x reduction, necessitating alternative mitigation strategies. Conventional diesel setups exhibited high NO_x levels (equivalent to 14.80 and 15.01 g/kWh for Vessels A and B). Significant reductions were achieved with MP1 using LNG (2.11 and 2.71 g/kWh) and MEOH (2.36 and 2.95 g/kWh), meeting Tier 3 limits. MP2 and DEP1 offered further improvements, with DEP2 yielding the lowest emissions: 1.32 and 1.40 g/kWh with LNG, and 1.36 g/kWh for both vessels with MEOH.

Ammonia DF engines exhibited higher NO_x emissions than LNG and MEOH, slightly exceeding Tier 3 limits, necessitating NO_x mitigation strategies such as SCR. The lowest NO_x values achieved with ammonia were 3.71 and 3.26 g/kWh for Vessels A and B, respectively, under CI-applied conditions. Appendix C, Table A6 presents the complete NO_x emission data across all configurations and scenarios (with and without CI), supporting the trends illustrated in Figure A3.

WtT emissions for the conventional system were quantified as 0.28 t SO_x and 16.81 t NO_x for Vessel A, and 0.33 t SO_x and 6.00 t NO_x for Vessel B. PM emissions from upstream processes were negligible. WtT emissions were generally reduced through hybrid configurations, except for FAME, which exhibited a slight increase in PM emissions. The most pronounced reductions were observed in the upstream emissions of MEOH and LNG under the DEP1 and MP1 configurations. In contrast, the incorporation of ammonia for onboard hydrogen production in DEP2 and MP2 resulted in marginally elevated NO_x and SO_x emissions. Based on the installation, operational, fuel, and carbon tax costs indicated in Section 2.8, the LCOE with and without CI was calculated and is shown in Table 9.

Compared with the conventional configuration, LNG, MEOH, and ammonia-based systems reduce LCOE under the low-fuel-price scenario. This trend persists under average fuel price conditions; however, the cost reduction associated with blue ammonia (average price scenario) is notably less than that achieved with grey ammonia (low price scenario). Under the high-fuel-price scenario, which assumes the use of green ammonia, the LCOE is significantly higher than that of the conventional system, indicating limited economic viability.

For FAME, the LCOE remains consistently higher than the conventional configuration. Specifically, Vessel A shows increments of approximately 11.18%, 15.00%, and 10.70% under low, average, and high scenarios, respectively. Vessel B exhibits even greater increases of 15.34%, 19.66%, and 29.78% across the same scenarios, suggesting that FAME is less competitive from a cost perspective.

Across all configurations, CI generally produces mixed effects on LCOE. Under the low, average, and high price scenarios, CI raised LCOE mainly in ammonia-based and some FAME configurations. For Vessel A, MP1-Ammonia increased by 1.66% (low) and 0.27% (average), showing CI tariffs outweigh savings, while high-price costs still fell slightly (−1.96%). DEP1-Ammonia also rose slightly (+1.68% at the low, +0.26% on average). The strongest penalties were observed in the MP2 and DEP2 configurations, where MP2-Ammonia increased by 4.86–6.04% for Vessel B and DEP2-Ammonia by 10.73–12.86%, indicating that CI is economically less unfavourable in zero-carbon electrification cases. FAME shows minor increases (≤ 0.36%) in some scenarios, suggesting nearly cost-neutral behaviour. Overall, CI becomes a cost burden primarily for ammonia and some FAME systems, especially under high-tariff scenarios. When the implementation of CI increased overall LCOE, the associated reductions in FC and TtW carbon emissions were insufficient to offset the annual tariff fees imposed by the CI infrastructure.

4. Discussion

In comparing DEP and MP configurations, DEP demonstrated superior load distribution across engines, yielding enhanced performance under low-load conditions and consequently reducing both liquid fuel and pilot fuel consumption. Conversely, MP DF systems exhibited lower gas fuel usage, attributable to the higher overall efficiency of the single large-scale plant. The validity of the configuration architecture modelling is substantiated by existing literature, reinforcing the credibility of the comparative analysis (Nguyen et al. 2021; Pamik and Nuran 2021). Moreover, the operational potential of DEP systems can be further augmented through the increased integration of renewable energy sources into the system architecture (Nguyen et al. 2021; Elkafas and Shouman 2022).

LNG DF configurations demonstrated superior economic performance compared to conventional systems under the carbon tax regime, while achieving GHG emission reductions aligned with the 2030 targets, despite elevated CH₄ emissions. Regarding compliance with operational indicators such as CII, LNG DF configurations remain a viable transitional solution through 2030 (Issa et al. 2022; Bayraktar and Yuksel 2023), particularly when complemented by WHRS and fuel cell/battery systems, which enhance overall efficiency and environmental performance (Islam Rony et al. 2023; Yuksel 2023).

MEOH, as a marine fuel, exhibited a comparable performance trend to LNG; however, when derived from grey production pathways, it falls short of meeting long-term decarbonisation objectives (Svanberg et al. 2018; Wang and Wright 2021; Bayraktar, Yuksel, et al. 2023). Nonetheless, both fuels contributed to substantial reductions in other emissions, thereby supporting compliance with prevailing IMO environmental requirements.

FAME failed to meet both TtW and WtT GHG reduction targets, with first-generation production pathways performing notably worse than second-generation alternatives. While the latter offered marginal improvements, neither was sufficient to align with long-term decarbonisation objectives, underscoring the need for third- or fourth-generation production technologies (Watanabe et al. 2022;

Table 9. LCOE (USD/MWh) with configurations.

