ROUTE-LEVEL TECHNO-ECONOMIC ASSESSMENT OF ALTERNATIVE FUELS FOR SHORT-SEA SHIPPING UNDER EU EMISSIONS TRADING SYSTEM

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Abstract. The inclusion of maritime transport in the EU Emissions Trading System (EU ETS) has introduced carbon pricing as a direct cost factor for short-sea shipping operations. This development alters fuel competitiveness and investment incentives, particularly on regional shipping routes serving peripheral ports. This study presents a route-level techno-economic assessment comparing conventional fossil fuel with different alternative marine fuels. The analysis integrates Tank-to-Wake emissions accounting for fuel expenditure modelling, capital requirements, total cost of ownership, and carbon price sensitivity, as the EU ETS applies carbon pricing to direct onboard emissions, ensuring consistency between the emissions boundary and the regulatory cost exposure of ship operators. Results indicate that fossil fuel remains the least-cost option under current carbon prices (≤100 EUR per tCO2-eq), although its cost advantage declines rapidly as allowance prices increase. BioLNG approaches cost parity with Marine Gas Oil (MGO) at approximately 150EUR per tCO2-eq, while biodiesel and hydrotreated vegetable oil (HVO) become competitive above 200-250EUR per tCO2-eq. Green hydrogen and ammonia eliminate operational emissions but remain economically uncompetitive due to high production and retrofit costs. The findings demonstrate that near-term decarbonisation of short-sea operations is most likely to rely on bio-based and LNG-derived fuels, whereas large-scale adoption of hydrogen and ammonia requires substantial cost reductions and infrastructure expansion.

Keywords: maritime decarbonization, carbon pricing, alternative marine fuels, sustainable regional development, just transition, short-sea shipping.

1. Introduction

Maritime transport plays a central role in regional connectivity, trade, and cross-border mobility, particularly for coastal and peripheral regions. Despite its relative energy efficiency compared to other transport modes, the sector accounts for approximately 3% of global greenhouse gas (GHG) emissions, and further reductions are required to align with European climate objectives [1].

The inclusion of maritime transport in the European Union Emissions Trading System (EU ETS) in 2024 has introduced direct carbon pricing into shipping operations [2]. Vessels calling at ports within the European Economic Area (EEA) are now required to surrender emission allowances, increasing operational costs in proportion to their GHG emissions [1]. While previous studies suggest that the EU ETS can incentivise emission reductions at moderate cost, its effects are not uniform across shipping segments. Short-sea shipping is particularly exposed due to its cost sensitivity and direct competition with land-based transport [1; 3].

Alternative marine fuels are considered an important option for reducing GHG emissions from maritime transport. Previous research has examined their technical performance and environmental characteristics. Nevertheless, integrated techno-economic assessments at the level of short-sea routes remain relatively scarce, particularly under explicit carbon-pricing conditions [2; 3]. Most existing studies analyse fleet-level impacts or long-distance shipping segments, while the combined effects of fuel choice, emission performance, operating costs, and infrastructure constraints at the route level are examined less frequently.

Studies addressing the EU ETS generally focus on aggregate decarbonisation effects at the system level [4; 5]. Research on alternative marine fuels and ferry operations concentrates mainly on technological characteristics, policy frameworks, and implementation barriers [6; 7]. As a result, the economic competitiveness of alternative fuels on specific short-sea routes under explicit carbon pricing remains insufficiently quantified.

In this context, the central research question of this study is: How does the inclusion of short-sea shipping in the EU ETS affect the relative technical and economic competitiveness of conventional and alternative marine fuels at the route level under different carbon pricing scenarios?

This study extends the existing literature by moving from aggregated and technology-specific assessments to a route-level techno-economic evaluation of fuel switching under the EU ETS. The

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analysis develops an integrated framework that combines route-specific operational assumptions, Tank-to-Wake (TtW) emissions accounting and pricing, fuel cost modelling, retrofit-related capital costs, and total cost of ownership. The novelty of the study lies in identifying route-specific carbon price thresholds at which alternative fuels become economically competitive with marine fossil fuels.

