

TOWARD ZERO-CARBON SHIPPING IN MALAYSIA: A COMPARATIVE ANALYSIS OF WTT AND TTW EMISSIONS

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ARTICLE INFO	ABSTRACT
<p>Article History: Received: 28 May 2025 Revised: 30 July 2025 Accepted: 30 July 2025 Published: 25 August 2025</p> <hr/> <p>Keywords: Shipping, WTT, TTW, Malaysia, decarbonisation.</p>	<p>The maritime sector in Malaysia is at a critical juncture in its pursuit of zero-carbon shipping, which requires a strategic shift toward cleaner fuel alternatives. This study conducts a comparative analysis of Well-to-Tank (WTT) and Tank-to-Wake (TTW) emissions for six alternative marine fuels namely Liquefied Natural Gas (LNG), methanol, biofuels, green ammonia, hydrogen, and shore power. Drawing on internationally recognised emission factors and contextualised with Malaysia's energy profile, the analysis reveals significant variations in emissions distribution across fuel types. Fuels such as green ammonia, hydrogen, and shore power exhibit zero TTW emissions, positioning them as long-term solutions, while biofuels offer a viable transitional pathway with a balanced emissions profile. Conversely, LNG and fossil methanol remain TTW-dominant and offer limited GHG reduction. The study presents a policy-oriented fuel selection framework, emphasising the importance of aligning fuel strategies with national decarbonisation goals, grid decarbonisation progress, and infrastructure readiness. The findings aim to support Malaysia's transition towards a sustainable and climate-resilient maritime sector.</p>

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Introduction

Maritime transport remains a critical enabler of global economic activity, facilitating over 80% of international trade by volume and approximately 70% by value (International Maritime Organisation, 2020). While the industry is indispensable to global supply chains, it also imposes considerable environmental costs. According to the Fourth IMO Greenhouse Gas (GHG) Study, international shipping accounted for nearly 2.89% of global anthropogenic GHG emissions in 2018, with emissions projected to increase by up to 130% by 2050 if no further action is taken (IMO, 2021). These trends underscore the urgency for systemic decarbonisation of the maritime

sector, particularly as global climate governance intensifies under the Paris Agreement and its net-zero ambitions.

Malaysia, a maritime nation strategically positioned along the Strait of Malacca, plays a central role in regional shipping and port logistics. Its economic reliance on maritime trade and coastal infrastructure places the country at the forefront of both opportunity and responsibility in the transition towards zero-carbon shipping. Nationally, Malaysia has committed to reducing its economy-wide emissions intensity of GHG by 45% on or before 2030, relative to 2005 levels, as outlined in its Nationally Determined Contributions (NDCs). Policy frameworks such

as the National Transport Policy 2019–2030, the Green Technology Master Plan (2017–2030), and the more recent National Energy Transition Roadmap (NETR) further emphasise the country's intent to decarbonise the transport sector. Yet, implementation has been uneven, with marine transport receiving comparatively less focus than road and energy sectors (Ministry of Transport Malaysia, 2019; KeTSA, 2023).

Among the key levers to decarbonise maritime operations is the adoption of alternative fuels, which offer varying degrees of emissions reduction and compatibility with existing ship technologies. Candidates include Liquefied Natural Gas (LNG), methanol, biofuels, green ammonia, hydrogen, and shore-to-ship electricity. However, their environmental performance is not uniform and depends heavily on the emissions produced during both upstream production (Well-to-Tank) and onboard combustion (Tank-to-Wake) stages. While fuels such as green hydrogen and ammonia are often praised for their zero-emission potential during use, their upstream production can be carbon-intensive if not powered by renewable sources. Conversely, LNG and fossil methanol, despite being relatively cleaner than conventional Heavy Fuel Oil (HFO) during combustion, still generates substantial TTW emissions and can lock in fossil fuel dependence (Brynnolf *et al.*, 2014; Bouman *et al.*, 2017).

Existing studies have primarily evaluated fuel pathways using full Life Cycle Assessment (LCA) methodologies, which, while comprehensive are often data-intensive and not easily applicable in policy or operational settings. Moreover, few assessments disaggregate emissions into WTT and TTW components, which is essential for understanding the strategic trade-offs in fuel selection, especially in countries like Malaysia where grid emission intensity, infrastructure readiness, and feedstock availability vary significantly. Furthermore, there is a dearth of research and emissions analysis that tailors to Malaysia's maritime sector requirements, where green port development and energy mix constraints shape the viability of the fuel transitions.

Despite the growing body of international literature on marine fuel decarbonisation, there is limited empirical work that systematically contrasts WTT and TTW emissions for alternative fuels in Southeast Asia and even less so with specific reference to Malaysia. This lack of localised emissions profiling in pieces the risks of the adoption of fuel strategies that may underperform in terms of actual climate impact or conflict with national energy realities.

This study addresses this gap by offering a comparative analysis of WTT and TTW emissions for six alternative marine fuels namely LNG, methanol, biofuels, green ammonia, hydrogen, and electricity in the Malaysian maritime context. By doing so, it bridges the gap between technical emissions data and actionable policy recommendations. The study also introduces a fuel selection framework that classifies fuels according to their emissions dominance profile (WTT or TTW-heavy), helping stakeholders make informed choices that are in line with Malaysia's carbon reduction goals and port decarbonisation pathways.

The primary objective of this study is to evaluate and compare the WTT and TTW greenhouse gas emissions of selected alternative marine fuels relevant to Malaysia's shipping and port sectors. Specifically, the study aims to:

- (a) Quantify and compare the WTT, TTW, and total Well-to-Wake (WTW) emissions for six key alternative marine fuels using international benchmarks adjusted for Malaysian Social, policy and economic conditions.
- (b) Analyse the emissions dominance profile of each fuel to identify where the bulk of environmental impact arises (upstream versus onboard).
- (c) Develop a strategic fuel selection framework to guide policymakers, port authorities, and shipping operators in prioritising fuel pathways.

The remainder of this article is structured as follows: Section 2 presents a literature review, Section 3 outlines the research methodology,

while Section 4 discusses the results and key findings. Finally, Section 5 concludes the study, highlights its limitations, and offers recommendations for future research.

Literature Review

Maritime transport is increasingly scrutinised for its contribution to global greenhouse gas (GHG) emissions. The Fourth IMO GHG Study (IMO, 2020) identifies the shipping and maritime logistics sector as responsible for 2.89% of global anthropogenic CO₂ emissions, a share that is expected to rise without stringent mitigation strategies. As international pressure mounts to align with the Paris Agreement and Sustainable Development Goals (SDGs), decarbonisation of hard-to-abate sectors like maritime has become a priority (UNCTAD, 2021). The International Maritime Organisation (IMO) has introduced a series of regulatory instruments, including the Energy Efficiency Existing Ship Index (EEXI) and the Carbon Intensity Indicator (CII), to drive down emissions from ships (IMO, 2021).