Configuration	Vessel A			Vessel B		
	Low	Average	High	Low	Average	High
Conventional	219.61	223.40	228.66	244.68	247.87	254.74
MP1-LNG	197.57	205.35	211.03	205.11	210.00	224.85
MP1-MEOH	202.59	212.53	222.01	217.19	215.52	218.61
MP1-Ammonia	146.65	194.85	422.87	165.12	213.15	441.06
MP1-FAME	217.15	229.01	237.91	259.96	270.90	278.47
DEP1-LNG	190.31	198.59	204.46	193.69	198.89	214.92
DEP1-MEOH	207.21	217.93	228.06	220.09	217.92	220.77
DEP1-Ammonia	140.61	193.13	442.41	154.54	208.10	462.98
DEP1-FAME	214.62	226.56	235.51	245.61	256.03	263.23
MP2-LNG	203.21	214.04	237.80	220.22	230.77	274.12
MP2-MEOH	214.73	227.52	254.73	237.69	242.58	275.83
MP2-Ammonia	162.24	209.79	435.56	190.68	238.29	464.71
MP2-FAME	222.39	236.15	262.38	274.06	289.54	326.62
DEP2-LNG	213.90	225.22	248.38	217.04	227.19	268.50
DEP2-MEOH	207.21	217.93	228.06	220.09	217.92	220.77
DEP2-Ammonia	167.18	219.62	469.01	183.89	234.25	474.16
DEP2-FAME	235.82	250.33	276.25	260.54	274.93	308.92

Configuration	Vessel A with CI			Vessel B with CI		
	Low	Average	High	Low	Average	High
Conventional	219.15	222.74	227.74	243.49	246.35	252.49
MP1-LNG	191.57	199.00	204.38	201.63	205.98	219.24
MP1-MEOH	202.25	211.75	220.79	216.44	214.91	217.60
MP1-Ammonia	149.09	195.38	414.57	179.81	227.74	455.45
MP1-FAME	217.83	229.10	237.55	260.89	270.73	277.54
DEP1-LNG	197.11	205.04	210.63	205.37	210.05	224.53
DEP1-MEOH	206.87	217.18	226.88	219.65	217.61	220.09
DEP1-Ammonia	142.97	193.64	434.35	169.10	222.57	477.27
DEP1-FAME	215.27	226.64	235.16	246.51	255.86	262.33
MP2-LNG	211.84	220.89	236.17	240.80	251.29	294.46
MP2-MEOH	223.46	234.46	253.19	256.74	261.67	294.88
MP2-Ammonia	170.11	215.86	433.00	211.97	259.57	485.99
MP2-FAME	232.71	244.69	262.44	295.09	310.47	347.47
DEP2-LNG	221.96	231.52	246.23	238.41	248.56	289.86
DEP2-MEOH	206.87	217.18	226.88	219.65	217.61	220.09
DEP2-Ammonia	174.02	224.70	465.64	203.61	253.97	493.88
DEP2-FAME	244.17	256.91	274.40	282.23	296.62	330.60

Bayraktar, Pamik, et al. 2023). Additionally, reductions in other regulated emissions were not observed, further limiting the environmental viability of FAME as a marine fuel under current regulatory frameworks. However, with respect to operational continuity, bunkering frequency, and logistical convenience, FAME biodiesel yielded the most favourable outcomes, thereby maintaining its validity as a viable candidate.

Ammonia DF systems presented a substantial reduction in TtW CO₂ emissions, along with notable decreases in other regulated pollutants. Although N₂O emissions increased, the overall GHG footprint remained significantly lower than that of conventional marine fuels. The environmental viability of ammonia as a marine fuel was largely determined by its production pathway (Yuksel et al. 2025). Grey ammonia, while economically favourable, led to considerable WtT emissions, thereby undermining its decarbonisation potential. Blue ammonia could be a more balanced alternative, particularly when carbon capture efficiency exceeds the initial assumptions given in the analysis. From an environmental perspective, green ammonia represented the most sustainable option, although its elevated production cost introduced a trade-off that required careful consideration in techno-economic evaluations (Bicer et al. 2017; Saygin et al. 2023; Bayraktar et al. 2025). As previously discussed, the Panama Canal's strategic volume makes it a critical hub for alternative bunkering. For vessels using LNG, MEOH, or ammonia, reliable infrastructure at this chokepoint is essential to offset the trade-offs between lower-energy-density fuel storage and cargo capacity on transoceanic routes.

Kouzelis et al. (2022) emphasised that alternative fuels influence optimal economic speed and voyage planning, thereby reinforcing the need for geographically strategic refuelling hubs such as the Panama Canal. As the maritime sector transitions to low-carbon operations, enhancing bunkering capabilities in the Canal could play a pivotal role in enabling fuel flexibility and sustaining the efficiency of global trade.

CI contributed to further reductions in port-side emissions by enabling vessels to shut down auxiliary engines and draw electricity from shore-based sources. However, its impact on PEMFC-integrated electrification systems was minimal, given the already low onboard emissions from fuel cell operations. This discrepancy sparks debate over infrastructure prioritisation: whether investment should focus on expanding CI facilities for conventional and transitional fleets, or on accelerating the deployment of PEMFC and other advanced electrification technologies. The decision carries strategic implications for policymakers, port authorities, and shipowners, shaping future ship and port designs considering long-term decarbonisation pathways.

The green port concept, which prioritises low-carbon infrastructure and the integration of sustainable energy systems to facilitate the adoption of alternative fuels, is a critical component of green corridor development. To achieve a fully decarbonised corridor, green energy-based CI can further mitigate GHG emissions, particularly when embedded within comprehensive green port and green supply chain frameworks (Yuksel et al. 2024). As highlighted by İnal

and Dere (2024), ports play a pivotal role in maritime decarbonisation, serving as strategic enablers of energy-efficient logistics and climate-resilient operational practices.

The economic feasibility of the scenarios examined in this study is subject to considerable uncertainty, arising principally from the volatility of capital expenditures, fuel prices, and carbon taxation regimes. Among the input parameters, alternative fuel price projections (covering green ammonia and methanol, in particular) carry the greatest degree of uncertainty, reflecting the immature commercial infrastructure and limited global trade volumes that currently characterise these fuel pathways (Gore et al. 2022; Mallouppas et al. 2022; Seyhan et al. 2026).

Fuel prices are acutely sensitive to geopolitical developments, which can induce severe price dislocations within compressed timeframes, thereby materially altering the cost–benefit calculus of DF transitions before projected payback periods can be realised (Cunado et al. 2020; Monge et al. 2023). Carbon taxation introduces a further compounding layer of uncertainty. Since carbon price trajectories are structurally coupled to fossil fuel market dynamics and region-specific regulatory cycles, a steeper-than-projected carbon levy could substantially accelerate the economic viability of hybrid propulsion configurations, whereas a more moderate trajectory would likely extend the cost competitiveness of conventional LNG relative to alternative fuels (Gore et al. 2022; Yuksel et al. 2025). Accordingly, although the technical outcomes reported here remain methodologically robust, the economic payback projections must be interpreted as scenario-conditional estimates, sensitive to prevailing market conditions and the pace of decarbonisation policy convergence across major flag states and port jurisdictions.