2. Literature review

2.1. Maritime decarbonisation and emissions pricing

The inclusion of maritime transport in the EU ETS has introduced carbon pricing as a direct cost component in shipping operations [1; 2]. Since 2024, large vessels calling at ports within the EEA have been required to purchase and surrender emission allowances covering a defined share of their GHG emissions, thereby internalising the cost of emissions under the ETS framework. Emissions from voyages between two EEA ports and emissions generated while ships are within EEA ports are fully covered, while 50% of emissions from voyages starting or ending outside the EEA are subject to the surrender requirement. The inclusion of maritime emissions in the EU ETS has been phased in over time, with surrender obligations covering 40% of verified emissions in 2024, 70% in 2025, and a full 100% of verified emissions from 2026 onward. From 2026, the scope of the EU ETS is broadened to include methane (CH_4) and nitrous oxide (N_2O) expressed as CO_2-equivalent emissions.

Short-sea shipping in the EU is comparatively more exposed to the EU ETS than deep-sea operations because a larger proportion of its emissions occurs within the regulated geographic scope [3; 8]. Under the current regulatory framework, compliance obligations are calculated on a TtW basis, whereby only direct onboard emissions are subject to carbon pricing. Evidence based on EU Maritime Monitoring, Reporting and Verification (MRV) data indicates that carbon costs are increasingly reflected in fuel-related expenditures, particularly for margin-sensitive services [3]. While operators may attempt to transfer compliance costs through freight surcharges, the extent of cost pass-through depends on competitive conditions and demand elasticity. In highly competitive corridors, including those where maritime services compete directly with road transport, full cost recovery may be limited [3].

Carbon pricing also affects long-term investment decisions. Operational measures with relatively low abatement costs are more likely to be adopted in the short term, whereas capital-intensive technological transitions require higher and more predictable carbon price signals [3]. Given the long service life of maritime assets, uncertainty regarding future allowance prices, fuel costs, and regulatory development can delay investment in alternative propulsion systems. Consequently, the economic impact of the EU ETS extends beyond immediate fuel costs and influences strategic decisions related to fleet renewal and fuel transition pathways, particularly in short-sea and peripheral routes [1; 2].

2.2. Alternative fuels for maritime transport

Alternative marine fuels constitute a central element of maritime decarbonisation strategies, particularly in the context of tightening EU climate regulations and the extension of carbon pricing to shipping [8]. Within the European framework, fuel selection is increasingly shaped by the combined effects of the EU ETS and the FuelEU Maritime Regulation, both of which create economic incentives to reduce GHG intensity in maritime transport [9]. For short-sea shipping, where margins are typically narrower and competition with road transport is direct, fuel choice is determined not only by emission performance but also by capital requirements, operational compatibility, and infrastructure availability [10].

Bio-based fuels, often referred to as drop-in fuels, including biodiesel and hydrotreated vegetable oil (HVO), are generally considered near-term options due to their compatibility with existing marine engines and bunkering systems. Biodiesel blends can be used with limited technical modification and contribute to reductions in sulphur oxides, particulate matter, and lifecycle CO_2 emissions, although lower energy density and feedstock constraints limit scalability [11]. HVO provides improved combustion characteristics and higher stability relative to conventional biodiesel, but production costs and competition for sustainable feedstocks remain significant barriers to wider deployment [11].

Non-drop-in fuels, such as green hydrogen (H_2) and green ammonia (NH_3), are often discussed as long-term zero-carbon fuels. Their operational advantage lies in the absence of direct CO_2 emissions at the point of use. H_2 has high gravimetric energy density and produces no exhaust emissions when used in fuel cells. However, its low volumetric energy density, storage constraints, safety requirements, and limited bunkering infrastructure currently restrict its application, particularly in short-sea shipping [8]. NH_3 benefits from an established global handling infrastructure and more favourable storage properties than H_2, which supports its potential use in green shipping corridors. Nevertheless, toxicity, NO_x emissions, high production costs, and the need for specialised engines and safety systems present significant barriers, especially for ports with limited access to capital [12].

