

Article

Voyage-Level Assessment of Slow Steaming and B30 Biofuel Strategies for Container Vessel Decarbonisation Under EU ETS and FuelEU Maritime

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Abstract

This study evaluates operational decarbonisation options for container vessels operating under the European Union Emissions Trading System (EU ETS) and FuelEU Maritime. This study analyses a 5000 TEU post-Panamax container vessel on the Rotterdam–Limassol route under nine operational scenarios combining three operating speeds (24, 21, and 19 kn) with three fuel configurations (HFO, MGO, and a B30 biofuel blend). The assessment included voyage-level fuel consumption, CO₂ emissions, Energy Efficiency Operational Indicator (EEOI), Tank-to-Wake (TTW) greenhouse-gas intensity, fuel cost, EU ETS exposure, Pareto trade-off analysis, and Monte Carlo uncertainty evaluation. Pareto analysis reduced the nine evaluated scenarios to three representative low-speed operating configurations corresponding to minimum cost (HFO, 19 kn), intermediate emissions reduction (MGO, 19 kn), and minimum emissions (B30, 19 kn). Among these configurations, the B30 case produced the lowest TTW GHG-intensity and EEOI values, whereas the HFO case remained the least-cost option under current market conditions. The break-even assessment indicates that B30 becomes cost-competitive with HFO slow steaming only at carbon prices of approximately 754 EUR/tCO₂ under reference market conditions—substantially above current EU ETS levels (50–80 EUR/tCO₂). Sensitivity analysis shows that reducing the B30 price from 900 USD/t to 720 USD/t lowers this threshold to approximately 406 EUR/tCO₂. The results quantify the current economic gap for transitional biofuels under the EU ETS alone and highlight the complementary role of FuelEU Maritime lifecycle incentives. Key limitations include TTW-based emissions accounting and steady-state operational assumptions.

Keywords: container vessels; slow steaming; EU ETS; FuelEU Maritime; biofuel blends; EEOI; carbon pricing; Pareto analysis; voyage-level decarbonisation



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1. Introduction

Maritime transport carries nearly 80–90% of global merchandise trade and plays a central role in international supply chains [1]. At the same time, the sector is responsible for about 3% of global anthropogenic CO₂ emissions, increasing pressure for both operational and technological decarbonisation measures [2,3]. In response, the International Maritime Organisation (IMO) and the European Union have introduced progressively stricter climate policies aimed at reducing greenhouse-gas (GHG) emissions from shipping. Within Europe, the inclusion of maritime transport in the European Union Emissions Trading System

(EU ETS) together with the implementation of FuelEU Maritime is expected to influence operational planning, fuel selection, and voyage economics [4,5].

For existing container vessels, especially ageing ships approaching the end of their commercial service life, large-scale retrofits and alternative propulsion conversions are often difficult to justify economically [6]. As a result, near-term decarbonisation efforts increasingly focus on operational optimisation and lower-carbon fuels [7,8]. Among the available measures, slow steaming and transitional biofuel blends have received considerable attention because they can reduce fuel consumption and carbon exposure without major propulsion-system modifications [7–9].

Recent research has examined operational speed reduction, alternative marine fuels, emissions mitigation, and carbon-pricing mechanisms from both technical and economic perspectives [7,10–12]. At the same time, AIS-derived operational datasets and EU Maritime MRV statistics now provide more detailed information on vessel fuel consumption, emissions, and transport efficiency under real operating conditions [10,13]. Despite these advances, several gaps remain in the current literature.

Most existing studies examine operational optimisation, fuel transition, carbon pricing, or regulatory exposure separately. Integrated voyage-level assessments combining operational performance, emissions intensity, EU ETS exposure, and AIS/MRV-based benchmarking are still relatively limited, particularly for ageing container vessels operating under evolving European decarbonisation requirements.