Alternative Marine Fuels: Promise and Challenges

The transition toward alternative marine fuels has gained significant momentum in response to increasing regulatory pressure, stakeholder expectations, and environmental imperatives (Bouman *et al.*, 2017; IMO, 2023). As maritime stakeholders seek to decarbonise operations, various fuel pathways have emerged, each with its own unique advantages, trade-offs, and uncertainties (Tabibian & Sharifzadeh, 2023). The key contenders include LNG, methanol, biofuels, green ammonia, hydrogen, and electricity (shore power). These fuels differ in terms of lifecycle emissions, energy density, storage requirements, safety profiles, and infrastructure needs, creating a complex decision-making landscape for policymakers and industry players alike (IEA, 2021).

LNG is often regarded as a transitional fuel due to its lower carbon dioxide (CO₂), nitrogen oxide (NO_x), sulphur oxide (SO_x), and particulate matter emissions compared to

HFO (Brynolf *et al.*, 2014; Balcombe *et al.*, 2019). However, LNG is a fossil-based fuel, and concerns about methane slip during extraction, processing, and combustion undermine its long-term viability as a sustainable option. Methane, a potent greenhouse gas, can significantly erode LNG's climate benefits if not effectively mitigated (Pavlenko *et al.*, 2020; ICCT, 2020). While LNG benefits from relatively mature infrastructure and engine compatibility, its contribution to meeting mid- and long-term decarbonisation targets remains questionable (ICCT, 2020; IMO, 2021).

Methanol, especially when derived from fossil sources, offers limited greenhouse gas (GHG) savings over conventional fuels (Svanberg *et al.*, 2018; Gilbert *et al.*, 2018). However, its low emissions profile for sulphur oxides (SO_x) and particulates, as well as ease of storage and handling, make it a practical option for retrofitting existing vessels (Pavlenko *et al.*, 2020; Barona *et al.*, 2025). The recent rise of interest in green methanol produced using renewable hydrogen and captured CO₂ has revitalised methanol's prospects, particularly for short-sea shipping and regional routes (Ammar, 2019; Akac *et al.*, 2025). Yet, scaling up production and ensuring certification of sustainability remain key barriers (Massarweh & Abushaikha, 2020).

Biofuels, including biodiesel and advanced bio-liquids, offer significant GHG reduction potential up to 90% when derived from second-generation feedstocks like used cooking oil, animal fats, or non-edible crops (IEA, 2021; Pavlenko *et al.*, 2020). Their primary advantage lies in their compatibility with existing engines and fuel infrastructure, making them attractive for near-term emissions reduction (IEA, 2022). However, supply chain limitations, indirect land-use change (ILUC), and sustainability certification challenges constrain their scalability (Searchinger *et al.*, 2008; Malins *et al.*, 2014). Concerns also remain regarding feedstock competition with food production and its potential impact on biodiversity, particularly when biofuel expansion drives agricultural

encroachment into forests or grasslands (Leite *et al.*, 2025; Nashath *et al.*, 2025; Sundaram *et al.*, 2025).

Green ammonia and hydrogen are often cited as long-term zero-carbon solutions. Green ammonia, synthesised using renewable hydrogen and atmospheric nitrogen via the Haber-Bosch process, produces no CO₂ when combusted. It offers relatively high volumetric energy density and is easier to store than hydrogen but poses challenges related to toxicity, handling safety, and combustion efficiency (Erfani *et al.*, 2024; Spatolisano & Figini, 2025; Shooshtari, 2025). Hydrogen, particularly in its green form produced through electrolysis powered by renewable electricity, has significant climate benefits. It emits only water vapour when used in fuel cells or combusted. However, its low volumetric energy density, cryogenic storage needs, and high production cost hinders immediate scalability (Algburi *et al.*, 2025; Elazab *et al.*, 2025; Mohsen *et al.*, 2026).

Electricity typically via shore power or cold ironing eliminates ship-side emissions when vessels are docked, significantly improving local air quality in port areas. Its environmental impact, however is contingent upon the carbon intensity of the electricity grid (Tang *et al.*, 2025). In countries like Malaysia, where grid decarbonisation is still underway, the full benefits of shore power can only be realised alongside a cleaner national energy mix. Nonetheless, electrification offers immediate benefits in emissions hotspots and serves as an essential complement to fuel-switching strategies.

In summary, while each alternative fuel holds promise, no single solution satisfies all technical, economic, and environmental criteria. Fuel adoption decisions must therefore consider lifecycle emissions, technology readiness levels, infrastructure availability, and alignment with national policy objectives. A context-specific assessment is necessary to balance short-term feasibility with long-term sustainability in the maritime sector.

Emission Accounting: From Tank-to-Wake to Well-to-Wake

Emission accounting in the maritime industry has evolved significantly over the past two decades, driven by the growing need to capture the full environmental impact of marine fuel usage. Traditional accounting frameworks focused primarily on direct emissions generated from fuel combustion onboard vessels commonly referred to as Tank-to-Wake (TTW) emissions (Saafi *et al.*, 2025). While this approach has been instrumental in setting regulatory baselines such as the International Maritime Organisation's EEXI and CII, it offers a limited view of a fuel's total climate footprint.

TTW accounting encompasses emissions such as CO₂, nitrogen oxides (NO_x), sulphur oxides (SO_x), and particulate matter released during propulsion and onboard energy use. However, it does not account for emissions generated upstream during fuel extraction, production, refinement, and transportation to the point of use (Zincir, 2025). As cleaner fuels like hydrogen, ammonia, and electricity become viable options, their production pathways can vary widely in carbon intensity depending on the energy mix. For instance, hydrogen produced via electrolysis using coal-fired power may have a greater climate impact than conventional fuels despite producing no emissions onboard (Lee *et al.*, 2024).

To address this gap, researchers and policy bodies have adopted the Well-to-Wake (WTW) framework, which integrates both WTT and TTW phases (Table 1). WTT emissions include all upstream processes, from raw material extraction to final fuel delivery. Together, WTT and TTW form a comprehensive WTW emissions profile that enables a holistic comparison of alternative marine fuels (Mustakim *et al.*, 2025). This distinction is particularly important in evaluating fuels that have low or zero TTW emissions, such as green hydrogen or shore power, whose upstream impacts are highly dependent on the source of electricity or production method.

Several studies reinforce the necessity of WTW approaches. Brynolf *et al.* (2014) and Gilbert *et al.* (2018) emphasise that exclusive reliance on TTW data can mislead decision-makers, especially when evaluating fuels like LNG, which have low TTW emissions but may produce substantial methane emissions during upstream stages. Similarly, Ou *et al.* (2021) argue that overlooking WTT emissions results in skewed carbon abatement strategies that may not align with long-term climate targets.

Table 1: Scope comparison

Scope	Includes	Example Fuel	Key Concern
TTW	Emissions from onboard combustion	LNG, HFO	Ignores upstream footprint
WTT	Emissions from extraction to delivery	Hydrogen, Methanol	Ignores use-phase emissions
WTW	Full lifecycle emissions	All fuels	Best for accurate comparison

Through WTW approach, it enables alignment with broader decarbonisation strategies, supports carbon pricing mechanisms, and encourages the development of low-carbon fuel supply chains (Oh *et al.*, 2024). In the context of Malaysia's evolving energy transition and maritime policies, incorporating WTW metrics is essential for identifying truly sustainable fuel pathways that reflect both national and global climate commitments.