Liquefied biomethane (BioLNG) represents a transitional pathway that leverages existing LNG propulsion systems and bunkering infrastructure. Lifecycle emission reductions of up to 80% compared to fossil LNG have been reported, conditional on controlled methane leakage across the supply chain [13]. For short-sea operators, the relative maturity of LNG technology lowers retrofit risks compared to hydrogen or ammonia. However, BioLNG availability remains constrained by feedstock supply and liquefaction costs, particularly in ports with limited infrastructure [9; 11].

Fuel choice is shaped by technical, strategic, and socio-economic factors, including port characteristics, regulatory uncertainty, public support mechanisms, and regional development priorities [14]. In short-sea shipping and peripheral corridors, these constraints are more pronounced, as limited traffic volumes and restricted access to capital reduce the feasibility of large-scale infrastructure investments. Recent studies, therefore, call for integrated, route-specific assessments that consider fuel options, infrastructure requirements, operating costs, and policy incentives when evaluating decarbonisation pathways under local conditions [9].

3. Materials and methods

The study applies a route-level techno-economic assessment to a representative short-sea vessel commencing operations in 2026 under the EU ETS. The modelling framework integrates vessel and route characteristics, fuel parameters, emission accounting, and economic variables, including capital expenditures (CapEx), operational expenditures (OpEx), fuel-related expenditures and GHG allowance costs (FuelEx$^+$).

The analysis follows a deterministic, scenario-based approach and employs explicit equations together with carbon-price sensitivity analysis to compare alternative fuel pathways. To ensure transparency and reproducibility, the input data are organised into four main categories: vessel and short-sea route characteristics; fuel properties and TtW emission factors obtained from regulatory and technical sources; fuel price assumptions based on published studies and Rotterdam bunker fuel quotations; and retrofit and technology cost estimates derived from feasibility studies on ship conversion and modernisation.

3.1. Vessel and route characteristics

The reference vessel represents a medium-sized short-sea ship of approximately 25,000 gross tonnage, with a total installed power of about 20,000 kW [10]. Marine Gas Oil (MGO) is used as the baseline fuel due to its widespread use in regional shipping within Sulphur Emission Control Areas, where its low sulphur content allows compliance without exhaust gas cleaning systems.

The route follows the Sillamäe–Kotka short-sea route concept [10], with a sailing distance of approximately 172 nautical miles (NM) and one round trip per day. Operations are assumed to be fully intra-EU, with 232 sailing days per year, accounting for maintenance and weather conditions. Fuel consumption during night operations is reduced by 10%, while port stays correspond to 10% of a standard sea-day consumption profile. These assumptions are applied consistently across all fuel options to ensure comparability.

3.2. Fuel properties and TtW emissions

Table 1 compares conventional MGO with five alternative fuels: biodiesel, HVO, green H_2, green NH_3, and BioLNG. Fuel properties, including lower heating value (LHV) and relative thermal efficiency (RTE), are based on maritime and technical literature [11; 15]. Fuel price (FP) assumptions are taken from published studies and cross-checked against Rotterdam bunker quotations [11; 16].

Table 1

Main physical and market characteristics of fuels

Parameter	MGO	Biodiesel	HVO	H_2	NH_3	BioLNG
LHV, MJ·kg^{-1}	42.8	37.5	44.1	120.0	18.6	49.0
RTE	1.00	0.96	0.99	1.21	1.03	1.04
Estimated FP, EUR·t^{-1}	600	1127	1456	5000	1100	1150

Table 2 presents the TtW emission factors for CO_2, CH_4, and N_2O used to calculate CO_2-equivalent emissions (EF_f) under the EU ETS framework. Conversion to CO_2-equivalents follows 100-year global warming potentials (CH_4 = 25; N_2O = 298). Only direct onboard emissions are considered; upstream lifecycle emissions are excluded. For biodiesel and HVO, direct CO_2 emissions are set to zero, reflecting their renewable origin and compliance with RED II sustainability criteria.

