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Comparative Well-to-Wake Life Cycle Assessment of Alternative Marine Fuels for Decarbonization in Maritime Transport Across Vessel Archetypes

Kadir Aydın[1*]
[1]Department of Mechanical Engineering, OSTİM Technical University, 06374 Ankara, Türkiye

Abstract: Marine fuel selection delivers a genuine climate benefit only when assessed on a well-to-wake (WtW) life-cycle basis. This study reports a comparative WtW life cycle assessment (LCA) of alternative marine fuels, conducted under ISO 14040/14044 and the IMO MEPC.391(81) guidelines within the INNSEA R&D project, and extended with techno-economic modelling and a beyond-greenhouse-gas (GHG) impact analysis. Up to nine fuel pathways were evaluated across eight vessel archetypes using a Python-based LCA engine, a weighted multi-criteria decision matrix, a 15-year total-cost-of-ownership and marginal-abatement-cost framework, and a 10,000-run Monte-Carlo sensitivity analysis. Relative to a heavy-fuel-oil/marine-gas-oil baseline of about 91 gCO_2e/MJ, the project's preliminary computation indicates WtW reductions of 16% for fossil LNG, 73% for bio-LNG, and 88–94% for e-methanol, green ammonia and green hydrogen, consistent with the literature. Fossil LNG can equal or exceed the fossil baseline at the 6.4% real-world 4-stroke methane-slip level. With selective catalytic reduction, two-stroke ammonia engines reportedly suppress N_2O to near zero. The combined EU Emissions Trading System and FuelEU Maritime cost is the dominant economic driver for EU-trading vessels. No single fuel is optimal across all ship types; the choice differs by vessel size, route and delivery date. The analysis is preliminary and literature anchored.

Keywords: Alternative Marine Fuels, Life Cycle Assessment, Well-To-Wake, Shipping Decarbonization, Methanol, Ammonia; Methane Slip, FuelEU Maritime, EU ETS, Multi-Criteria Decision Analysis.

Research Paper

***Corresponding Author:**
Kadir Aydın
Department of Mechanical Engineering, OSTİM Technical University, 06374 Ankara, Türkiye

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1. INTRODUCTION

International shipping emitted roughly one billion tons of CO_2-equivalent in 2020, about 2.8–3.0% of global anthropogenic GHG emissions, while carrying close to 90% of world trade by volume [1]. The revised IMO GHG Strategy adopted at MEPC 80 in July 2023 targets at least a 20% reduction (striving for 30%) by 2030, at least 70% (striving for 80%) by 2040, and net-zero emissions by around 2050, relative to 2008, and requires that at least 5% (striving for 10%) of the energy used by international shipping originate from zero or near-zero GHG fuels by 2030 [2].

The European Union has introduced binding economic measures ahead of global action. The extension of the EU Emissions Trading System (ETS) to maritime transport phases in allowance surrender from 40% of verified emissions in 2024 to 70% in 2025 and 100% from 2026, when CH_4 and N_2O are also included; the threshold falls from 5000 GT to 400 GT in 2027 [3]. FuelEU Maritime, in force since 1 January 2025, mandates a progressive reduction of the WtW GHG intensity of energy used on board relative to a 2020 reference of 91.16 gCO_2eq/MJ, 2% in 2025, 6% in 2030, 14.5% in 2035, 31% in 2040 and 80% in 2050 [4]. Operational efficiency instruments (EEDI, EEXI and the CII rating scheme) tighten the technical envelope further [5, 6].

At the global level, the IMO Net-Zero Framework (NZF), a goal-based marine fuel standard with a two-tier GHG fuel-intensity mechanism referenced to a 2008 baseline of 93.3 gCO_2eq/MJ, was approved in principle at MEPC 83 in April 2025, deferred at the extraordinary session MEPC ES.2 in October 2025 by a 57–49–21 vote, and broadly re-supported at MEPC 84 in spring 2026; a second extraordinary session (MEPC ES.3) was rescheduled to December 2026, with the earliest entry into force in 2028 under the MARPOL tacit-acceptance procedure [7]. The 2026 regime is therefore effectively two-track: a binding

EU package already applied to ships, and a delayed but advancing global IMO instrument.