5. Conclusion

The study assessed the integration of alternative fuels with DF engines across DEP and MP configurations, as well as DF engines combined with PEMFC and battery systems for electrification. CI was evaluated independently to highlight its potential contribution to green corridor development, with a particular focus on the Panama Canal as a strategic hub. A scenario-based analysis was conducted using two case study vessels operating along Panama Canal routes, examining both emission profiles and economic performance. The principal findings derived from the fuel consumption calculation and environmental analysis are summarised as follows:

- DEP configurations facilitate more effective engine load distribution, which enhances low-load performance and minimises liquid and pilot fuel consumption. In contrast, MP-DF systems achieve lower gas fuel usage due to the superior thermal efficiency of a single large-scale power plant.
- LNG DF systems achieve GHG reductions aligned with 2030 targets despite CH₄ slip, especially when integrated with WHRS and fuel cells. MEOH offers comparable emission benefits; however, grey production pathways significantly limit its long-term decarbonisation potential.
- FAME fails to meet both TtW and WtT GHG targets, showing minimal improvement even in second-generation pathways. Despite these environmental limitations, its logistical simplicity, reduced bunkering frequency, and operational continuity make it a practical candidate for immediate maritime application.
- Ammonia dual-fuel systems deliver substantial reductions in TtW CO₂ and pollutants. Nevertheless, their overall sustainability remains heavily dependent on production methods, with green ammonia being the most environmentally sound but economically challenging option.

- Implementing CI reduces port-side emissions by replacing auxiliary engine use with shore power. This impact is less pronounced in systems already integrated with PEMFC, as these configurations already maintain exceptionally low onboard emission levels.
- The Panama Canal's high transit volume positions it as a vital bunkering hub for alternative fuels. Since LNG, methanol, and ammonia require significantly larger storage volumes, reliable refuelling infrastructure at this chokepoint is essential to mitigate trade-offs between fuel tank size and cargo capacity on transoceanic routes.

The main findings of the economic performance evaluation are listed below:

- LNG, MEOH, and ammonia-based systems offer a lower LCOE compared to conventional configurations under low and average fuel-price scenarios. However, the cost advantage of blue ammonia is notably smaller than that of grey ammonia, while green ammonia currently lacks economic viability as LCOE levels exceed conventional systems.
- FAME consistently results in higher LCOE across all scenarios. The cost penalty is particularly severe for vessels with higher energy demands and larger operational profiles, highlighting a significant reduction in competitiveness for larger-scale maritime applications.
- The economic impact of CI is highly dependent on the energy carrier. While it generally increases LCOE for ammonia and FAME systems, the reductions in fuel consumption and TtW emissions are often insufficient to offset high annual infrastructure and tariff costs.
- For vessels with lower power requirements, ammonia-fuelled mechanical and diesel-electric configurations show relatively stable costs. Conversely, for vessels with higher power demands, these same ammonia configurations incur the most significant cost penalties, suggesting that zero-carbon electrification via CI is economically less favourable for high-capacity vessels under current tariff structures.

Limitations of the study can be listed as follows:

- The WtW approach excluded manufacturing emissions of PEMFCs and batteries, potentially slightly underestimating total environmental impact.
- The analysis focused solely on emissions regulated under IMO frameworks, omitting other environmental indicators.
- Emission and efficiency coefficients were based on current industrial data; future technological developments may alter these estimates.
- Energy consumption data were used to calculate alternative fuel usage, with inherent assumptions.
- End-of-life values, including scrap prices for batteries and PEMFCs, were not considered in the economic evaluation.
- While the study provides a comparative analysis of two specific vessel profiles, the findings may not be directly transferable to all maritime market segments. Differences in operational profiles, deadweight capacities, and power requirements for other vessel types, such as bulk carriers or specialised offshore vessels, could lead to varying economic and environmental performance outcomes.

Future research should focus on optimising the techno-economic viability of zero-carbon fuels by refining production pathways and improving integration with advanced propulsion systems. Attention should be given to enhancing the lifecycle performance of

green ammonia and third-generation biofuels, including the development of cost-effective carbon capture and renewable feedstock technologies.

To better account for these economic fluctuations, future research should incorporate stochastic modelling and Monte Carlo simulations to evaluate the impact of variable input data on the Total Cost of Ownership. Future studies could focus on dynamic pricing models that account for real-time geopolitical risk factors and their direct influence on alternative fuel availability. Furthermore, a multi-variable sensitivity analysis on carbon tax thresholds would provide deeper insights into the exact 'tipping point' where hybrid-electric and ammonia-fuelled systems become more cost-effective than traditional mechanical propulsion. This would offer shipowners and policymakers a more resilient framework for decision-making under high-uncertainty market conditions.

Additionally, expanding the scope of analysis to include multi-port green corridor networks and intermodal supply chain interactions would provide a more comprehensive understanding of infrastructure synergies and emission mitigation. Incorporating real-world operational data and stakeholder feedback will also be essential to validate model assumptions and guide policy alignment with IMO decarbonisation targets.