Table 2

TtW emission factors of fuels

Parameter	MGO	Biodiesel	HVO	LH_2	NH_3	BioLNG
C_{fCO2}, g_{CO2} per g_f	3.206	0.000	0.000	0.000	0.000	2.750
C_{fCH4}, g_{CH4} per g_f	0.00005	0.00005	0.00005	0.000	0.000	0.000
C_{fN2O}, g_{N2O} per g_f	0.00018	0.00018	0.00018	0.000	0.000	0.00011
EF_f, tCO_2-eq·t^{-1}	**3.261**	**0.055**	**0.055**	**0.000**	**0.000**	**0.033**

Fuel consumption for each alternative fuel (C_f) is calculated on an energy-equivalent basis:

$$C_f = C_{MGO} \times \frac{LHV_{MGO}}{LHV_f} \times \frac{RTE_f}{RTE_{MGO}}, \tag{1}$$

where C_{MGO} – baseline consumption, t·NM^{-1};
LHV_i – denotes lower heating value, MJ·kg^{-1};
RTE_i – represents relative thermal efficiency.

Annual fuel demand is then determined as:

$$C_{f,annual} = C_f \times S \times d, \tag{2}$$

where C_f – fuel consumption, t·NM^{-1};
S – daily sailing distance, NM;
d – number of operating days per year.

Fuel expenditure is extended to include EU ETS compliance costs. The resulting metric ($FUELEX_f^+$) combines fuel purchase costs and emission allowance expenses:

$$FUELEX_{f,annual}^{+} = C_{f,annual} \times FP_f + C_{f,annual} \times EF_f \times P_{CO2}, \tag{3}$$

where $C_{f,annual}$ – annual fuel consumption, t;
FP_f – fuel price, EUR·t^{-1};
EF_f – TtW emission factor of the fuel, tCO_2-eq·t^{-1};
P_{CO2} – carbon allowance price (EUR per tCO_2-eq).

3.3. Economic evaluation framework

The economic assessment covers a 30-year vessel life cycle and applies cash-flow analysis to compare fuel pathways under EU ETS carbon pricing. Total Cost of Ownership (TCO) consists of annualised CapEx, OpEx, and FuelEx$^+$. To reflect regulatory and market uncertainty, carbon price scenarios from from 100 to 650 EUR per t CO_2-eq, in 50 EUR increments, are evaluated.

CapEx includes vessel acquisition and, where necessary, retrofit investments for non-drop-in fuels, such as specialised storage systems, safety equipment, and propulsion modifications. Drop-in fuels (biodiesel and HVO) are assumed not to require significant technical changes. OpEx covers recurring costs, including labour, maintenance, port charges, insurance, contracted services, and administrative expenses. The classification of CapEx and OpEx is based on established approaches in maritime techno-economic assessment and aligns with cost structures applied in recent studies on ferry route feasibility and decarbonisation [8; 11; 17].

Annual OpEx is defined as:

$$OPEX_{f,annual} = C_{labor} + C_{services} + C_{insurance} + C_{maintenance} + C_{port} + C_{admin} + C_{other} , \quad (4)$$

where C_i – cost components, which represent annual labour, contracted services, insurance, maintenance, port-related charges (incl. water charges, pilotage), administrative, and other operating costs.

The composition of OpEx is based on observed cost patterns in maritime operations and on earlier cost–benefit assessments of the Sillamäe–Kotka route [18; 19].

Annualised CapEx is calculated as:

$$CAPEX_{f,annual} = \frac{CAPEX_{f,total}}{n}, \quad (5)$$

where CAPEX$_{f,total}$ – total capital expenditure for fuel pathway f (EUR), and n is the economic lifetime of the vessel. The assumed lifetime (30 years) aligns with established practices in maritime investment appraisal and ferry route feasibility studies in the Baltic Sea region [8; 18].

Finally, annual TCO is given by:

$$TCO_{f,annual} = CAPEX_{f,annual} + FUELEX^{+}_{f,annual} + OPEX_{f,annual}. \quad (6)$$

This formulation aligns with lifecycle cost frameworks applied in recent studies on maritime decarbonisation and integrates engineering parameters, regulatory cost exposure, and lifecycle economic evaluation within a unified route-level modelling [19; 20].