To address this gap, the present study evaluates alternative speed and fuel configurations for a 5000 TEU post-Panamax container vessel operating on the Rotterdam–Limassol route, an intra-EU voyage fully covered by the EU ETS and FuelEU Maritime Regulation. The proposed framework combines voyage-level fuel consumption, TTW greenhouse-gas intensity, EU ETS cost exposure, operational benchmarking, and economic trade-off assessment within a unified comparative analysis.

In addition to comparing operational and economic performance, the study estimates the carbon-price level at which lower-carbon biofuel operation becomes economically competitive with conventional slow-steaming strategies. The analysis also highlights how operating speed, fuel selection, and carbon pricing interact under current European maritime regulation, particularly for ageing vessels operating under commercial and environmental constraints [6].

The main contributions of the study are:

- (1) the development of an integrated voyage-level assessment framework combining fuel consumption, CO₂ emissions, EEOI, TTW GHG intensity, EU ETS exposure, and economic evaluation;
- (2) the comparative analysis of operational scenarios based on different vessel speeds and fuel configurations (HFO, MGO, and B30);
- (3) the evaluation of operational trade-offs through Pareto analysis, break-even carbon-price estimation, and Monte Carlo uncertainty assessment.

2. Literature Review

2.1. Operational Optimisation and Slow Steaming

Operational optimisation remains one of the most practical decarbonisation measures for existing container vessels, particularly where large-scale retrofits or alternative propulsion systems are economically constrained [14,15]. Among the available measures, slow steaming has consistently demonstrated significant reductions in fuel consumption and voyage-level CO₂ emissions because propulsion power demand increases nonlinearly with vessel speed.

Previous studies reported fuel-consumption reductions of approximately 25–45% for container vessels operating below design speed, depending on vessel type and operational profile [10,15]. However, reduced speed also increases voyage duration and may affect schedule reliability and vessel-utilisation costs. Most previous studies focus primarily on fuel savings or emissions reduction associated with slow steaming, while the interaction between operational performance, regulatory carbon exposure, and voyage-level economic trade-offs remains less consistently addressed under the current EU ETS and FuelEU Maritime framework.

2.2. Alternative Marine Fuels and Biofuel Blends

Alternative marine fuels are increasingly considered transitional solutions for reducing greenhouse-gas emissions from existing vessels [6,7]. Among these options, biofuel blends are particularly attractive because they can generally be introduced without major propulsion-system modifications.

Previous studies confirmed the technical feasibility of biodiesel use in marine engines, although fuel performance depends on blend ratio, fuel properties, and engine operating conditions [8,9]. Biofuel blends can reduce operational CO₂ intensity, but their environmental performance depends on the emissions-accounting framework applied. This distinction is particularly relevant in the European regulatory context, as FuelEU Maritime mandates a Well-to-Wake (WTW) lifecycle approach for greenhouse-gas intensity assessment, whereas the EU ETS has traditionally been based on Tank-to-Wake (TTW) emissions [16]. Consequently, the environmental and economic benefits associated with biofuel use may differ depending on whether lifecycle emissions or onboard operational emissions are considered [6,17].

Although biofuel blends are increasingly discussed as transitional marine fuels, existing studies often focus either on engine compatibility or lifecycle emissions, while comparatively limited attention is given to their operational–economic performance under combined EU ETS and FuelEU Maritime exposure.

2.3. Maritime Decarbonisation Policies and Carbon Pricing

European maritime climate policies increasingly influence operational decision-making in shipping. The inclusion of maritime transport within the European Union Emissions Trading System (EU ETS) directly monetises onboard CO₂ emissions through carbon pricing [5,16], while FuelEU Maritime establishes progressively stricter Well-to-Wake (WTW) greenhouse-gas intensity limits for energy used on board ships. Relative to the 2020 reference value of 91.16 gCO₂eq/MJ, the regulation requires reductions of 2% from 2025, 6% from 2030, 14.5% from 2035, 31% from 2040, 62% from 2045, and 80% from 2050 [4]. These requirements are intended to accelerate the uptake of low-carbon and renewable marine fuels.