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Appendices

Appendix A

Conventional Diesel Configuration

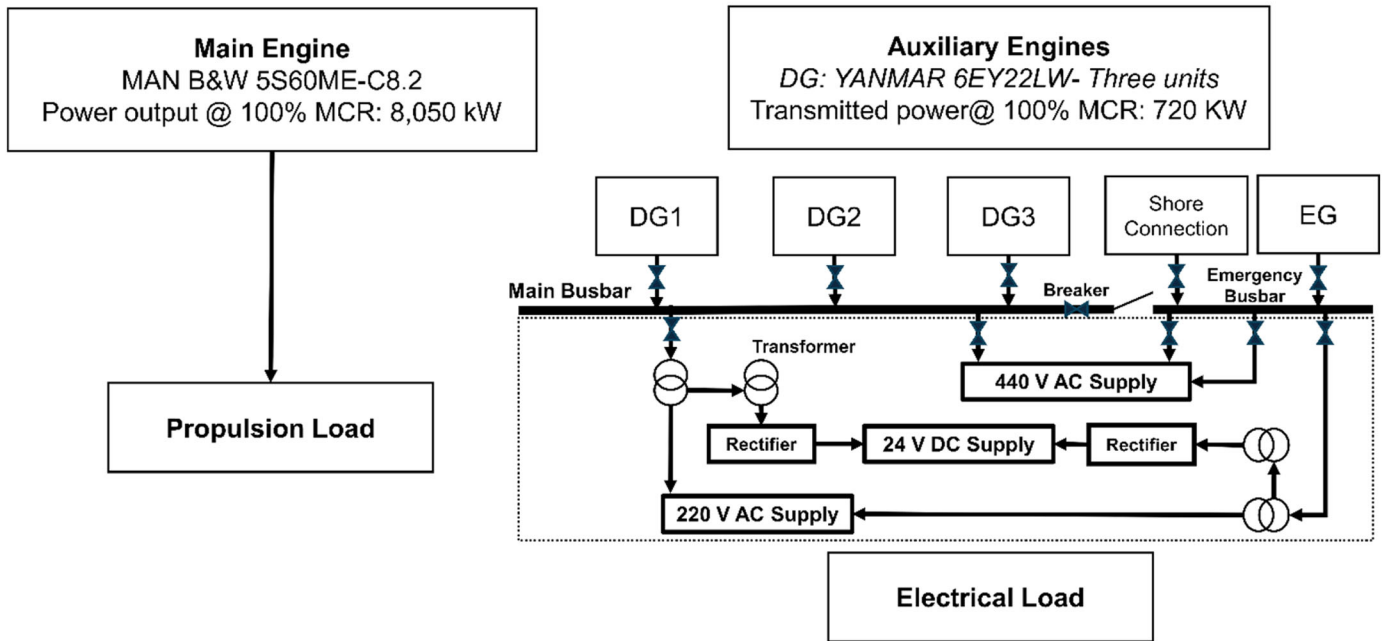


Figure A1. Simplified scheme of conventional configuration.

Appendix B

Table A1. SFC, SPOC, and HR values of engines.

Wartsila 6L25DF					
Load (%)	Heat Rate (kJ/kWh)	SFC (g/kWh)	SPOC (g/kWh)	$\dot{m}_{ex}$ (kg/s)	T_{in} (°C)
50	8280	194.4	17.6	1.67	322
75	7790	185.1	8.0	2.21	337
85	7660	182.6	6.6	2.48	344
100	7500	182.1	4.6	2.89	338
MAN 6L23/30DF					
Load (%)	Heat Rate (kJ/kWh)	SFC (g/kWh)	SPOC (g/kWh)	$\dot{m}_{ex}$ (kg/s)	T_{in} (°C)
25	12603	240	10.40	N/A	N/A
50	9895	208	9.01	N/A	N/A
75	9304	206	7.04	N/A	N/A
100	8913	207	3.97	N/A	N/A
MAN 6G45ME-C9.5-GI					
Load (%)	LNG SGC (g/kWh)	SFC (g/kWh)	SPOC (g/kWh)	$\dot{m}_{ex}$ (kg/s)	T_{in} (°C)
25	136.56	176.1	21.5	19.3	240
30	137.08	174.2	19.1	18.8	227
35	137.19	172.5	17.2	18.3	216
40	137.08	170.8	15.8	17.6	207
45	136.77	169.3	14.6	16.9	199
50	136.35	167.9	13.6	16.1	194
55	136.56	167.1	12.7	15.1	193
60	136.77	166.5	12	14.2	195
65	137.08	166.2	11.4	13.2	198
70	137.92	166.5	10.8	12.2	203
75	139.69	167.9	10.4	11.1	210
80	141.35	169.2	9.9	10.1	218
85	142.92	170.4	9.5	8.9	228
90	145.00	171.7	9.2	7.8	240
95	147.19	173	8.8	6.6	254
100	149.38	174.5	8.6	6.7	216

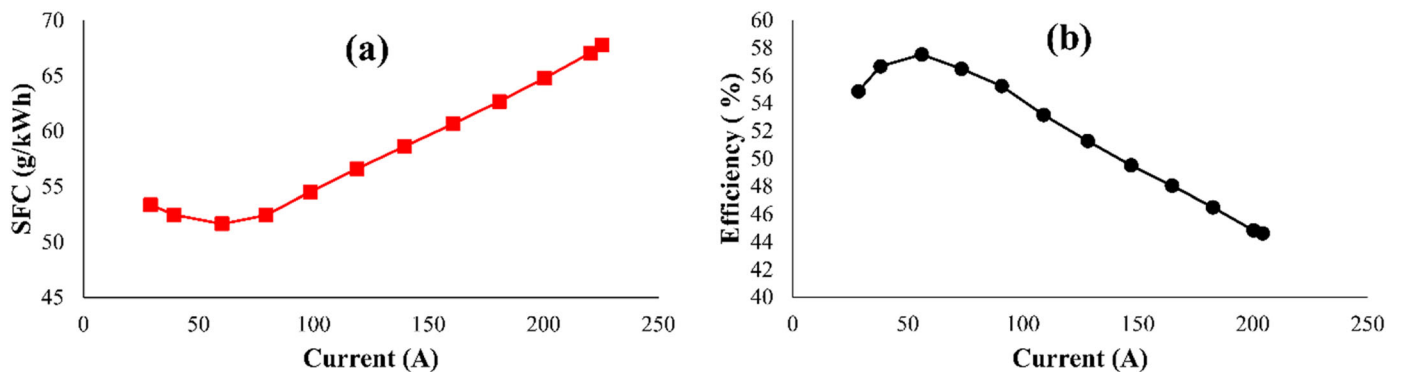


Figure A2. SFC curves for PEMFC.

Appendix C

Table A2. FC values in t regarding the ME and AEs.