Because a large share of a fuel's emissions can occur upstream, fuel selection must be assessed on a WtW basis (the sum of well-to-tank (WtT) and tank-to-wake (TtW) contributions) rather than on combustion accounting alone. The IMO codified a harmonized WtW methodology in Resolution MEPC.391(81) [8]. Reflecting the resulting pressure, the alternative-fueled fleet and orderbook have expanded rapidly, with 275 alternative-fueled newbuild orders recorded in 2025 (47% below the 2024 record of 515), LNG and methanol dominant [9], the green-shipping technology market is projected to grow at a high compound annual rate [10], and longer-term scenarios anticipate ammonia and bioenergy becoming dominant marine fuels by 2050 [11].

This paper synthesizes the state-of-the-art review and the comparative WtW LCA of the INNSEA R&D project "Development of Alternative Measures to Reduce CO_2 Emissions from Ships", a 24-month project hosted at the West Mediterranean Technology Development Zone (Antalya Teknokent) in academic partnership with OSTİM Technical University. Relative to the project's earlier output, the present study adds detailed techno-economic modelling (15-year total cost of ownership, marginal abatement cost, EU allowance forward curves and fuel-switch breakeven thresholds) and a beyond-GHG environmental comparison (NOx, SOx, particulate matter and water footprint). The objective is to quantify and compare the WtW performance of the candidate pathways across representative vessel archetypes, to embed the results in transparent multi-criteria and techno-economic frameworks, and to derive ship-specific and Türkiye-specific recommendations.

2. METHODOLOGY

2.1. Goal, Functional Unit and System Boundary

The study is a comparative attributional LCA of up to nine marine fuel pathways evaluated for vessels operating predominantly in EU and Mediterranean waters. The primary functional unit is 1 MJ of fuel energy delivered to the engine (gCO_2eq/MJ); a secondary functional unit of one ton-nautical-mile of cargo transported is used in the vessel case studies. The system boundary is WtW per MEPC.391(81) §3.1–3.5 and the attributional conventions of ISO 14044 [8,12]. Co-products are allocated by energy content; biogenic CO_2 is reported as a memo item under IPCC AFOLU rules; and the upstream land, additional-carbon and carbon-capture terms are set to zero pending further IMO guidance, consistent with the initial MEPC.391(81) defaults [8]. (Figure 1).

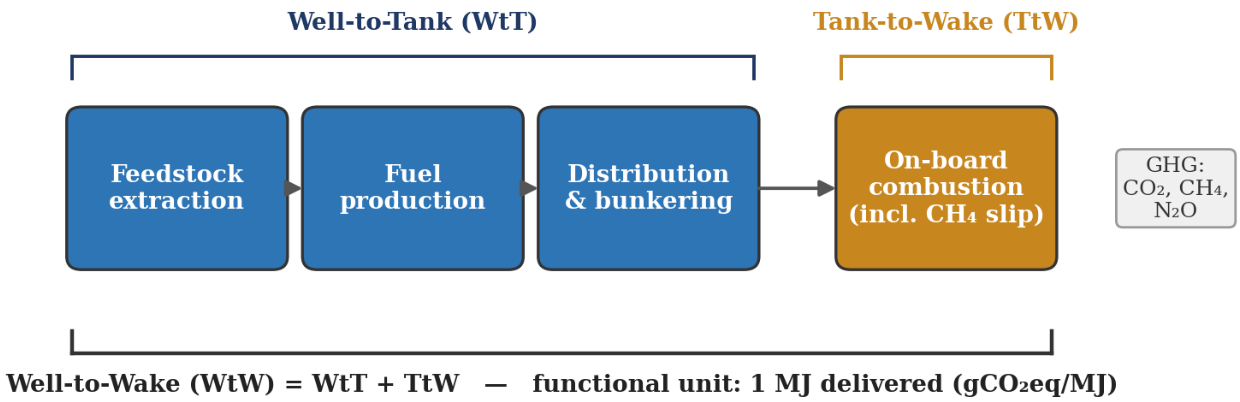

Figure 1: System boundary of the well-to-wake (WtW) life cycle assessment, comprising the well-to-tank (WtT) upstream stages and the tank-to-wake (TtW) on-board stage; the functional unit is 1 MJ of fuel energy delivered to the engine.