The interaction between these regulatory mechanisms creates additional complexity for ship operators. In addition, several published assessments treat the EU ETS and FuelEU Maritime independently, despite the fact that ship operators will be exposed simultaneously to both operational carbon costs and lifecycle-based fuel-intensity requirements. Lower operating speeds reduce fuel consumption and EU ETS exposure, whereas lower-carbon fuels may improve lifecycle emissions performance while increasing direct voyage cost. Although recent studies have examined carbon pricing and alternative fuels, integrated operational–regulatory assessments remain comparatively limited.

2.4. AIS/MRV-Based Benchmarking and Voyage-Level Modelling

AIS-derived operational datasets and EU Maritime MRV statistics enable increasingly realistic evaluation of vessel fuel consumption, emissions, and operational efficiency [10,11]. Existing modelling approaches range from simplified deterministic methods to advanced data-driven and machine-learning models [18]. However, highly detailed data-driven models often require extensive operational datasets that may not be available for ageing commercial vessels or comparative voyage-level screening studies.

Although high-fidelity models may improve predictive accuracy, simplified voyage-level approaches remain widely used because of their transparency and moderate data requirements, particularly for ageing commercial vessels. These characteristics make them suitable for preliminary assessments of alternative operational and fuel-transition strategies before more detailed analyses are undertaken. However, relatively few studies combine operational benchmarking, regulatory exposure, and economic trade-off analysis within a unified decarbonisation framework.

2.5. Research Gaps and Positioning of the Present Study

The reviewed literature shows that operational optimisation, alternative fuels, lifecycle emissions, and carbon-pricing mechanisms are often analysed independently. Integrated voyage-level assessments combining fuel-consumption modelling, emissions indicators, EU ETS exposure, FuelEU Maritime contextual evaluation, AIS/MRV benchmarking, and Pareto-based trade-off analysis remain comparatively limited for existing container vessels operating under evolving European regulatory constraints.

Accordingly, the present study develops an integrated voyage-level framework that combines operational, environmental, regulatory, and economic assessments for ageing container vessels operating under European maritime decarbonisation policies.

Table 1 shows that previous maritime decarbonisation studies typically focus on individual aspects such as slow steaming, alternative fuels, carbon pricing, or operational efficiency. Only limited research combines voyage-level fuel consumption, emissions performance, EU ETS exposure, operational benchmarking, and economic trade-off analysis within the same assessment framework. In addition, comparatively few studies evaluate the interaction between operational speed reduction and biofuel use under both operational carbon pricing and FuelEU Maritime-related lifecycle considerations. The present study addresses these gaps through a comparative voyage-level assessment integrating operational, environmental, and economic evaluation for container vessels operating under European maritime decarbonisation policies.

Table 1. Comparative overview of representative maritime decarbonisation studies.

Study	Slow Steaming	Alternative Fuels	EU ETS	FuelEU Maritime	Efficiency Indicator	Economic Analysis	Pareto/Multi-Criteria	Voyage-Level	Existing Vessels	AIS/MRV Benchmarking	Integrated Operational-Regulatory-Economic Coupling
[14]	Yes	No	No	No	No	Yes	No	No	Yes	No	No
[6]	Yes	Yes	No	No	Partial	Partial	No	No	Yes	Partial	No
[7]	Yes	Yes	Partial	No	No	Yes	No	No	Partial	No	No
[12]	No	No	Yes	No	No	Yes	No	No	No	No	No
[8]	Yes	Yes	Partial	No	No	Yes	No	No	Partial	Partial	No
[18]	Partial	Partial	No	No	No	No	No	No	Partial	Partial	No
[13]	Yes	Partial	No	No	Yes	Partial	No	No	Yes	Yes	No
[9]	No	Yes	No	No	No	No	No	No	Yes	No	No

Table 1. Cont.