Fuel Strategy and Policy Alignment

The selection and adoption of alternative marine fuels are deeply influenced by strategic, regulatory, and infrastructural considerations that extend beyond technical viability. While the technological performance of low- and zero-carbon fuels is critical, their integration into the maritime sector is largely determined by the readiness of supporting infrastructure, policy incentives, port governance, and market mechanisms (Park *et al.*, 2024). Aligning fuel strategies with national and international decarbonisation targets requires a cohesive policy framework that coordinates actors across the maritime value chain.

Several studies emphasise that policy support plays a pivotal role in driving fuel transitions. For example, Psaraftis (2019) argues that decarbonisation is as much a governance challenge as it is a technological one, with success depending on cross-sector collaboration and regulatory harmonisation. In Europe, port authorities have actively promoted low-emission

fuels through differentiated port fees, access to green berths, and investment in bunkering infrastructure (Acciaro *et al.*, 2014). Japan and South Korea have adopted long-term national maritime strategies that embed alternative fuels within broader green shipping visions.

In contrast, many developing economies face capacity constraints, fragmented port governance, and limited access to capital, which hinder the adoption of alternative fuels. In these contexts, policies must address not only emissions reduction but also institutional coordination, financing models, and workforce training. Malaysia's National Transport Policy (2019–2030) and the National Energy Transition Roadmap (NETR) provide high-level direction for sustainable transport, but operationalising these ambitions in the maritime sector requires granular action plans that support fuel diversification, technology pilots, and public-private partnerships.

Port readiness is another crucial determinant. The deployment of fuels like green ammonia and hydrogen demands new storage, transfer, and safety systems, which must be standardised and regulated (Brækken *et al.*, 2025; Li *et al.*, 2025). Similarly, shore power adoption hinges on grid connectivity, pricing signals, and emissions accounting practices that incentivise ship operators to plug in (Li *et al.*, 2025). A coherent policy environment must therefore consider not just the fuel itself, but the entire ecosystem needed for its deployment including upstream energy supply, port-side

infrastructure, crew training, and compliance verification (Elsisi *et al.*, 2025).

Market-based mechanisms, such as carbon pricing, emissions trading schemes, and low-carbon fuel standards, also play a role in accelerating fuel adoption. These instruments can help internalise the external environmental costs of traditional fuels and create economic signals favouring cleaner alternatives (Marrero & Martínez-López, 2023; Chen *et al.*, 2025). Without such mechanisms, cleaner fuels may remain commercially unattractive, especially in a cost-sensitive industry like shipping (Kou *et al.*, 2025).

To ensure alignment between national strategies and fuel deployment, policy coherence must be pursued across ministries and regulatory bodies. Maritime fuel strategies should be integrated with national energy planning, environmental regulation, and port development frameworks (Barone *et al.*, 2025). Importantly, such alignment should also be iterative, adapting to technology advancements and market shifts to maintain momentum in the low-carbon transition (Gao *et al.*, 2025).

While global literature provides robust evaluations of fuel alternatives, lifecycle emissions, and policy frameworks, few studies offer disaggregated WTT and TTW assessments tailored to specific national contexts. In Malaysia, a data-driven framework that compares upstream and operational emissions across fuel types is needed to support evidence-based fuel selection. Furthermore, integrating this analysis into a strategic fuel selection tool grounded in emissions dominance, infrastructure

compatibility, and policy coherence could fill a critical gap in national maritime planning.

This study builds on existing international research while contributing a novel, Malaysia-specific assessment of marine fuel pathways using the WTT–TTW framework. It aims to support policymakers, port authorities, and industry stakeholders in making informed decisions that advance Malaysia’s maritime decarbonisation agenda.

Methodology

Data Collection

This study relies on secondary data collected from a combination of peer-reviewed literature, technical reports, and internationally recognised databases to estimate the lifecycle emissions of selected marine fuels. The primary sources include the GREET model (developed by Argonne National Laboratory), the International Energy Agency (IEA), the International Maritime Organisation (IMO) and SEA-LNG. Data was extracted for six alternative fuels namely LNG, methanol, biofuels, green ammonia, hydrogen, and electricity (shore power) focusing on their WTT and TTW emissions expressed in grams of CO₂-equivalent per megajoule (g CO₂e/MJ) (Table 2).

Where country-specific data was unavailable, global or regional estimates were used with an emphasis on ensuring consistency and comparability. Emission factors for electricity were adjusted based on Malaysia’s national grid carbon intensity, estimated at approximately 0.5 kg CO₂/kWh. All data was cross-referenced for accuracy and relevance to the Malaysian maritime context.

Table 2: Source of data

Data	Source	Relevance and Justification
LNG	GREET 2022, SEA-LNG	Widely accepted for transport sector analysis; includes methane slip, a critical factor for LNG
Green Ammonia	IEA, Ammonia Energy Association	Based on electrolysis-derived hydrogen; upstream energy intensity and toxicity are well-studied
Methanol	Ecoinvent, Methanol Institute	Represents fossil-derived production pathways; values consistent across major LCA models

Hydrogen	REET, IEA Hydrogen Roadmap	Differentiates between grey and green pathways; renewable hydrogen considered for WTW analysis
Biofuels	IEA Bioenergy, Ecoinvent	Focused on second-generation feedstocks (e.g., used cooking oil); sustainable source assumptions
Shore Power	National Grid Factors	Grid emission factor (~0.5 kg CO ₂ /kWh) aligned with national reporting and energy-sector studies

Emission Calculation

This study adopts a WTW emissions assessment framework to capture the complete lifecycle greenhouse gas (GHG) impact of marine fuels. Unlike conventional TTW approaches, which focus solely on emissions generated during onboard fuel combustion, the WTW method incorporates both upstream and operational emissions. This comprehensive perspective enables a more accurate comparison of marine fuels by accounting for the full chain of environmental impact from resource extraction to energy use onboard vessels.

Well-to-Tank (WTT) Emissions

WTT emissions refer to the upstream GHG emissions generated during fuel production, processing, and distribution before it reaches the ship's tank. WTT emissions were extracted or interpolated from peer-reviewed lifecycle

assessment (LCA) studies and international databases such as REET, Ecoinvent, and IEA reports. Emission values were expressed in grams of CO₂-equivalent per megajoule (g CO₂e/MJ) and adjusted for the Malaysian context and relevant particularly for electricity-based fuels, which aligned with Malaysia's national grid emission factor (~0.5 kg CO₂/kWh).

Examples of WTT emissions estimation include:

- (a) Green hydrogen: Electrolysis-based emissions + electricity use, scaled by Malaysia's grid carbon intensity.
- (b) Biofuels: Emissions from feedstock collection, processing, and transport, based on second-generation sources such as used cooking oil (UCO) or palm residues.
- (c) LNG: Methane leakage during extraction and transport, liquefaction processes, and shipping to Malaysian ports.

The general formula used for estimating WTT emissions is:

$$WTT_{Fuel} = \frac{\sum(\text{Feedstock Emissions} + \text{Processing Emissions} + \text{Transport Emissions})}{\text{Energy Content (MJ)}} \quad (1)$$

These values serve as the upstream component of total fuel emissions and are critical for

identifying hidden carbon costs, especially in fuels with otherwise low operational emissions.