2.2. Impact Assessment

GHG impacts (CO_2, CH_4, N_2O) are characterized with IPCC AR5 global warming potentials over 100 years (GWP100: CO_2 = 1, CH_4 = 28, N_2O = 265) as prescribed in MEPC.391(81) §2.4; a 20-year horizon (CH_4 = 84) is computed informatively to test methane sensitivity [8]. Because MEPC.391(81) excludes SOx, NMVOC, particulate matter and black carbon, a beyond-GHG comparison of NOx, SOx, acidification, eutrophication, photochemical ozone formation, human toxicity, ecotoxicity and water footprint was added using ReCiPe 2016 and ILCD characterization, drawing on published marine-fuel environmental assessments [13,14].

2.3. Inventory Data and Computation

Upstream electricity, heat and material flows are drawn from ecoinvent v3.10 (cut-off allocation), the GREET 2024 marine fuels module and Sphera/GaBi Professional 2024; steam-methane reforming, Haber-Bosch and methanol-synthesis processes were modelled in Aspen HYSYS v14. Where MEPC.391(81) Appendix 2 provides populated defaults these take precedence; for the many pathways that remain unpopulated, peer-reviewed and classification-society values are used as primary anchors, principally the comparative WtW study of Zamboni *et al*., [15], with corroboration from Lindstad *et al*., [16], the EMSA ammonia study [17], and DNV's Maritime Forecast to 2050 [18]. A Python-based LCA engine computes WtW intensities and vessel-level scenarios. It must be emphasized that MEPC.391(81) Appendix 2 is largely unpopulated, only the fossil-liquid combustion factors, the LNG methane-slip table and a few WtT defaults are fixed, so the reported values are preliminary and literature-anchored, to be revised once the GESAMP-LCA Working Group defaults are adopted [8].

2.4. Vessel Archetypes

Eight vessel archetypes representative of the project's target market were modelled: three core cases (A–C) developed in detail and five extended cases (D–H). Their principal characteristics and assumptions are summarized in Table 1.

Table 1: Vessel archetypes and modelling assumptions

Case	Type / size	Main engine; SFOC; load factor; hours; distance	Baseline annual CO_2 (HFO)
A	General cargo, 12,000 DWT (rotor-sail compatible)	4.5 MW; 175 g/kWh; 60%; 3,500 h; 6,000 nm	5,140 t
B	Container, 4,000 TEU	25 MW; 170 g/kWh; 65%; 6,500 h; 80,000 nm	55,200 t
C	Crude tanker, 110,000 DWT	17 MW; 165 g/kWh; 55%; 5,500 h; 60,000 nm	26,800 t
D	RoPax/RoRo, 1,500 lane-m (intra-Europe)	Extended case	—
E	Cruise, 50,000 GT (Mediterranean)	Extended case	—
F	Offshore supply vessel (PSV) / wind-farm support	Extended case	—
G	Fishing trawler, ~300 GT	Extended case	—
H	Handysize bulk carrier, 35,000 DWT	Extended case	—

Cases A–C are modelled in detail; cases D–H are extended-edition archetypes. Source: INNSEA project LCA model (preliminary).

2.5. Techno-Economic and Multi-Criteria Frameworks

The economic analysis combines a 15-year total-cost-of-ownership (TCO) model (CAPEX premium, OPEX, fuel cost, carbon cost, 6–10% discount rate, residual value), marginal-abatement-cost (MAC) curves, EU allowance (EUA) forward scenarios and fuel-switch breakeven thresholds [19,18]. To integrate dimensions a single GHG metric cannot capture, the pathways were scored 1 (poor) to 10 (excellent) against seven weighted criteria, which are WtW GHG reduction (25%), technical maturity (15%), 15-year TCO feasibility (15%), infrastructure readiness (15%), safety profile (10%), regulatory acceptance (10%) and scalability (10%). A 10,000-run Monte-Carlo simulation with Spearman rank correlation was used for global sensitivity.

3. RESULTS

3.1. Comparative WtW GHG Intensity

Table 2 reports the comparative WtW GHG intensity. The literature ranges follow the project review after Zamboni *et al*., [15], and the project central estimates are the point values computed by the Python LCA engine, with the reduction relative to the HFO/MGO reference and the model uncertainty band.