MP1	ME_LNG	ME_MGO	AE_LNG	AE_MGO	AE_Ammonia	ME_Ammonia	ME_MGO	AE_Ammonia	AE_MGO
Vessel A	734.82	65.17	51.22	58.47	N/A	1,809.08	102.99	126.10	61.11
Vessel B	286.13	30.75	42.38	29.26	N/A	704.45	45.47	104.34	31.45
MP1	ME_MEOH	ME_MGO	AE_MEOH	AE_MGO	AE_Ammonia	ME_FAME	AE_FAME	AE_Ammonia	
Vessel A	1,772.43	65.17	123.54	58.47	N/A	946.46	166.97	N/A	
Vessel B	690.17	30.75	102.23	29.26	N/A	399.66	98.80	N/A	
DEP1	ME_LNG	ME_MGO	AE_LNG	AE_MGO	AE_Ammonia	ME_Ammonia	ME_MGO	AE_Ammonia	AE_MGO
Vessel A	839.49	43.57	46.68	32.17	N/A	2,066.77	86.78	114.93	33.02
Vessel B	340.79	20.11	38.25	9.37	N/A	838.99	37.65	94.16	10.08
DEP1	ME_MEOH	ME_MGO	AE_MEOH	AE_MGO	AE_Ammonia	ME_FAME	AE_FAME	AE_Ammonia	
Vessel A	2,044.62	43.57	112.60	32.17	N/A	1,060.87	93.08	N/A	
Vessel B	829.72	20.11	92.26	9.37	N/A	431.13	57.09	N/A	
MP2	ME_LNG	ME_MGO	AE_LNG	AE_MGO	AE_Ammonia	ME_Ammonia	ME_MGO	AE_Ammonia	AE_MGO
Vessel A	734.82	65.17	0.59	0.81	165.48	1,809.08	65.17	166.93	0.84
Vessel B	286.13	30.75	4.35	6.43	113.24	704.45	30.75	123.96	6.66
MP2	ME_MEOH	ME_MGO	AE_MEOH	AE_MGO	AE_Ammonia	ME_FAME	AE_FAME	AE_Ammonia	
Vessel A	1,772.43	65.17	2.22	0.81	165.48	946.46	2.35	165.48	
Vessel B	690.17	30.75	16.72	6.43	113.24	399.66	23.35	113.24	
DEP2	ME_LNG	ME_MGO	AE_LNG	AE_MGO	AE_Ammonia	ME_Ammonia	ME_MGO	AE_Ammonia	AE_MGO
Vessel A	823.52	42.28	0.00	0.00	156.59	2,027.46	84.66	156.59	0.00
Vessel B	326.23	16.85	0.00	0.00	106.83	803.16	33.64	106.83	0.00
DEP2	ME_MEOH	ME_MGO	AE_MEOH	AE_MGO	AE_Ammonia	ME_FAME	AE_FAME	AE_Ammonia	
Vessel A	1,986.39	42.28	0.00	0.00	156.59	1,040.70	0.00	156.59	
Vessel B	786.89	16.85	0.00	0.00	106.83	412.75	0.00	106.83	

Table A3. Energy consumption and CO₂e emissions associated with grid electricity consumption during berthing.

Energy Consumption (MWh)		
Country	Vessel A	Vessel B
Brazil	53.65	N/A
United States	30.60	79.29
Panama	31.27	37.62
Canada	98.95	N/A
Guatemala	N/A	85.37
Total	214.47	202.28
CO ₂ e Emissions (t)		
Country	Vessel A	Vessel B
Brazil	5.53	N/A
United States	11.75	30.45
Panama	8.10	9.74
Canada	17.32	N/A
Guatemala	N/A	23.31
Total	42.69	63.50

Table A4. TtW emissions of CO₂, CH₄, and N₂O in t under CI application across all configurations.

TtW with CI application						
Configuration	Vessel A			Vessel B		
	CO ₂	CH ₄	N ₂ O	CO ₂	CH ₄	N ₂ O
Conventional	2,946.98	0.05	0.17	1,259.82	0.02	0.07
MP1-LNG	2,416.69	1.12	0.10	968.50	0.44	0.04
MP1-MEOH	2,844.94	0.01	0.02	1,135.50	0.00	0.01
MP1-Ammonia	462.86	0.01	1.67	206.59	0.00	0.65
MP1-FAME	2,898.93	0.04	0.08	1,229.06	0.01	0.03
DEP1-LNG	2,538.49	1.27	0.10	1,011.54	0.51	0.04
DEP1-MEOH	2,538.49	1.27	0.10	905.52	0.43	0.04
DEP1-Ammonia	325.81	0.01	1.74	206.59	0.00	0.65
DEP1-FAME	3,009.94	0.03	0.07	1,201.00	0.01	0.03
MP2-LNG	2,232.39	1.09	0.09	905.52	0.43	0.04
MP2-MEOH	2,648.87	0.00	0.01	1,067.64	0.00	0.01
MP2-Ammonia	332.73	0.01	1.61	206.59	0.00	0.65
MP2-FAME	2,598.12	0.03	0.07	1,145.58	0.01	0.02
DEP2-LNG	2,400.22	1.22	0.10	951.16	0.48	0.04
DEP2-MEOH	2,866.82	0.00	0.01	951.16	0.48	0.04
DEP2-Ammonia	271.43	0.00	1.67	107.86	0.00	0.69
DEP2-FAME	2,851.53	0.03	0.07	1,130.92	0.01	0.03
TtW without CI application						
Configuration	Vessel A			Vessel B		
	CO ₂	CH ₄	N ₂ O	CO ₂	CH ₄	N ₂ O
Conventional	3,107.71	0.05	0.18	3,155.95	1,407.44	0.02
MP1-LNG	2,558.01	1.17	0.11	2,619.46	1,095.82	0.49
MP1-MEOH	3,003.36	0.01	0.02	3,009.41	1,281.95	0.00
MP1-Ammonia	526.11	0.01	1.71	977.94	246.61	0.00
MP1-FAME	3,050.81	0.04	0.08	3,072.40	1,365.78	0.02
DEP1-LNG	2,679.81	1.32	0.11	2,745.97	1,136.87	0.56
DEP1-MEOH	2,679.81	1.32	0.11	2,745.97	918.04	0.43
DEP1-Ammonia	389.06	0.01	1.78	858.32	246.61	0.00
DEP1-FAME	3,161.83	0.04	0.08	3,182.70	1,337.71	0.01
MP2-LNG	2,233.91	1.09	0.09	2,288.97	918.04	0.43
MP2-MEOH	2,651.68	0.00	0.01	2,654.91	1,091.17	0.00
MP2-Ammonia	332.89	0.01	1.64	766.28	246.61	0.00
MP2-FAME	2,599.75	0.03	0.07	2,618.98	1,159.05	0.01
DEP2-LNG	2,400.22	1.22	0.10	2,460.33	951.16	0.48
DEP2-MEOH	2,866.82	0.00	0.01	2,868.89	951.16	0.48
DEP2-Ammonia	271.43	0.00	1.67	711.55	107.86	0.00
DEP2-FAME	2,851.53	0.03	0.07	2,870.76	1,130.92	0.01