Tank-to-Wake (TTW) Emissions

TTW emissions quantify the GHGs mainly CO₂, with possible contributions from CH₄ and N₂O released during the actual use of the fuel onboard a vessel. This represents the operational phase of the fuel's lifecycle and is also measured in g CO₂e/MJ.

The TTW emissions for each fuel was determined based on their carbon content and combustion characteristics:

- (a) Fossil fuels (e.g., LNG, methanol): Emissions calculated based on full oxidation of the fuel's carbon content. LNG, for instance, emits approximately 56 g CO₂e/MJ, with methane slip considered in upstream calculations.
- (b) Biofuels: TTW emissions are relatively low (~5 g CO₂e/MJ), reflecting assumptions of biogenic carbon neutrality. However, they

- are not treated as entirely zero-emission due to minor non-CO₂ combustion byproducts.
- (c) Green ammonia, hydrogen, and shore power: TTW emissions are considered

zero, under the assumption that these fuels are used in non-combustion systems (e.g., fuel cells, electric motors) or with external electricity while the vessel is berthed.

To ensure accuracy, TTW values were adjusted for complete combustion efficiency and full oxidation of carbon content. The general formula applied for CO₂-only TTW emissions is:

$$TTW_{CO_2e} = (\text{Carbon content per MJ}) \times \left(\frac{44}{12}\right) \quad (2)$$

This conversion reflects the molecular ratio of carbon (C) to carbon dioxide (CO₂). Where appropriate, global warming potential (GWP) adjustments were included for non-CO₂ emissions, such as CH₄ (methane slip from LNG).

Total Well-to-Wake Emissions

The total lifecycle emissions of each fuel, expressed as WTW emissions are obtained by summing the upstream (WTT) and operational (TTW) components:

$$WTW = WTT + TTW \quad (3)$$

where:

- (a) WTW: Total emissions from production to onboard use (g CO₂e/MJ)
- (b) WTT: Emissions from feedstock extraction, processing, and transport
- (c) TTW: Emissions from fuel combustion or energy release onboard the vessel

By calculating and comparing WTT, TTW, and total WTW emissions for each fuel, this study provides a robust, lifecycle-based evaluation of alternative marine fuels. The results form the basis for identifying viable decarbonisation pathways in Malaysia's maritime sector, aligning emission performance with strategic fuel adoption and infrastructure planning.

Results and Discussion

WTT Vs. TTW Emissions Dominance

A key finding from the emissions analysis lies in the contrasting dominance between upstream (Well-to-Tank, WTT) and operational (Tank-to-Wake, TTW) emissions across fuel types (Figure 1). By disaggregating total Well-to-Wake (WTW) emissions, the study reveals three distinct categories of marine fuels based

on where their environmental impact primarily arises. This classification not only facilitates clearer strategic planning but also helps to identify the direction for regulatory and investment focus.

TTW-dominant fuels, such as LNG and fossil-based methanol, exhibit high emissions during onboard combustion approximately 79% and 71% of their total WTW emissions, respectively. Despite being perceived as "cleaner" than HFO, these fuels retain substantial operational carbon intensity. LNG, in particular, poses a double risk: first, due to methane slip, a potent short-lived climate pollutant; and second, due to its fossil-based production chain. Methanol, while retrofit-compatible and attractive for short-term compliance, offers limited long-term benefit unless transitioned to

renewable production routes. As a result, both fuels are best relegated to short-term transitional roles, with a clear roadmap for phase-out and substitution by greener alternatives.

Balanced fuels, represented by biofuels, show a more equitable distribution of emissions, with roughly 67% arising from upstream processing and 33% during combustion. This dual-characteristic makes biofuels a viable bridge solution particularly in regions where infrastructure for zero-emission fuels remains underdeveloped. However, the sustainability of biofuels is conditional on the feedstock used. Unsustainable sources could trigger indirect land-use change (ILUC), threatening food security and biodiversity. Hence, policy support for biofuels must be matched with rigorous certification standards (e.g., ISCC, RSPO) and feedstock traceability systems.

In contrast, WTT-dominant fuels, including green ammonia, green hydrogen, and shore power, demonstrate zero TTW emissions and thus entirely shift their climate burden to upstream energy inputs. Their emissions profiles are fundamentally shaped by the carbon intensity of electricity used during production making them highly attractive for long-term decarbonisation, particularly if supported by a clean national grid. Green ammonia and hydrogen, both emerging technologies, are best suited for long-haul or auxiliary applications where their zero-emission characteristics help meet IMO compliance targets, such as the CII. Shore power, meanwhile, provides immediate air quality and GHG benefits in ports, but its net impact is contingent on the carbon profile of national grids. In Malaysia, where grid emissions are currently estimated at ~0.5 kg CO₂/kWh, electrification strategies must be synchronised with broader renewable energy expansion to fully realise their potential.

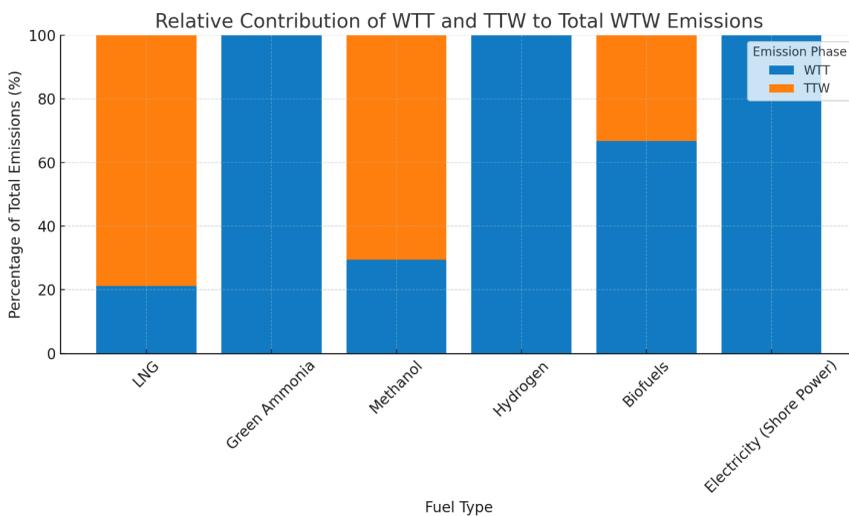


Figure 1: WTT vs. TTW emissions

Table 3 reinforces these findings by mapping fuel types against their emissions dominance profiles and proposing tailored strategic recommendations. LNG and methanol require near-term regulation and eventual

phase-out. Biofuels offer medium-term utility with sustainability caveats. Green ammonia, hydrogen, and electricity warrant long-term investment in infrastructure, safety protocols, and upstream energy transformation.