Table 2: Comparative WtW GHG intensity, reduction, model uncertainty, and technology readiness level (TRL)

Fuel pathway	Literature WtW (gCO_2e/MJ)	Project estimate (gCO_2e/MJ)	Reduction (%)	Uncertainty	TRL
HFO/MGO (reference)	88–94	91.2	—	±3%	9
Fossil LNG	72–85	76.5	16.1	±8%	9
Bio-LNG	18–30	24.3	73.4	±15%	8–9
Bio-methanol	15–30	—	66–83	—	8
E-methanol	8–12	10.5	88.5	±20%	7–8
Green ammonia	5–15	8.2	91.0	±25%	5–6
Green hydrogen	0–12	5.1	94.4	±30%	5–6

Literature ranges after Zamboni et al., [15]; project central estimates, reductions and uncertainty bands are preliminary INNSEA LCA outputs.

Green hydrogen, green ammonia and e-methanol form the deep-decarbonization tier (88.5–94.4% reduction) at the lowest technology readiness (TRL 5–6 for hydrogen and ammonia) and the widest uncertainty (±25–±30%); bio-LNG and bio-methanol form an intermediate tier (66–83%); and fossil LNG delivers only 16.1%, with a strong dependence on methane slip discussed below (Figure 2).

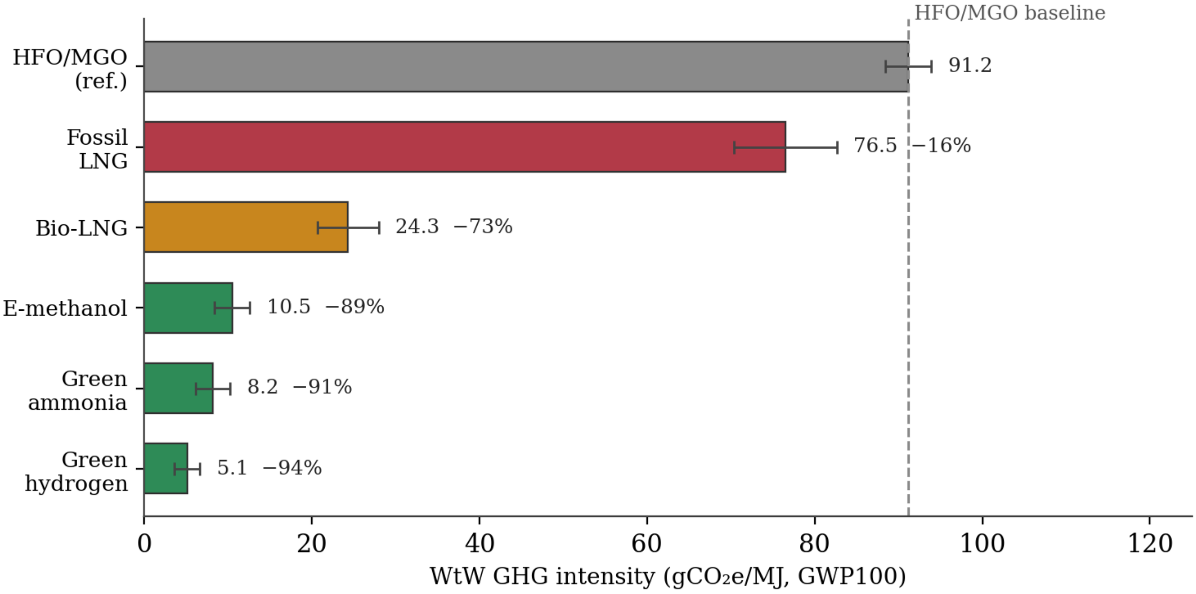

Figure 2: WtW GHG intensity of the principal fuel pathways (project central estimates; error bars show the model uncertainty band), with the percentage reduction relative to the HFO/MGO baseline of 91.2 gCO_2e/MJ (dashed line)

3.2. Beyond-GHG Environmental Comparison

Table 3 summarizes the fuel-specific NOx and well-to-hull SOx performance. Methanol and ammonia eliminate fuel-borne SOx, and lean-burn LNG and after-treated ammonia reach IMO NOx Tier III, whereas the GHG-optimal fuels can introduce other trade-offs (e.g., ammonia toxicity and the water footprint of hydrogen production) [20, 14].