Table A5. WtT CO₂e emissions.

Configuration	Vessel A		Vessel B	
	CO ₂ e	CO ₂ e – CI	CO ₂ e	CO ₂ e – CI
Conventional	733.58	696.29	325.87	228.75
MP1-LNG	808.99	767.92	344.31	305.51
MP1-MEOH	1,475.81	1,454.32	623.00	611.98
MP1- Grey NH ₃	3,760.18	3,745.51	1,577.73	1,568.44
MP1- Blue NH ₃	2,502.32	2,396.20	1,052.02	940.47
MP1- Green NH ₃	464.58	436.75	200.37	176.37
MP1-1G FAME	601.81	571.85	269.42	242.45
MP1-2G FAME	484.12	460.02	216.73	195.04
DEP1-LNG	864.70	823.64	367.69	329.35
DEP1-MEOH	1,663.90	1,596.10	708.99	640.76
DEP1- Grey NH ₃	4,191.85	4,177.18	1,790.78	1,781.95
DEP1- Blue NH ₃	2,773.75	2,667.63	1,184.22	1,073.14
DEP1- Green NH ₃	476.42	448.59	201.61	178.07
DEP1-1G FAME	623.71	593.75	263.88	236.91
DEP1-2G FAME	501.74	477.64	212.28	190.58
MP2-LNG- Grey NH ₃	1,031.02	890.72	505.53	363.68
MP2-LNG- Blue NH ₃	923.46	831.49	431.92	337.70
MP2-LNG- Green NH ₃	749.21	735.55	312.68	295.61
MP2-MEOH- Grey NH ₃	1,764.91	1,594.77	823.61	673.53
MP2-MEOH- Blue NH ₃	1,657.35	1,535.54	750.00	635.57
MP2-MEOH- Green NH ₃	1,483.09	1,439.59	708.99	593.49
MP2-Grey NH ₃	3,792.18	3,652.34	1,596.58	1,458.54
MP2- Blue NH ₃	2,507.77	2,414.67	1,058.12	954.51
MP2- Green NH ₃	426.98	413.56	185.40	170.24
MP2-1G FAME-Grey NH ₃	823.05	682.92	434.60	294.19
MP2-1G FAME-Blue NH ₃	715.48	623.69	361.00	268.22
MP2-1G FAME-Green NH ₃	541.23	527.75	241.76	226.13
MP2-2G FAME-Grey NH ₃	722.93	582.87	391.24	251.36
MP2-2G FAME-Blue NH ₃	615.37	523.64	317.64	225.38
MP2-2G FAME-Green NH ₃	441.12	427.69	198.40	183.29
DEP2-LNG- Grey NH ₃	1,090.67	951.45	517.48	385.90
DEP2-LNG- Blue NH ₃	988.89	897.80	448.04	361.95
DEP2-LNG- Green NH ₃	824.00	810.89	335.54	323.16
DEP2-MEOH- Grey NH ₃	1,806.09	1,636.46	799.77	656.14
DEP2-MEOH- Blue NH ₃	1,704.31	1,582.81	730.33	632.19
DEP2-MEOH- Green NH ₃	1,539.42	1,495.89	617.83	593.40
DEP2-Grey NH ₃	4,168.99	4,029.77	1,735.81	1,604.23
DEP2- Blue NH ₃	2,749.35	2,658.27	1,144.31	1,058.23
DEP2- Green NH ₃	449.55	436.44	186.09	173.70
DEP2-1G FAME-Grey NH ₃	856.89	717.67	423.94	292.36
DEP2-1G FAME-Blue NH ₃	755.11	664.02	354.49	268.41
DEP2-1G FAME-Green NH ₃	590.22	577.11	242.00	229.61
DEP2-2G FAME-Grey NH ₃	746.89	607.67	380.31	248.73
DEP2-2G FAME-Blue NH ₃	645.10	554.02	310.87	224.78
DEP2-2G FAME-Green NH ₃	480.21	467.11	198.37	185.98