Table 3: Fuel strategy based on WTT–TTW emissions contrast

Fuel Type	Emissions Dominance	Strategic Recommendation	Rationale
LNG	TTW-dominant (~79%)	Transitional fuel with short-term use only if methane slip is minimised	High onboard emissions and upstream fossil origin; risk of carbon lock-in
Methanol (fossil-based)	TTW-dominant (~71%)	Phase out over time or shift to green methanol	Useful retrofit compatibility, but onboard combustion limits long-term potential
Biofuels	Balanced (WTT ~67%, TTW ~33%)	Short- to medium-term bridge solution with sustainability safeguards	Compatible with existing engines; feedstock origin must avoid ILUC/deforestation
Green Ammonia	WTT-dominant (~100%)	Long-term strategic fuel; invest in production and safety protocols	Zero TTW emissions critical for IMO compliance; high upstream energy demand
Green Hydrogen	WTT-dominant (~100%)	High-potential niche fuel; support R&D and pilot projects	Ideal for auxiliary power or small vessels; production must be RE-based
Electricity (shore power)	WTT-only (~100%)	Immediate deployment in ports where grid is low-carbon	Strong local air quality and GHG benefits; dependent on grid decarbonisation

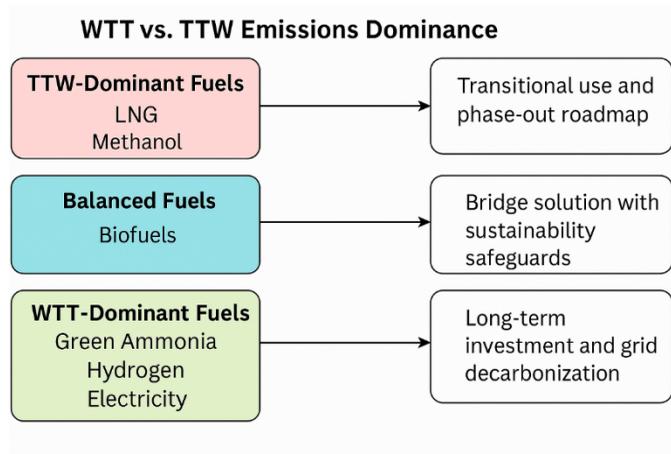


Figure 2: WTT vs. TTW emissions dominance

Figure 2 emphasises that fuel selection should be based on where emissions occur, as this determines where mitigation and investment should be concentrated either for upstream systems or onboard technologies. Thus, aligning fuel adoption with national energy trajectories, grid modernisation, and port readiness is critical. For Malaysia, this means embedding WTW considerations into maritime strategy,

port planning, and emissions regulations to ensure a resilient, scalable, and climate-aligned transition.

Tank-to-Wake (TTW) Emissions

The TTW emissions analysis provides a vital lens through which to evaluate the operational carbon footprint of alternative marine fuels. It reaffirms that green ammonia, hydrogen, and shore

power produce zero emissions during vessel operation, making them highly advantageous in meeting stringent decarbonisation benchmarks. This zero-emission profile is particularly valuable in emission control areas (ECAs) and densely populated urban coastal regions, where localised air pollution from port and shipping activities significantly affects human health and environmental quality. In addition to mitigating global GHG emissions, these fuels contribute to the reduction of nitrogen oxides (NO_x), sulphur oxides (SO_x), and particulate matter, thereby offering dual climate and public health benefits. Their compatibility with performance-based regulatory instruments such as the IMO's CII and EEXI further strengthens their strategic positioning in long-term maritime decarbonisation.

Biofuels, though not zero-emission, also deliver substantial TTW benefits, emitting only around 5 g CO₂e/MJ. Their reduced combustion emissions and high compatibility with existing ship engines enhance their practicality as a transitional measure, especially

in contexts where green hydrogen or ammonia infrastructure remains underdeveloped. Their use can significantly reduce onboard carbon intensity without requiring major technological overhauls, making them a low-barrier interim option while zero-emission alternatives are scaled.

In contrast, LNG and fossil methanol continue to exhibit high TTW emissions, measured at 56 g and 48 g CO₂e/MJ, respectively. These values, although lower than those of traditional HFO, remain inadequate for meeting medium- to long-term emissions reduction targets, particularly when lifecycle (WTW) emissions are taken into account. LNG, while often cited as a “cleaner” transition fuel, suffers from methane slip, the release of unburned methane during production, transfer, and combustion which substantially undercuts its climate advantage due to methane's high global warming potential. Fossil methanol's reliance on carbon-intensive production processes further diminishes its suitability as a decarbonisation solution.

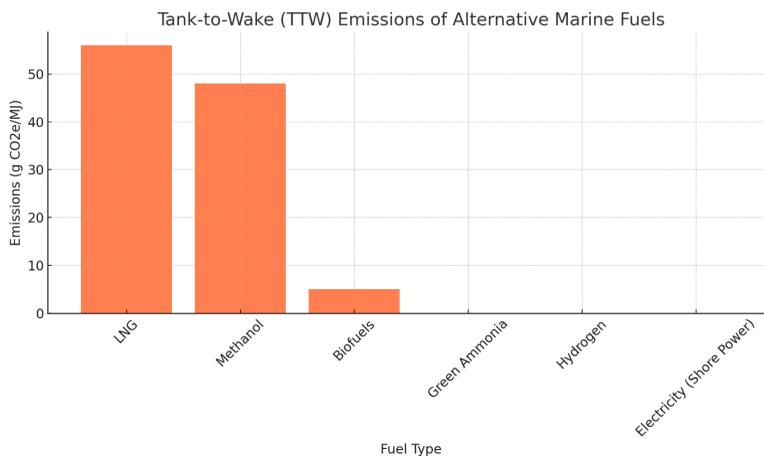


Figure 3: TTW emissions

These findings align with prior studies, such as Bouman *et al.* (2017), who warn against the overvaluation of LNG's climate performance, emphasising that short-term gains may come at the cost of long-term carbon lock-

in. Consequently, while LNG and methanol may fulfil interim compliance roles under current regulatory frameworks, they should not be relied upon as foundational components of future-ready maritime energy systems.

Figure 3 visually reinforces these differences in TTW emissions, illustrating the operational emissions spectrum from zero-emission fuels to TTW-intensive options. This underscores the critical need for a strategic shift toward fuels with minimal or no TTW emissions, particularly as performance-based emission regulations tighten and stakeholder expectations for sustainable operations rise globally.

Total Well-to-Wake (WTW) Emissions

The comparative assessment of WTW emissions reveals significant disparities in the total climate impact of alternative marine fuels, reinforcing the importance of lifecycle-based evaluations for maritime decarbonisation strategies. As shown in Table 4 and Figure 4, fuels such as green ammonia, green hydrogen, and shore power demonstrate the lowest total WTW emissions, ranging from approximately 0.5 g to 2 g CO₂e/MJ, assuming their upstream energy inputs are sourced from renewables. This positions them as prime candidates for long-term net-zero shipping, particularly in alignment with the IMO's 2050 GHG targets and emerging regulations such as the EU's FuelEU Maritime Initiative. Their operational and upstream performance makes them especially well-suited for integration into clean maritime energy ecosystems (Ingwersen *et al.*, 2025).