Study	Slow Steaming	Alternative Fuels	EU ETS	FuelEU Maritime	Efficiency Indicator	Economic Analysis	Pareto/Multi-Criteria	Voyage-Level	Existing Vessels	AIS/MRV Benchmarking	Integrated Operational-Regulatory-Economic Coupling
[15]	Yes	No	No	No	Yes	Yes	No	Yes	Yes	Partial	No
[10]	Yes	No	No	No	Yes	Yes	No	Yes	Yes	Yes	No
[16]	Partial	No	Yes	No	No	Yes	No	No	No	No	No
This study	Yes	Yes	Yes	Qualitative assessment	Yes	Yes	Yes	Yes	Yes	Yes *	Yes

Note: * AIS/MRV benchmarking refers to quantitative comparison of model predictions with published operational data from AIS-derived studies and EU MRV datasets for comparable vessel types (4000–6000 TEU). The present study uses published benchmark ranges from [10,13,15], not primary AIS data. Source: Authors' compilation based on literature review.

3. Materials and Methods

The proposed methodology evaluates voyage-level decarbonisation performance under alternative speed and fuel configurations for an existing container vessel. The analytical framework combines fuel-consumption estimation, CO₂-emissions calculation, EEOI assessment, TTW GHG-intensity evaluation, EU ETS cost exposure, and Pareto-based cost-emissions trade-off analysis.

Figure 1 summarises the workflow adopted in the study.

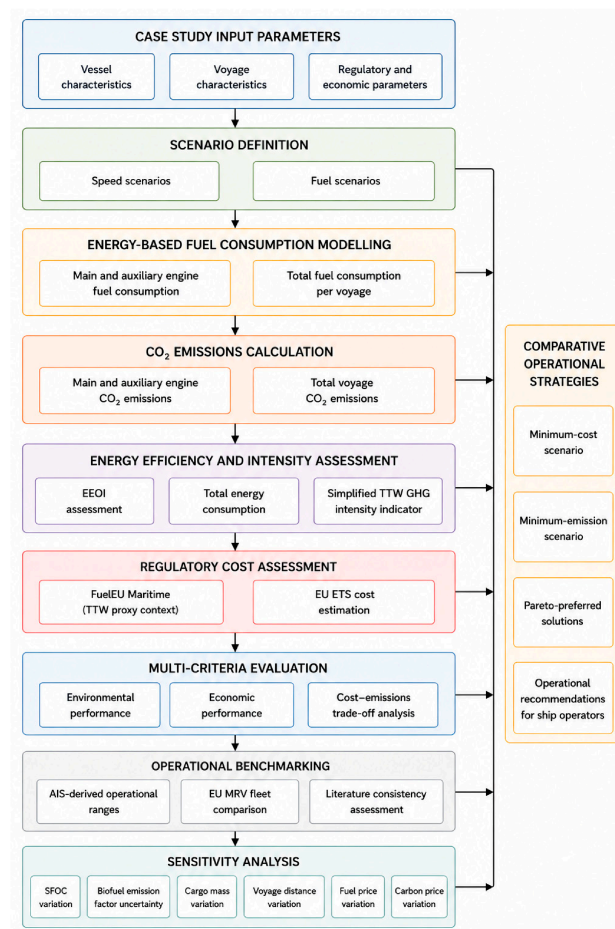


Figure 1. Integrated voyage-level framework for fuel consumption, emissions, regulatory cost, and Pareto-based decarbonisation assessment.

Figure 1 outlines the analytical sequence adopted in the study. The methodology begins with the definition of vessel characteristics, voyage conditions, fuel properties, and regulatory assumptions, followed by the generation of alternative operational scenarios based on vessel speed and fuel type.

Fuel consumption and CO₂ emissions are calculated for both the main and auxiliary engines, allowing the estimation of EEOI, a simplified TTW GHG-intensity indicator, and EU ETS cost exposure. The TTW approach is adopted because certified Well-to-Tank (WTT) fuel-pathway data required for full FuelEU Maritime WTW compliance assessment are outside the scope of the present voyage-level analysis. The voyage-level model, the sensitivity analyses, and the Monte Carlo simulation were implemented in Python (v3.11.9). The same environment was used to generate the analytical figures.