4. Results and discussion

4.1. Fuel demand and emission performance

Table 3 summarises fuel demand (C_f) per nautical mile and annulised consumption, EU ETS compliance costs, and annual fuel-related operating costs (FuelEx$^+$) under an assumed carbon price of 80 EUR per tCO2-eq within the EU ETS framework, calculated according to Eqs. (1-3). Differences in fuel consumption are primarily driven by variations in LHV and energy density.

At a baseline carbon price, annual fuel-related expenditure for MGO amounts to 4.96 million EUR, with approximately 30% attributable to EU ETS compliance costs. Biodiesel and HVO substantially reduce direct emissions; however, their annual fuel expenditures exceed those of MGO by 44% and 63%, respectively. This difference is primarily associated with higher market fuel prices rather than carbon allowance payments.

Table 3

Fuel-related consumption and operating costs

Parameter	MGO	Biodiesel	HVO	H_2	NH_3	BioLNG
C_f, t·NM^{-1}	0.15	0.164	0.144	0.065	0.356	0.136
$C_{f,annual}$, t·year^{-1}	5,756	6,294	5,526	2,494	13,662	5,219
EU ETS costs, million EUR·year^{-1}	1.502	0.028	0.024	0.000	0.000	0.014
$FUELEX^{+}_{f,annual}$, million EUR·year^{-1}	4.960	7.120	8.070	12.470	15.030	6.020

BioLNG represents the closest alternative to MGO. At the baseline carbon price, it increases annual fuel-related expenditure by approximately 21% relative to MGO, while requiring comparatively moderate transition investments. Green H_2 and NH_3 produce no direct TtW emissions under the assumptions applied in this study and therefore do not incur carbon allowance costs. However, their annual fuel expenditures are approximately 150% higher for hydrogen and more than 200% higher for ammonia relative to MGO, largely because of current production costs and the limited maturity of their supply chains, consistent with recent techno-economic assessments [20].

These findings suggest that, under current market conditions, strong emission performance does not by itself ensure economic viability. Transitional options such as biofuels and BioLNG appear to involve lower adoption barriers, while hydrogen and ammonia are likely to depend on substantial cost reductions and further infrastructure development before they can become competitive in short-sea operations [6; 7]. This contrast highlights the difference between short-term feasibility and long-term decarbonisation potential. The identified route-specific threshold structure aligns with the findings of Karvounis et al. [21], which demonstrate that the competitiveness of hydrogen and ammonia is highly sensitive to assumptions regarding carbon pricing and fuel costs.

The present analysis shows at a quantitative and route-specific level that, under current EU ETS exposure, the near-term competitive advantage is more likely to arise first for BioLNG and drop-in biofuels than for hydrogen- or ammonia-based pathways.

4.2. OpEx, CapEx and total costs of ownership

Table 4 was calculated according to Eqs. (4-6) for the comparison of annual expenditures across different fuel scenarios. Annual OpEx remain broadly comparable across fuel scenarios, averaging approximately 8.6 million EUR. Fuel-specific adjustments are limited to maintenance differentials: BioLNG increases annual maintenance costs by approximately 80,000 EUR, H_2 by about 60,000 EUR, and NH_3 by roughly 100,000 EUR due to additional safety and handling requirements [17; 18; 21; 22]. These differences are modest relative to total operating costs and do not significantly alter overall cost structures.