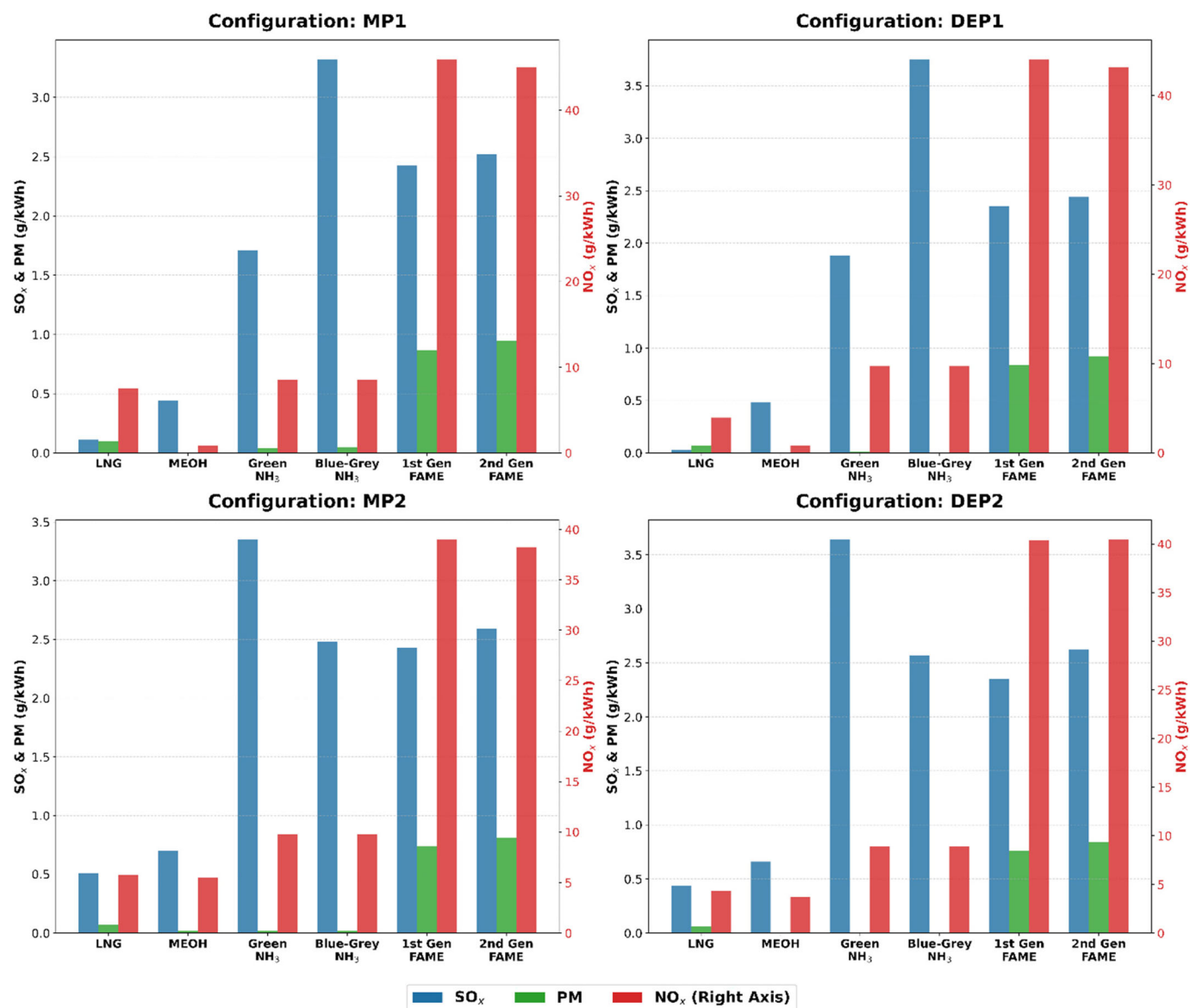


Figure A3. WtW SO_x, NO_x, and PM emissions of Vessel B.

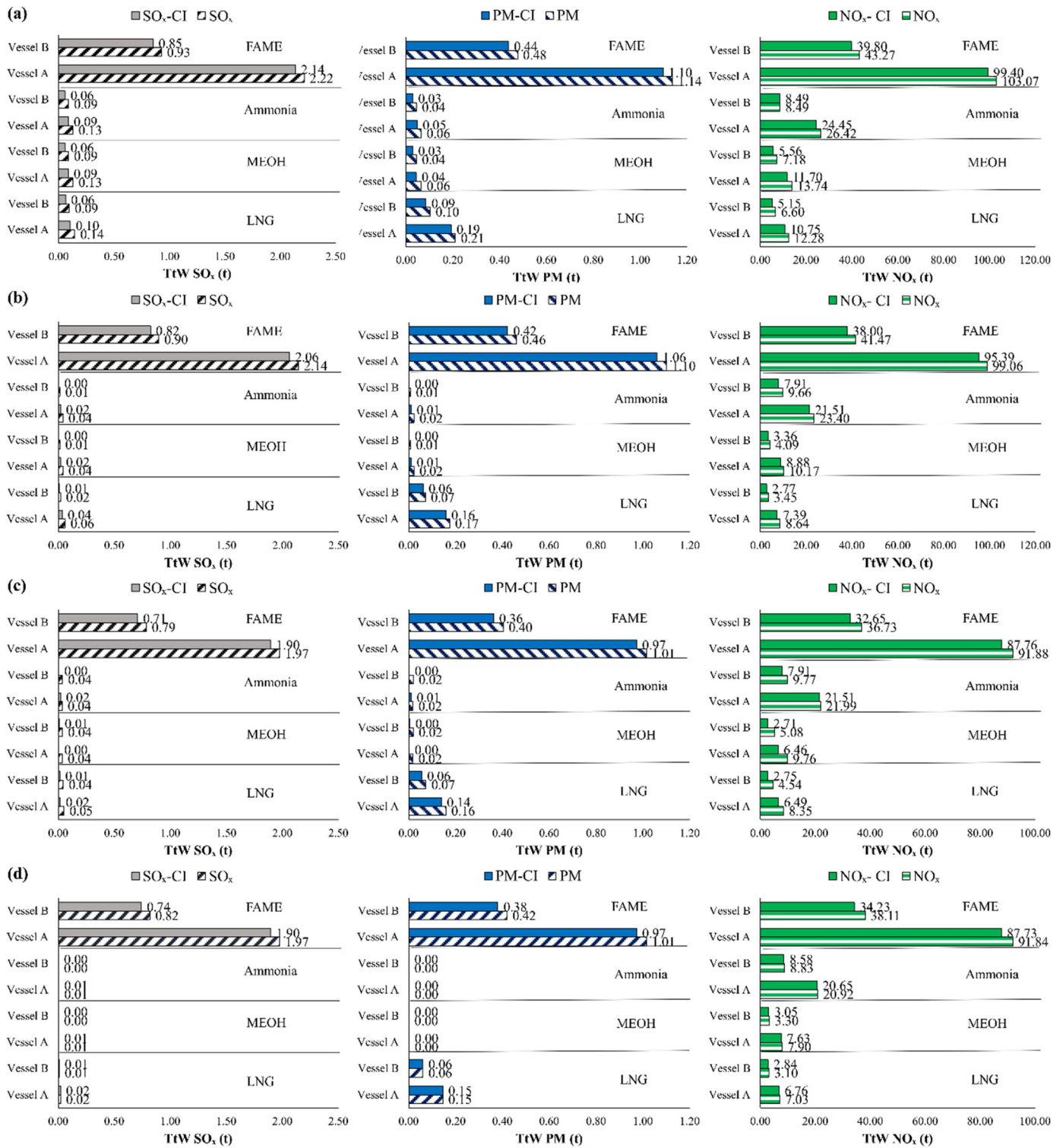


Figure A4. Other TtW emissions for MP1 (a), DEP1 (b), MP2 (c), and DEP2 (d) configurations.