3.1. Fuel Consumption and Emissions Modelling

The seagoing voyage fuel consumption is calculated as the sum of main-engine and auxiliary-engine fuel consumption:

$$FC_{ME} = \frac{P_{ME} \cdot SFOC_{ME} \cdot t}{10^6} \quad (1)$$

$$FC_{AE} = \frac{P_{AE} \cdot SFOC_{AE} \cdot t}{10^6} \quad (2)$$

where

- C_{ME} and FC_{AE} [t] are the fuel consumptions of the main and auxiliary engines;
- P_{ME} [kW] and P_{AE} [kW] are the engine power demands;
- $SFOC_{ME}$ and $SFOC_{AE}$ [g/kWh] are the specific fuel oil consumption values;
- t [h] is the operating time.

The voyage duration is calculated as:

$$t = D/v \quad (3)$$

where

- D [nm] is the voyage distance;
- v [kn] is the vessel speed.

The main-engine power demand is estimated using a generalised speed–power relationship [14,15]:

$$P(v) = P_{design} \times \left(v/v_{design}\right)^3 \quad (4)$$

where

- $P(v)$ [kW] is the engine power at operational speed v ;
- P_{design} [kW] is the reference engine power at design speed;
- v_{design} [kn] is the design speed.

In the baseline model, $n = 3$ is adopted, consistent with conventional slow-steaming and maritime energy-efficiency studies for container vessels [14,15]. This cubic approximation reflects the dominant relationship between hull resistance, propulsion demand, and vessel speed under simplified steady-state conditions. However, the exponent is not universal. In real operation, its value may vary with loading condition, hull fouling, propeller performance, water depth, weather, and sea state. Therefore, the sensitivity analysis considers a representative range of $n = 2.8$ – 3.2 , consistent with empirical slow-steaming applications and simplified Holtrop-type resistance assumptions.

To address the potential overestimation of slow-steaming benefits under low-load operation, a simplified partial-load SFOC correction factor is introduced:

$$SFOC_{corr} = SFOC_{ref} (1 + \beta) \quad (5)$$

where

- $SFOC_{corr}$ [g/kWh] is the corrected specific fuel oil consumption;
- $SFOC_{ref}$ [g/kWh] is the reference SFOC value;
- β [–] is the partial-load correction factor.

In this study, β is treated as a fixed partial-load correction factor and is applied only within the sensitivity analysis. For the baseline calculations, $\beta = 0$ is assumed in order to preserve comparability between scenarios. However, for low-load operation near approximately 40–45% MCR, additional sensitivity cases with $\beta = 0.10$ and $\beta = 0.15$ are evaluated to represent the possible increase in SFOC caused by off-design engine operation, reduced turbocharger efficiency, and lower combustion efficiency under deep slow-steaming conditions. This correction is particularly relevant for the 19 kn scenarios, where the estimated main-engine load is approximately 42% MCR [14,15,19].

To assess the robustness of the adopted low-load assumptions, the load-dependent fuel-consumption correction methodology applied in the Fourth IMO GHG Study 2020 [2] was also evaluated for the analysed slow-steaming conditions. The corresponding comparison is presented in Supplementary Materials Section S8.2.

The total voyage-level CO₂ emissions are calculated as:

$$m_{CO_2} = m_{CO_2,ME} + m_{CO_2,AE} \quad (6)$$

with engine-specific emissions obtained from:

$$m_{CO_2,ME} = FC_{ME} \cdot CF_{ME} \quad (7)$$

$$m_{CO_2,AE} = FC_{AE} \cdot CF_{AE} \quad (8)$$

where

- m_{CO_2} [tCO₂] is the total voyage-level CO₂ emissions;
- $m_{CO_2,ME}$ [tCO₂] and $m_{CO_2,AE}$ [tCO₂] are the CO₂ emissions produced by the main and auxiliary engines, respectively;
- CF_{ME} and CF_{AE} [tCO₂/t fuel] are the fuel-specific carbon emission factors for the main and auxiliary engines.