However, the practical deployment of these fuels remains constrained by several challenges. Green ammonia and hydrogen, while emission-free at the point of use, require energy-intensive production processes such as electrolysis and ammonia synthesis, both of which depend on the availability of affordable, large-scale renewable electricity. Additionally, their adoption

is hindered by infrastructure immaturity, particularly in bunkering, and complex handling requirements related to toxicity (ammonia) and flammability (hydrogen). These safety and technical hurdles require substantial investment in R&D, regulatory adaptation, and capacity-building before these fuels can be widely adopted in commercial shipping (IEA, 2021).

Shore power, similarly, delivers nearly zero WTW emissions (0.5 g CO₂e/MJ) when powered by clean grids and provides immediate benefits in port settings through the elimination of local air pollutants. However, its effectiveness is dependent on grid carbon intensity, which in Malaysia currently stands at approximately 0.5 kg CO₂/kWh. As such, realising the full emission reduction potential of shore power requires synchronised investments in grid decarbonisation, particularly through renewable energy integration.

In contrast, biofuels occupy a middle ground, with a WTW emissions profile of around 15 g CO₂e/MJ. Their attractiveness lies in their drop-in compatibility with existing marine engines and fuel systems, making them highly deployable with minimal technological disruption. They are especially valuable as transitional fuels, enabling emissions reductions in legacy fleets or infrastructure-limited ports. Nonetheless, their overall climate benefit is contingent on feedstock sustainability. Unsustainable sourcing such as from food crops or deforested lands can negate climate gains through indirect land-use change (ILUC) and biodiversity loss. Therefore, rigorous certification systems (e.g., ISCC, RSPO) and clear feedstock governance are essential to ensure that biofuels fulfil their climate promise.

Table 4: Emission factor for fuels

Fuel Type	WTT Emissions (g CO₂e/MJ)	TTW Emissions (g CO₂e/MJ)	Total WTW Emissions (g CO₂e/MJ)	Grid Dependency	GHG Reduction Potential vs HFO (%)
LNG	15	56	71	Low	20
Green Ammonia	1	0	1	No	100
Methanol	20	48	68	Low	25

Hydrogen	2	0	2	High	100
Biofuels	10	5	15	No	70
Electricity (Shore Power)	0.5	0	0.5	High	100

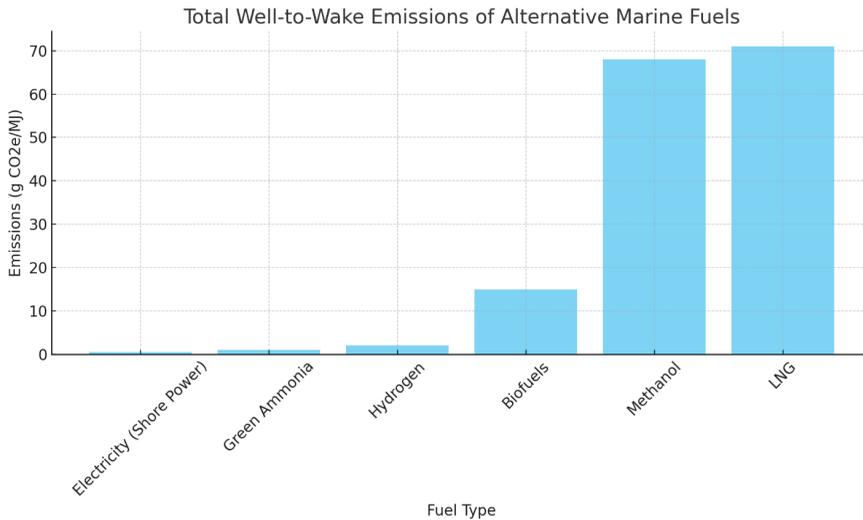


Figure 4: Total WTW Emissions

On the other end of the spectrum, fossil-based methanol and LNG exhibit the highest WTW emissions at 68 g CO₂e/MJ and 71 g CO₂e/MJ, respectively. Despite being promoted as transition options, these fuels pose substantial long-term climate risks. LNG’s relatively low TTW emissions are counteracted by significant upstream methane leakage, a potent greenhouse gas with a global warming potential over 80 times that of CO₂ over a 20-year period. Similarly, methanol’s carbon intensity is rooted in its fossil-based production processes, which currently dominate global methanol supply chains. These findings are consistent with those of Pavlenko *et al.* (2020) and Brynolf *et al.* (2014), both of whom argue that unless sourced renewably, such fuels offer limited decarbonisation benefit and risk creating infrastructure lock-in that delays the adoption of more sustainable alternatives.

Overall, the WTW emissions analysis affirms the necessity of evaluating fuels across their full lifecycle. Relying solely on TTW or

operational emissions can lead to misleading conclusions and inefficient policy incentives, particularly when upstream emissions are substantial. A lifecycle-based assessment ensures that fuels are not only compliant at the point of use but also sustainable throughout their production and supply chain. For Malaysia and other developing maritime economies, adopting WTW-centric evaluation frameworks will be crucial for aligning national fuel strategies with international climate ambitions and preventing long-term environmental and economic inefficiencies.

Policy and Strategic Implications

Building on the comparative emissions assessment, this study proposes a structured fuel selection framework that aligns with Malaysia’s maritime decarbonisation objectives. The framework groups fuels into three categories based on lifecycle GHG emissions, infrastructure readiness, and strategic suitability, offering targeted recommendations for each.

Category 1: Long-Term Decarbonisation Fuels (Zero-Emission Candidates)

Green ammonia and green hydrogen emerge as the most promising long-term solutions, each offering near 100% WTW GHG reduction when produced with renewable energy. Both are characterised by zero TTW emissions and WTT-dominant profiles. Green ammonia is particularly suited for deep-sea shipping and long-haul vessels due to its relatively higher volumetric energy density and non-combustion application. Hydrogen, on the other hand is optimal for short-sea shipping, auxiliary power, and onboard fuel cell systems. However, the successful deployment of these fuels depends on the decarbonisation of upstream electricity and the development of dedicated bunkering and safety infrastructure. To support the deployment of long-term zero-emission marine fuels such as green ammonia and green hydrogen, several policy actions are essential. First, there is a critical need to prioritise research and development (R&D) focused on safe handling, storage, and bunkering technologies for these fuels, particularly given their complex chemical properties and safety risks. Second, it is important to integrate these fuels into national green port taxonomies and long-term investment frameworks to ensure strategic alignment across infrastructure, financing, and regulatory dimensions.

Finally, the successful decarbonisation of these fuel pathways depends heavily on upstream energy sources; therefore, Malaysia must expand its national renewable energy capacity particularly solar and wind to enable the clean production of hydrogen and ammonia at scale.

Category 2: Transitional and Bridge Fuels

Biofuels and shore power represent pragmatic intermediate solutions. Biofuels, with a balanced WTT–TTW profile and around 70% WTW emissions reduction, are particularly attractive for use in existing fleets, given their drop-in compatibility. Sustainability, however, hinges on feedstock traceability and the avoidance of

indirect land-use change (ILUC). Shore power offers zero TTW emissions and immediate local air quality benefits at port areas. Yet, its effectiveness is dependent on grid emissions intensity and port electrification levels, which in Malaysia require simultaneous investment in cleaner energy sources.