Table 3: Fuel-specific NOx (engine-out) and well-to-hull SOx, relative to HFO

Fuel / engine	NOx (g/kWh)	NOx tier	WtH SOx (g/MJ)	SOx vs HFO
HFO, 2-stroke (real-world)	12–14	Tier II	1.35	baseline
VLSFO (0.5% S)	—	—	0.26	−81%
MGO/ULSFO (0.1% S)	—	—	0.06	−95%
LNG Otto LPDF 4-stroke	≤3.4	Tier III (lean burn)	~0	−99%+
LNG HPDF 2-stroke	~Tier II raw	Tier III with EGR/SCR	~0	−99%+
Methanol dual fuel	~30% < HFO	Tier II raw; III with SCR	0	−100%
Ammonia 2-stroke + SCR	NOx (g/kWh) = "raw 40–50% < diesel"	NOx tier = "Tier III"	0	−100%
Hydrogen SI ICE	8–12	SCR + ASC required	0	−100%

WtH SOx after U.S. MARAD/Argonne marine LCA; NOx tiers per IMO MARPOL Annex VI Reg. 13. Source: project compilation.

3.3. Vessel-Level Case Studies

For Case A the HFO baseline emits about 5,140 t CO_2/yr; a Lloyd's Register-validated 8.2% rotor-sail wind-assist credit lowers this to roughly 4,625 t/yr [21, 22], while a dual-fuel bio-methanol configuration reduces net CO_2 to a biogenic memo value at about 2.3× the MGO tank volume. For Case B the HFO baseline of about 55,200 t CO_2/yr falls to roughly 43,500 t/yr with a 2-stroke high-pressure dual-fuel (HPDF) LNG engine, but a 4-stroke LNG engine at the real-world methane-slip level rises to about 58,000 t CO_2e/yr — above the fossil baseline [23]. For Case C a green-ammonia two-stroke newbuild reduces annual CO_2 from about 26,800 t to roughly 4,800 t at a capital-cost premium of 20–30 M€ per vessel. The extended cases (D–H) confirm that the practical ranking is archetype-specific: short-sea RoPax and harbor craft favor battery-hybrid and shore power, while deep-sea bulk and tanker tonnage favor ammonia or methanol newbuilds.

3.4. Multi-Criteria Decision Matrix

Table 4 presents the weighted matrix. On a static snapshot the incumbent option scores highest, but this ranking inverts once a rising carbon-price trajectory is integrated over a 15-year horizon (Section 3.5).

Table 4: Weighted multi-criteria decision matrix (1 = poor to 10 = excellent; weights in parentheses). MeOH = methanol; NH_3 = ammonia; H_2 = hydrogen; HPDF = high-pressure dual fuel.

Criterion (weight)	HFO/ MGO	LNG HPDF	Bio-LNG	Grey MeOH	Bio-MeOH	Green MeOH	Grey NH_3	Green NH_3	Green H_2
WtW GHG reduction (25%)	1	3	7	1	7	9	1	9	9
Technical maturity (15%)	10	9	8	9	7	6	8	5	4
Economic feasibility (15%)	9	7	5	7	4	3	6	4	2
Infrastructure readiness (15%)	10	8	5	6	4	3	3	2	1
Safety profile (10%)	8	7	7	6	6	6	3	3	4
Regulatory acceptance (10%)	5	6	7	6	8	9	5	8	8
Scalability (10%)	10	7	5	8	6	7	8	7	6
Weighted total	**6.95**	**6.60**	**6.45**	**5.95**	**5.95**	**6.30**	**4.95**	**5.85**	**5.05**

3.5. Techno-Economic Results

Table 5 lists indicative CAPEX premiums and fuel-switch breakeven carbon prices. Methanol dual-fuel carries the lowest premium (USD 8–12 M) and ammonia the highest among combustion routes (USD 20–30 M), while hydrogen fuel cells remain economically distant [24, 18].

Table 5: Indicative CAPEX premiums and fuel-switch breakeven carbon prices

Option	CAPEX premium	Fuel-switch breakeven (15-yr NPV)
LNG retrofit/newbuild	USD 15–25 M	EUA €55–70/t vs HFO (Case B), bio-LNG mass-balance
Methanol dual fuel newbuild	USD 8–12 M	Bio-MeOH B30 vs VLSFO at EUA > €85/t
Ammonia dual fuel newbuild	USD 20–30 M	Green NH_3 vs HFO at EUA > €200/t or NZF Tier 2
H_2 PEM fuel cell (integrated)	USD 40–60+ M	Not competitive at current costs
Battery hybrid	USD 1.5–3 M/MWh	3–7 yr (port-proximate routes)
Rotor sail (2 × 24 m)	USD 1.5–3 M	4–6 yr (long voyages)

Synthesis of DNV/ABS/LR 2024–2026 CAPEX data and project breakeven analysis (15,000–110,000 DWT reference).