For the main analysis, the adopted CF values were 3.114 tCO₂/t fuel for HFO, 3.206 tCO₂/t fuel for MGO, and 2.70 tCO₂/t fuel for the B30 blend [2]. These values were used for TTW CO₂-emission calculations.

3.2. Operational Efficiency and GHG Intensity Indicators

The Energy Efficiency Operational Indicator is calculated as [20]:

$$EEOI = \frac{\sum_i (FC_i \cdot CF_i)}{m_{cargo} \cdot D} \quad (9)$$

where

- $EEOI$ [tCO₂/t·nm] is the Energy Efficiency Operational Indicator;
- FC_i [t fuel] is the fuel consumption of the fuel type i ;
- CF_i [tCO₂/t fuel] is the carbon emission factor of the fuel type i ;

- m_{cargo} [t] is the transported cargo mass;

For consistency with the presentation of results, EEOI values are converted from $tCO_2/t\cdot nm$ to $gCO_2/t\cdot nm$ by multiplication with 10^6 .

The total voyage energy consumption is calculated using the lower heating values (LHV) of the consumed fuels [2]:

$$E_{total} = \sum_i (FC_i \cdot LHV_i) \quad (10)$$

or equivalently

$$E_{total} = (FC_{ME} \cdot LHV_{ME}) + (FC_{AE} \cdot LHV_{AE}) \quad (11)$$

where

- E_{total} [MJ] is the total energy consumption;
- LHV [MJ/t] is the lower heating value of the corresponding fuel.

Fuel-consumption differences between HFO, MGO, and B30 are evaluated using an energy-equivalent approach [6].

$$FC_{fuel} = FC_{HFO} \times \left(\frac{LHV_{HFO}}{LHV_{fuel}} \right) \quad (12)$$

where

- FC_{fuel} [t/voyage] is the energy-equivalent fuel consumption of any alternative fuel;
- FC_{HFO} [t] is the reference HFO fuel consumption;
- LHV_{HFO} [MJ/t] is the lower heating value of HFO;
- LHV_{fuel} [MJ/t] is its lower heating value.

Since MGO has the highest lower heating value (42,700 MJ/t), followed by B30 (41,000 MJ/t) and HFO (40,200 MJ/t), the corresponding fuel mass consumption follows the order $MGO < B30 < HFO$ for the same delivered energy.

The resulting correction factors and derived SFOC values are summarised in Supplementary Materials (Table S6).

This assumption isolates the effect of fuel energy content while avoiding unsupported claims regarding engine-efficiency variation between fuels.

The simplified TTW GHG-intensity indicator is calculated as:

$$GHG_{intensity} = \frac{m_{CO_2}}{E_{total}} \quad (13)$$

where

- $GHG_{intensity}$ [gCO_2/MJ] is the greenhouse-gas intensity indicator;
- m_{CO_2} [gCO_2] is the total voyage CO_2 emissions;
- E_{total} [MJ] is the total voyage energy consumption.

This indicator is used only to compare the operational carbon intensity of the analysed scenarios. Full FuelEU Maritime compliance requires WTW lifecycle accounting and certified fuel-pathway data, which are outside the scope of the present voyage-level model.

3.3. Regulatory Accounting Boundaries

The present assessment distinguishes between Tank-to-Wake (TTW) operational emissions, Well-to-Wake (WTW) lifecycle considerations, and direct carbon-cost exposure under the EU ETS.

EU ETS costs are calculated using onboard CO₂ emissions derived from voyage fuel consumption and fuel-specific emission factors. Accordingly, the economic assessment is based exclusively on TTW operational emissions.

The TTW GHG-intensity indicator used in this study is intended for comparative operational evaluation of alternative speed and fuel scenarios. Upstream emissions associated with fuel production, processing, transport, and distribution are not included.