To accelerate the adoption of transitional marine fuels, targeted policy interventions are necessary. Fiscal incentives and blending mandates should be implemented to encourage the uptake of sustainable biofuels, particularly in sectors where retrofitting is not feasible. In parallel, shore power deployment should be prioritised in high-traffic urban ports by incorporating specific electrification targets into port masterplans. This will help reduce local air pollution and support compliance with emissions regulations. Furthermore, the environmental integrity of biofuel supply chains must be safeguarded through the enforcement of internationally recognised sustainability standards, such as the International Sustainability and Carbon Certification (ISCC) and the Roundtable on Sustainable Palm Oil (RSPO).

Category 3: Limited-Impact Fuels

LNG and fossil-based methanol, while offering minor GHG reductions of between 20% and 25% are constrained by high TTW emissions and questionable long-term compatibility with global climate targets. LNG's methane slip and fossil origin undermine its climate credibility. Methanol, though retrofit-compatible, only becomes viable if sourced renewably. These fuels should be considered only in clearly defined transitional contexts and phased out in alignment with international decarbonisation timelines.

Policy measures targeting legacy or limited-impact fuels should focus on accelerating the transition toward cleaner alternatives. Subsidies and infrastructure support for LNG should be phased out beyond 2030, as continued investment risks locking the maritime sector

into a high-emission pathway. To internalise the environmental cost of fossil-based fuels, carbon pricing mechanisms or emissions penalties should be introduced, particularly for TTW intensive fuels like LNG and fossil methanol. At the same time, policymakers should actively promote a strategic shift toward green methanol or other scalable zero-emission fuels by supporting research and development (R&D), pilot projects, and commercial deployment initiatives.

To ensure a coherent and effective transition toward low- and zero-emission marine fuels, several cross-cutting policy measures must be implemented. First, WTW emissions metrics should be embedded in public procurement processes, national fuel standards, and port certification schemes to promote lifecycle-based decision-making. Fuel selection must also be context-sensitive, considering port infrastructure readiness, vessel characteristics, and route profiles to ensure operational and economic feasibility. In addition, Malaysia's maritime strategy should be fully aligned with international regulatory frameworks, including the IMO 2023 GHG targets, the CII, and the FuelEU Maritime initiative. Finally, long-term success depends on developing robust supply chains for renewable fuel inputs. This includes investments in grid decarbonisation, hydrogen production infrastructure, and electrolyser capacity to support the scale-up of green fuel technologies.

A phased, fuel-specific approach is needed. In the short term, biofuels and shore power should be prioritised where infrastructure exists. In the medium term, Malaysia must develop the capability to pilot green ammonia and hydrogen. Meanwhile, in the long term, deep integration of zero-emission fuels into maritime, energy, and port policy is essential. Crucially, the study highlights the need to move beyond TTW metrics and embrace a lifecycle-based (WTW) view to guide investment, regulation, and innovation across the sector.

Stakeholder Perspectives and Local Implementation Challenges

While the earlier emissions analysis offers a technically robust assessment of alternative marine fuels based on WTT, TTW, and WTW metrics, effective implementation in Malaysia is shaped by institutional capacity, operational readiness, and stakeholder alignment. In this context, insights from key national stakeholders, including the MISC Group, port authorities, and regulatory bodies such as the Marine Department of Malaysia reveal critical considerations for translating lifecycle assessments into feasible policy and industry pathways.

Industry Perspective: Challenges from Shipowners

Stakeholder feedback including that from leading shipowners such as MISC, underscores the significant capital investment required for the transition to zero-emission fuels like green ammonia and hydrogen. Although these fuels are environmentally advantageous, they impose a notable cost premium and financing burden relative to conventional options, particularly for smaller operators with limited access to green capital (MISC, 2024). For small and medium-sized shipowners, this cost premium is compounded by limited access to concessional financing and uncertainty regarding regulatory timelines, infrastructure readiness, and safety protocols (Hellenic Shipping News, 2023).

Industry stakeholders, including shipowners in Malaysia, have raised concerns about the potential risk of stranded assets if transitional fuels such as LNG or fossil methanol are phased out without adequate policy clarity, retrofit incentives, or infrastructure support. This risk is particularly relevant for shipowners that have already made investments based on existing fuel transition trajectories (IEA, 2021; ICCT, 2023).

By contrast, biofuels are generally perceived as a more practical short- to medium-term option, given their compatibility with existing

vessel engines and fuelling systems. However, shipowners have also cautioned that price volatility and unclear sustainability certification practices may undermine the viability of biofuels in the absence of policy safeguards and traceability systems.

Port Operator Perspective: Infrastructure and Grid Dependency

Malaysian port operators particularly those managing high-volume terminals such as Westports have acknowledged the near-term potential of shore power (cold ironing) to reduce port-side air pollution and facilitate compliance with international environmental regulations. Nevertheless, several operational and infrastructural challenges remain. Most notably, Malaysia's national grid currently has an estimated carbon intensity of approximately 0.5 kg CO₂/kWh, which constrains the net greenhouse gas (GHG) reduction benefits of shore power unless accompanied by parallel efforts in grid decarbonisation (Westports, 2023). Additionally, the lack of standardised shore connection systems and interoperability across port terminals introduces logistical complexity and cost inefficiencies, thereby inhibiting scalable deployment of cold ironing infrastructure (ICCT, 2023).

Port operators have also voiced concerns regarding exposure to future carbon pricing regimes. For example, under port-state-aligned carbon pricing policies (such as in Singapore), the estimated carbon liability for a single terminal operator such as Westports could exceed RM 17.9 million annually (Westports, 2023). These financial risks further complicate the business case for rapid electrification or alternative fuel adoption at the port level.

Regulatory Institutions: Data Limitations and Institutional Gaps

Regulatory authorities particularly the Marine Department of Malaysia have taken active steps to implement IMO decarbonisation measures such as the CII and the EEXI, in line with the IMO's initial GHG Strategy. While lifecycle-based

(Well-to-Wake) evaluation frameworks are not yet formally embedded in national regulation, their relevance is increasingly recognised in ongoing maritime policy dialogues. However, a recurring challenge is the absence of Malaysia-specific lifecycle inventory (LCI) data for marine fuels. Current emission factors employed in most analyses are derived from global databases such as GREET, Ecoinvent, and the International Energy Agency (IEA), which are based on assumptions and input-output conditions that may not reflect Malaysia's specific energy mix, feedstock availability, or fuel logistics (Gorman *et al.*, 2019; IEA, 2021).

To advance lifecycle-based fuel evaluation frameworks, cross-institutional collaboration among key national actors such as multinational oil and gas company Petronas (upstream fuel data), Tenaga Nasional Berhad (TNB) (electricity grid emissions), and major port authorities (bunkering and vessel activity data) will be essential. Although not yet formalised, the adoption of regulatory sandboxes and pilot projects has been identified in international literature as a pragmatic approach to support the phased implementation of WTW-based fuel standards within complex, multi-actor maritime systems (IEA, 2021; ICCT, 2023).