The carbon-price stack increasingly governs operational decisions. The April 2026 EUA spot averaged about €72/tCO_2e, peaking at €75.51 on 16 April 2026, within a 2025–2026 trading range of €60–95; combined with the FuelEU penalty of €2,400/t VLSFOe (≈€640/tCO_2eq), a vessel calling at EU ports faces an annual carbon liability of the order of €1–5 million by the end of 2026 [4, 25]. Figure 3 gives the EUA price scenarios used in the 15-year analysis.

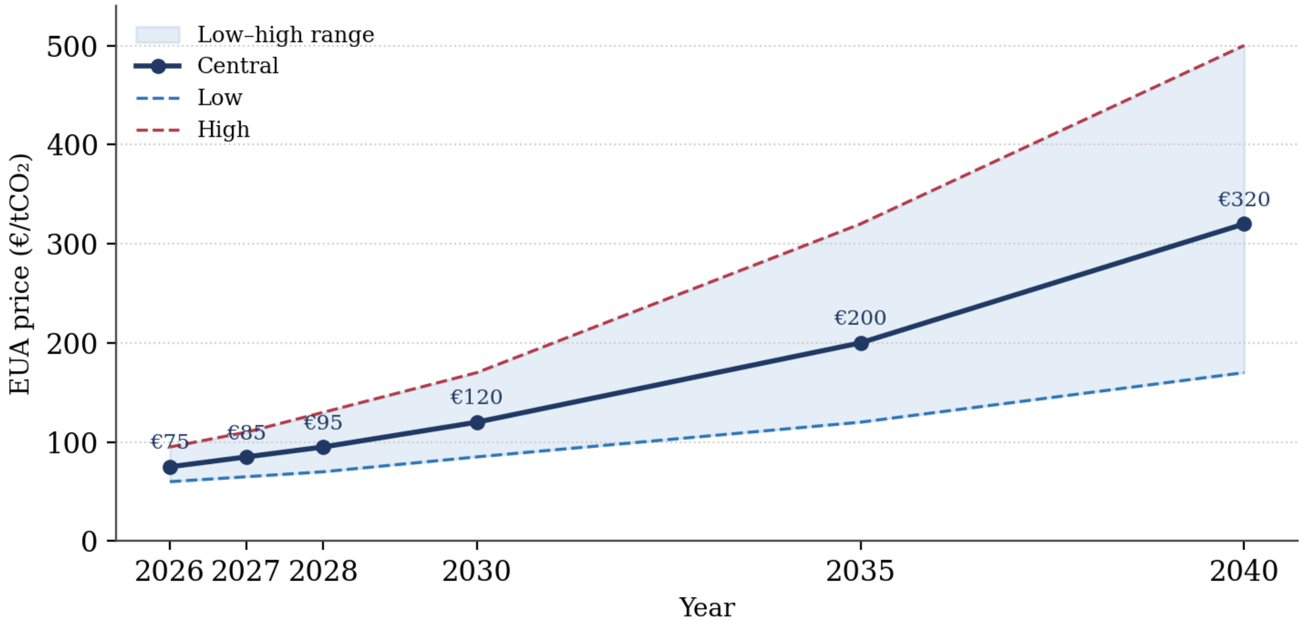

Figure 3: EU allowance (EUA) price projection scenarios used in the 15-year techno-economic analysis (low, central and high), anchored on the 2026 spot environment and an industry-consensus escalation of about 7% per year

Under the central trajectory, MAC analysis indicates that the IMO 2030 target is reachable at 50–100 USD/tCO_2, whereas the 70–80% reductions implied for 2040 require e-fuels at 200–400 USD/tCO_2 [19], consistently, DNV reports that only about 4% of the announced low-GHG fuel project pipeline has reached final investment decision and about 1% is operational [18], and the IEA places low-emission hydrogen output at about 1 Mtpa in 2025 against an announced 2030 pipeline of about 37 Mtpa [26].