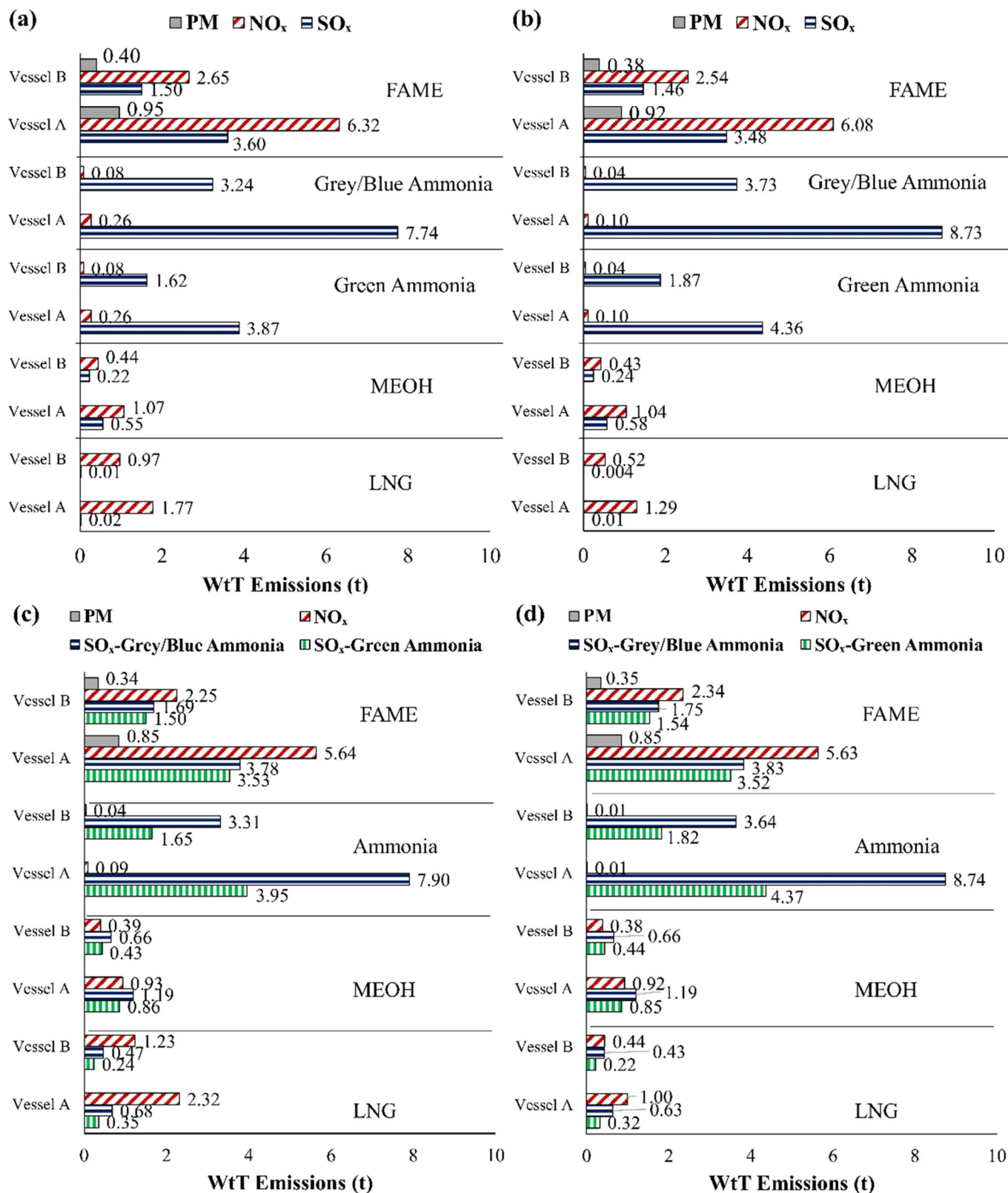


Figure A5. WtT PM, NO_x, and SO_x emissions from MP1 (a), DEP1 (b), MP2 (c), and DEP2 (d).

Table A6. NO_x in g/kWh for all configurations.

MP1		
Fuel	Vessel A	Vessel B
LNG	2.11	2.71
MEOH	2.36	2.95
Ammonia	4.54	3.49
FAME	17.71	17.75
DEP1		
Fuel	Vessel A	Vessel B
LNG	1.49	1.42
MEOH	1.75	1.69
Ammonia	4.04	3.98
FAME	17.10	17.10
MP1 -CI		
Fuel	Vessel A	Vessel B
LNG	1.85	2.11
MEOH	2.01	2.28
Ammonia	4.20	3.49
FAME	17.08	16.33
DEP1-CI		
Fuel	Vessel A	Vessel B
LNG	1.28	1.14
MEOH	1.53	1.39
Ammonia	3.71	3.26
FAME	16.47	15.67
MP2		
Fuel	Vessel A	Vessel B
LNG	1.56	2.14
MEOH	1.83	2.39
Ammonia	4.12	4.60
FAME	17.21	17.29
DEP2		
Fuel	Vessel A	Vessel B
LNG	1.32	1.40
MEOH	1.36	1.36
Ammonia	3.61	3.64
FAME	15.85	15.71
MP2-CI		
Fuel	Vessel A	Vessel B
LNG	1.22	1.29
MEOH	1.21	1.28
Ammonia	3.71	3.61
FAME	16.44	15.37
DEP2-CI		
Fuel	Vessel A	Vessel B
LNG	1.27	1.29
MEOH	1.32	1.26
Ammonia	3.57	3.54
FAME	15.14	14.11