Table 4

Operating expenditures and capital costs

Parameter	MGO	Biodiesel	HVO	H_2	NH_3	BioLNG
$OPEX_{f,annual}$, million EUR·year^{-1}	8.560	8.560	8.560	8.620	8.660	8.640
$CAPEX_{f,annual}$, million EUR·year^{-1}	0.670	0.670	0.670	1.500	1.040	0.900
$TCO_{f,annual}$, million EUR·year^{-1}	14.190	16.350	17.300	22.590	24.730	15.560

Capital requirements differ substantially between drop-in and non-drop-in fuel pathways. For conventional MGO and chemically compatible biofuels, total CapEx corresponds to vessel acquisition costs of 20 million EUR, equivalent to an annualised capital cost of approximately 0.67 million EUR over a 30-year lifetime. In contrast, fuels requiring dedicated storage and propulsion systems involve significant retrofit investments [22]. Total CapEx amounts to approximately 27 million EUR for BioLNG, 31 million EUR for NH_3, and 45 million EUR for H_2, resulting in annualised CapEx of 0.90 million EUR, 1.04 million EUR, and 1.50 million EUR, respectively. H_2 and NH_3, therefore, require substantially higher upfront investment, whereas BioLNG represents a comparatively moderate capital adjustment [22].

When CapEx, OpEx and fuel-related expenditures are aggregated over a 30-year horizon, clear differences in TCO emerge. MGO remains the least-cost option, with an annual TCO of approximately 14 million EUR. Biodiesel and HVO increase annual TCO by 15-22%. H_2 and NH_3 show substantially higher total costs. BioLNG represents the closest alternative to MGO, with an annual TCO of about 15.6 million EUR, corresponding to a cost premium of roughly 10%. These results indicate that, once CapEx is included, the relative advantage of drop-in and LNG-derived pathways over hydrogen and ammonia is greater than suggested by fuel-expenditure analysis alone.

Across all scenarios, fuel expenditures constitute the primary driver of cost variation, while higher capital intensity further constrains the economic feasibility of hydrogen and ammonia under current market conditions. Accordingly, annual TCO provides a more robust basis for comparing fuel pathways than fuel-expenditure analysis alone.

Carbon price sensitivity and break-even thresholds

To evaluate the impact of carbon pricing on fuel competitiveness, annual fuel-related expenditures ($FuelEx^+$) were modelled according to Eqs. (3) across carbon allowance prices ranging from 100 EUR to 650 EUR per tCO_2-eq. The results are presented in Fig. 1, which depicts alternative fuel competitiveness as the ratio of fuel-specific expenditures to those of MGO ($FuelEx^+_f/FuelEx^+_{MGO}$). Values above 1 indicate higher costs relative to MGO, whereas values below 1 indicate a cost advantage.

At current EU ETS levels (≤100EUR per tCO_2-eq), MGO remains the least-cost option. The figure shows distinct differences in carbon price sensitivity across fuel pathways. As the benchmark fuel, MGO exhibits a linear increase in annual fuel-related expenditures with rising carbon prices. Each 50 EUR per tCO_2-eq increment increases MGO costs by approximately 0.95 million EUR, reflecting its full exposure to emission allowance obligations. As allowance prices increase, the relative cost position of low-emission fuels improves accordingly.

H_2 and NH_3 are not directly affected by carbon price increases within the applied TtW framework, as their operational GHG emissions are zero. Their competitiveness index, therefore, declines as MGO becomes more expensive. Model results indicate that hydrogen reaches cost parity with MGO at approximately 500 EUR per tCO_2-eq, while ammonia approaches parity at around 650 EUR per tCO_2-eq. Below these levels, both fuels remain above the parity threshold (index = 1), indicating that avoided carbon payments do not compensate for their higher production costs.

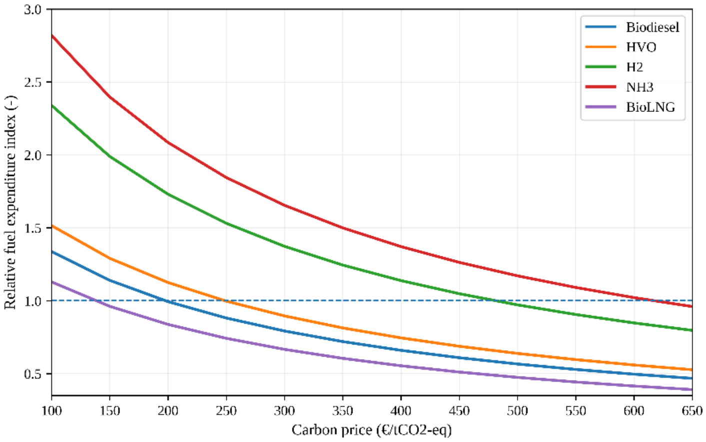

Fig. 1. **Relative fuel expenditure index of alternative fuels compared with MGO by carbon price**