3.6. Global Sensitivity

Table 6 ranks the uncertain inputs by Spearman correlation with the WtW outcome. The electricity grid carbon intensity for e-fuels dominates, followed by LNG methane slip and the N_2O factor for ammonia.

Table 6: Global sensitivity of the WtW outcome (Monte-Carlo, 10,000 runs)

Uncertain input	Spearman ρ	Key finding
Grid CO_2 intensity (e-fuels)	0.85	E-methanol WtW ≈ 10 gCO_2e/MJ at 50 gCO_2/kWh but ≈ 220 gCO_2e/MJ at 400 gCO_2/kWh; certified additional renewable supply is essential.
LNG methane slip	0.70	Replacing the 3.5% IMO default with the 6.4% FUMES value pushes 4-stroke LNG WtW from ≈ 95 to ≈ 119 gCO_2e/MJ; the 2-stroke HPDF default (0.15%) is robust.
N_2O factor for ammonia	0.55	At the upper bound (≈ 0.0005 g/g) ammonia adds ≈ 70 gCO_2e/MJ unless SCR is specified; recent engine data indicate near-zero N_2O with SCR.
Biomass feedstock / ILUC	0.45	Forestry residue 5–15 vs 60–120 gCO_2e/MJ for high-ILUC crops; only ISCC-EU/RED III Annex IX-A feedstocks should be procured.
EUA price	0.40	A €60–120/t range drives an annual cost swing of order ±€0.8 M for a typical container ship.

4. DISCUSSION

4.1. A Two-Track Regulatory Regime and an Engine-Readiness Inflection

As of mid-2026 the regulatory landscape is split between the binding EU package and the delayed IMO NZF [7]. Engine readiness, by contrast, reached an inflection at the 2025/2026 boundary: the WinGD X-DF-A two-stroke ammonia engine passed type-approval testing in January 2026 and entered first commercial service on an LPG/ammonia carrier in early 2026, and the MAN/Everllence ME-LGIA was scheduled for first shipyard delivery in Q1 2026 for a very-large ammonia carrier [27, 28]. Methanol two-stroke engines, in service for years and exceeding 600,000 running hours, are available even at ultra-large container-ship scale [29, 30].

4.2. Fossil LNG and Methane Slip

The decisive qualification of the LNG pathway is methane slip. The FUMES campaign measured an average real-world slip of 6.4% on the most common low-pressure dual-fuel 4-stroke engine, well above the 3.1–3.5% regulatory assumptions; at that level, with CH_4 at GWP100 = 28, 4-stroke LNG can equal or exceed HFO on a WtW basis, while only the 2-stroke HPDF class (0.15% default) preserves a 15–20% reduction [23].

Fossil LNG is therefore defensible only with the HPDF class and only as a transitional bridge, whereas bio-LNG can reach up to about 80% reduction using existing infrastructure [31, 15].

4.3. Resolution of the Ammonia N_2O Concern

Earlier analyses flagged N_2O — with GWP100 = 265 — as a potential erosion of the ammonia benefit [32]. Recent in-service data revise this: two-stroke ammonia engines report 40–50% lower engine-out NOx than fuel-oil mode (IMO Tier II), and with selective catalytic reduction both leading two-stroke designs achieve Tier III with engine-out N_2O at or below a few ppm and effectively zero N_2O across the catalyst [33, 20]. Provided SCR is specified contractually, the green-ammonia WtW benefit of 70–86% is preserved.

4.4. Techno-Economics and the Carbon-Price Stack

For EU-trading vessels the combined EU ETS and FuelEU burden, rather than upstream fuel economics alone, drives the business case [3, 34]. Under the central EUA trajectory and a ratcheting FuelEU target, green methanol and green ammonia become NPV-positive against the incumbent within the asset's economic life, which inverts the static multi-criteria ranking. Subsidy mechanisms shorten the gap: the EU Hydrogen Bank has contracted renewable-hydrogen capacity through successive auctions [35], and financial-sector instruments such as the Poseidon Principles exert parallel pressure on the supply of conventional-fuel tonnage finance [36]. Bridging tonnage required before the green-fuel supply chain matures is best served by mass-balance bio-LNG or fuel-flexible designs [31].