Strategic Implications

Collectively, these stakeholder perspectives highlight the necessity of a phased, context-sensitive decarbonisation strategy. There is broad consensus among industry and regulatory actors on the following trajectory:

- (a) In the short term, the use of sustainable biofuels and shore power should be accelerated where supporting infrastructure exists and where grid emissions intensity is relatively low.
- (b) In the medium term, efforts should focus on enabling conditions for green ammonia and hydrogen through pilot projects, public-private partnerships, and capacity-building.
- (c) In the long term, Malaysia should institutionalise Well-to-Wake (WTW)

metrics into national fuel standards, procurement practices, and port investment frameworks.

A uniform or technology-neutral approach may not be appropriate in the Malaysian context. Instead, tailoring fuel transition strategies to reflect stakeholder readiness, port infrastructure maturity, and evolving national energy trajectories is essential for ensuring a just, efficient, and strategically aligned maritime decarbonisation process.

Conclusions

This study provides a comprehensive assessment of alternative marine fuels for Malaysia's maritime sector by disaggregating WTT and TTW emissions. Through this approach, the analysis exposes critical differences in lifecycle greenhouse gas (GHG) performance across fuel types, offering evidence-based insights to guide national fuel strategy and policy design.

The results underscore that fuels such as green ammonia, green hydrogen, and shore power hold the greatest potential for long-term decarbonisation, given their near-zero TTW emissions and significant WTW reductions provided they are produced using clean electricity. However, the scalability of these zero-emission fuels hinges on upstream energy transformation, robust safety protocols, and supportive infrastructure. In the short- to medium-term, biofuels and shore power offer pragmatic bridge solutions, particularly for legacy fleets and port operations, though they require strict sustainability governance and accelerated port electrification. Conversely, the continued reliance on TTW-intensive fuels such as LNG and fossil-based methanol presents a risk of infrastructure lock-in and insufficient emissions reduction, reinforcing the need for a clear phase-out timeline and redirecting investment toward scalable, zero-emission fuels.

From a policy perspective, the study advances a fuel selection framework that aligns emission dominance profiles with strategic deployment horizons. This framework highlights the need for phased, context-specific adoption,

prioritising biofuels and shore power in the near term while preparing for the infrastructure and regulatory demands of ammonia and hydrogen. It also stresses the importance of embedding lifecycle-based (WTW) metrics into procurement criteria, certification schemes, and maritime policy instruments, ensuring that fuel choices reflect true climate impact rather than superficial compliance.

For Malaysia, realising a zero-carbon maritime future will require coordinated action across transport, energy, and environmental domains. This includes aligning port development with renewable energy expansion, supporting innovation through targeted R&D and pilot projects, and adopting flexible policies that adapt to evolving fuel markets and technologies. As global and regional climate regulations continue to evolve, the insights from this study offer a critical foundation for Malaysia's maritime sector to navigate a just and effective energy transition.

Limitations of Study

While this study provides a robust comparative analysis of alternative marine fuels based on WTT and TTW emissions, several limitations should be acknowledged particularly concerning data reliability and representativeness. The emission factors and lifecycle inventory data used are primarily drawn from globally recognised databases such as GREET (developed by Argonne National Laboratory), IEA (International Energy Agency), and Ecoinvent. These sources are widely regarded for their methodological rigour, transparency, and comprehensive coverage. However, each comes with contextual limitations.

For instance, greenhouse gases, regulated emissions, and energy use in technologies (GREET) reflects fuel pathways and grid mixes calibrated largely for the United States and Organisation for Economic Co-operation and Development (OECD) markets, which may not align with Malaysia's energy infrastructure or fuel sourcing practices. The IEA's emission factors are often global or regional averages and

may not account for country-specific deviations in fuel mix or industrial processes. Ecoinvent, while extensive, aggregates data at a European or global level and lacks granularity for Southeast Asian economies.

Due to these limitations, the use of such global datasets can result in generalised or non-representative estimates when applied in a Malaysian context, especially in areas such as upstream fuel processing, transportation logistics, and electricity grid carbon intensity. Unfortunately, local primary life cycle assessment data for Malaysia is currently unavailable or not publicly accessible. There is limited transparency in sectoral emissions reporting by national oil and gas producers (Petronas), energy utilities (TNB), and port operators, and no centralised LCA database exists for Malaysian fuels or maritime operations. In addition, barriers such as data confidentiality, lack of standardised reporting protocols, and fragmented institutional coordination have hindered access to real-time or disaggregated Malaysian lifecycle data. As such, this study had to rely on globally available proxies, which while methodologically sound, may introduce inaccuracies in reflecting Malaysia-specific emission intensities and supply chain characteristics

Second, the analysis is based on static assumptions; it offers a snapshot of emissions that does not reflect potential temporal changes in fuel technologies, progress in grid decarbonization, or evolving regulatory frameworks; all of which can significantly influence lifecycle emissions over time.

Third, the study emphasises environmental performance without addressing economic and cost considerations, such as capital investment, operational expenditure, or payback periods, which are vital for informed investment and policy decisions. Fourth, operational diversity is not explored in depth such as variations in ship type, route profiles, and engine technologies are not disaggregated, yet these factors could significantly affect the emissions performance and suitability of each fuel option. Lastly,

the study excludes social impacts, such as workforce training needs, the port labour transition, and stakeholder acceptance which are critical elements for ensuring a just and inclusive transition toward alternative marine fuels.

Recommendation for Future Research

Future research should prioritise the development of local emission factors tailored to Malaysia's context. This includes generating Malaysia-specific lifecycle data for marine fuels, particularly addressing upstream emissions linked to the national energy mix, infrastructure conditions, and feedstock availability. Additionally, a techno-economic assessment should be integrated into future studies, encompassing cost modelling, investment risk evaluation, and sensitivity analysis to identify fuel transition pathways that are not only environmentally sound but also economically viable under varying policy and market conditions.

Moreover, route- and vessel-specific analysis is essential. Future research should examine emissions performance and fuel suitability across different vessel types such as container ships, bulk carriers, and ferries as well as voyage profiles, distinguishing between short-sea and deep-sea operations to support more targeted decarbonisation strategies. The application of dynamic scenario modelling using system dynamics or forecasting tools is also recommended to account for technological progress, evolving energy grid characteristics, and changing regulatory landscapes, thereby providing deeper insight into the optimal timing and sequencing of fuel transitions.

In terms of practical application, policy design trials and stakeholder engagement should be a focus. This includes the development of local emission factors and Malaysia-specific lifecycle assessment datasets for marine fuels which entails establishing robust data collection pathways in collaboration with key national stakeholders such as Petronas (for upstream fuel production and refining data), TNB (for electricity generation profiles and grid carbon

intensity), and Malaysian port authorities (for port-level infrastructure, fuel handling, and bunkering emissions). Such partnerships would enable more accurate modelling of upstream and infrastructure-related emissions under local conditions, enhancing the precision and relevance of LCA outputs.

Lastly, future research would benefit from an integrated sustainability assessment that incorporates environmental, economic, and social dimensions such as employment effects, equity implications, and occupational safety to ensure a just and inclusive transition for Malaysia's maritime sector.

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Conflict of Interest Statement

The authors declare that there are no conflicts of interest related to the publication of this article.

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