Transitional and bio-based fuels exhibit moderate but economically relevant carbon price sensitivity. BioLNG reaches parity with MGO at approximately 150 EUR per tCO_2-eq. Biodiesel achieves break-even at around 200 EUR per tCO_2-eq, followed by HVO at approximately 250 EUR per tCO_2-eq. Beyond these thresholds, these fuels become less costly than MGO on a fuel-expenditure basis. Whereas prior research has focused mainly on fuel characteristics, technological maturity, or policy alignment, these estimates establish route-specific competitiveness thresholds based on explicit carbon pricing assumptions [6; 7]. They therefore translate broader findings on maritime decarbonisation into operationally meaningful indicators for fuel-switching decisions among short-sea operators.

Overall, Fig. 1 illustrates that carbon pricing significantly alters relative fuel competitiveness in short-sea shipping. However, for green hydrogen and ammonia, structural cost factors remain the primary constraint under current market conditions. These findings are consistent with previous studies highlighting the interaction between carbon pricing and fuel cost structures in maritime decarbonisation pathways [20].

From a policy perspective, the results indicate that carbon pricing alone is unlikely to stimulate large-scale adoption of hydrogen and ammonia in short-sea shipping under current market conditions. The primary barriers for these fuels remain the high production costs, the requirement for additional onboard storage, and the capital intensity of vessel retrofits. In contrast, BioLNG and drop-in biofuels respond more readily to carbon pricing, as they rely on established technologies and necessitate fewer modifications at the vessel level.

For regional operators and peripheral ports, these findings suggest that near-term decarbonisation is more likely to depend on transitional fuels and incremental infrastructure development rather than the immediate deployment of entirely new fuel systems. This pattern is particularly relevant for peripheral short-sea routes, where low traffic volumes and limited access to capital constrain the feasibility of rapid, infrastructure-intensive fuel transitions.

Conclusions

The techno-economic assessment identifies marked differences in the economic viability of alternative fuels for short-sea ferry operations. In the baseline scenario, MGO remains the most cost-competitive option, with annual fuel-related expenditures of 4.96 million EUR and an annual TCO of 14.19 million EUR. Among the alternatives considered, BioLNG performs closest to MGO, with annual fuel-related expenditures of 6.02 million EUR and an annual TCO of 15.56 million EUR. BioLNG approaches TCO parity with MGO at a carbon price of approximately 150 EUR per tCO_2-eq.

Biodiesel and HVO achieve substantial reductions in direct emissions; however, under current price conditions, both remain less economically favourable than MGO. Fuel-cost parity with MGO is estimated at around 200 EUR per tCO_2-eq for biodiesel and 250 EUR per tCO_2-eq for HVO. Hydrogen and ammonia eliminate direct TtW emissions, but in the baseline scenario, they remain economically uncompetitive, with annual TCO values of 22.59 and 24.73 million EUR, respectively. Their estimated parity thresholds are considerably higher, reaching approximately 500 EUR per tCO_2-eq for hydrogen and 650 EUR per tCO_2-eq for ammonia.

These findings suggest that, in the near term, decarbonisation in short-sea shipping under the EU ETS will depend more on bio-based and LNG-derived fuels than on hydrogen- or ammonia-based alternatives. The route-level modelling framework developed in this research provides a quantitative basis for evaluating fuel transition pathways in the context of EU ETS carbon pricing in short-sea shipping.

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Author contributions

Hrenov, G.: Conceptualisation, methodology and writing – original draft preparation; Küttim, M.: project administration and funding acquisition, writing – review and editing; Tasane, H. and Gerstlberger, W: writing – review and editing. All authors have read and agreed to the published version of the manuscript.

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