4.5. Beyond-GHG Trade-Offs

A GHG-only lens is incomplete. Methanol and ammonia eliminate fuel-borne SOx and, with appropriate combustion or after-treatment, reach NOx Tier III, which matters as emission control areas expand — the Mediterranean SOx/PM ECA took effect in May 2025 and Canadian Arctic and Norwegian Sea ECAs in March 2026 [37,38]. Conversely, ammonia toxicity, the water footprint of electrolytic hydrogen [14], and methanol's lower volumetric energy density introduce trade-offs that a complete decision must weigh [13, 39].

4.6. Vessel-Specific Selection

No single fuel is optimal across all ship types. For the general-cargo/rotor-sail archetype, a dual-fuel methanol newbuild burning ISCC-EU bio-methanol with rotor sails offers a commercially mature (TRL 9) 65–80% reduction [40, 30]. For the medium container ship, dual-fuel methanol transitioning to e-methanol follows the proven Maersk pathway [30, 41]. For the large crude tanker, a green-ammonia two-stroke newbuild with SCR within the IMO interim ammonia safety guidelines [42], is the preferred long-term route, with HPDF LNG as the only credible bridge before the ammonia supply chain matures [28]. Early liquid-hydrogen vessels such as MF Hydra confirm hydrogen's feasibility while underscoring supply-chain immaturity [43].

4.7. Complementary Efficiency Measures

Fuel switching stacks with efficiency measures the project also assesses: wind-assisted propulsion (validated 5–25% savings) [22,40], air lubrication (5–10%) [44], organic-Rankine-cycle waste-heat recovery (5–9%) [45], AI route/speed optimization [46], and on-board carbon capture, which advanced to commercial availability with up to ~70% capture [47]. These improve the CII rating without a new fuel supply chain.

4.8. Türkiye Positioning

Türkiye is structurally positioned as a green H_2/NH_3 supplier to Europe. Its 2023 National Hydrogen Technologies Strategy targets 2 GW electrolysis by 2030, 5 GW by 2035 and 70 GW by 2053, with levelized hydrogen-cost goals of USD 2.4/kg by 2035 and USD 1.2/kg by 2053 [48,49]. Turkish shipyards already export alternative-fueled newbuilds, chiefly to North European owners, yet the domestic flag fleet remains largely conventional and bunkering infrastructure beyond LNG is limited; e-fuels produced from grid-mix electricity will not qualify under FuelEU without dedicated renewable supply, given a grid carbon intensity in the few-hundred gCO_2/kWh range [50, 51].

4.9. Limitations

The results are preliminary and literature-anchored: MEPC.391(81) Appendix 2 is largely unpopulated, so most bio-, e- and green-fuel WtT values will change once GESAMP-LCA defaults are adopted [8]. Real-world LNG methane slips for 4-stroke engines exceed defaults roughly twofold, so LNG analyses must be stress-tested against both [23]. Fuel-price and carbon-price volatility require periodic re-pricing. Finally, this study is a research synthesis for internal decision support and is not a certifiable ISO 14044 LCA until a full primary-data inventory, a data-quality (pedigree-matrix) assessment and an independent critical-review panel are completed [12].

5. CONCLUSION

This study compared the WtW performance of up to nine alternative marine fuel pathways across eight vessel archetypes under ISO 14040/14044 and IMO MEPC.391(81), extended with techno-economic and beyond-GHG analysis. Relative to an HFO/MGO baseline of about 91 gCO_2e/MJ, green hydrogen, green ammonia and e-methanol achieve 88–94% reductions, bio-LNG and bio-methanol 66–83%, and fossil LNG only about 16%; fossil LNG is robust only with the 2-stroke HPDF engine class. With selective catalytic reduction, two-stroke ammonia engines suppress N_2O to near zero, preserving the green-ammonia benefit. The combined EU ETS and FuelEU cost is the dominant economic driver for EU-trading vessels, and over a 15-year horizon green methanol and green ammonia overtake the incumbent. No single fuel is optimal across all ship types; dual-fuel methanol for small and medium tonnage and green ammonia for large tonnage (with HPDF LNG as a bridge) emerge as the defensible near-term choices, complemented by mature efficiency measures. The next phase will complete the inventory, data-quality assessment and independent review required for a certifiable LCA and will refresh the results once the GESAMP-LCA defaults are adopted.

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Conflict of Interest: The author declares no conflict of interest.

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