By contrast, FuelEU Maritime applies a WTW lifecycle approach that also incorporates upstream fuel-pathway emissions. Therefore, the reported TTW values should not be interpreted as direct FuelEU Maritime compliance values. Formal FuelEU Maritime compliance assessment would require certified fuel-pathway data and corresponding WTT values, which are beyond the scope of the present study.

For the B30 scenarios, an additional sustainability-certified reference case under the current Renewable Energy Directive (RED) framework, comprising Directive (EU) 2018/2001 and its amendment by Directive (EU) 2023/2413, is included to illustrate the influence of lifecycle accounting and sustainability certification on the resulting emissions assessment.

Emissions are quantified on a Tank-to-Wake (TTW) basis to allow direct comparison between operational scenarios. The results are assessed against the FuelEU Maritime regulatory framework using the regulation's own GHG-intensity baseline and RED II (Directive 2018/2001) biofuel sustainability criteria. The reported TTW GHG-intensity values are compared with the 2025 FuelEU Maritime reference threshold of 89.3 gCO₂eq/MJ; since this threshold is defined on a Well-to-Wake (WTW) basis, the difference in system boundary is a recognised methodological limitation, discussed in Section 5.5.

3.4. Economic Assessment and EU ETS Cost Formulation

The voyage-level operational cost is calculated as:

$$C_{voyage} = C_{fuel} + C_{ETS} \quad (14)$$

where

- C_{voyage} [EUR/voyage] is the direct voyage-level cost, including fuel cost and EU ETS carbon cost;
- C_{fuel} [EUR/voyage] is the fuel cost;
- C_{ETS} [EUR/voyage] is the EU ETS carbon cost.

Fuel cost is calculated as:

$$C_{fuel} = \sum_i (FC_i \cdot P_i) \quad (15)$$

where

- FC_i [t fuel] is the fuel consumption of fuel type i ;
- P_i [EUR/t fuel] is the fuel price of fuel type i .

The EU ETS cost is estimated as:

$$C_{ETS} = m_{CO_2} \cdot P_{CO_2} \cdot \alpha \quad (16)$$

where

- C_{ETS} [EUR] is the EU ETS cost;
- m_{CO_2} [tCO₂] is the total voyage CO₂ emissions;
- P_{CO_2} [EUR/tCO₂] is the carbon allowance price;
- α [-] is the ETS coverage factor.

The ETS coverage factor reflects the phased integration of maritime transport into the EU ETS framework [5]. In accordance with Directive (EU) 2023/959, α is determined by the geographical scope of the voyage. For intra-EU voyages, $\alpha = 1.0$ from 2026 onward, whereas for voyages between an EU port and a non-EU port, $\alpha = 0.5$.

To account for the commercial effect of increased voyage duration under reduced-speed operation, an additional time-cost sensitivity term is included [21]:

$$C_{voyage,time} = C_{fuel} + C_{ETS} + (R_{hire} \times \Delta t) \quad (17)$$

where

- R_{hire} [EUR/day] is the daily vessel-utilisation cost;
- Δt is the additional voyage duration relative to the 24 kn reference case.

The parameter R_{hire} represents the daily charter-related vessel utilisation cost (e.g., vessel hire and other time-related operating costs) used to estimate the additional cost associated with longer voyage durations under slow-steaming operation.

This formulation does not represent a full freight-market profitability model. Instead, it provides a controlled voyage-level cost comparison between alternative speed and fuel configurations.

3.5. Pareto Trade-Off and Marginal Decarbonisation Analysis

The cost–emissions trade-off is evaluated using Pareto dominance analysis. A scenario is considered non-dominated when no other scenario simultaneously achieves both lower voyage cost and lower CO₂ emissions.

The marginal abatement cost between two scenarios is calculated as [22,23]:

$$MAC = \frac{\Delta C}{\Delta m_{CO_2}} \quad (18)$$

where

- MAC [EUR/tCO₂] is the marginal decarbonisation cost,
- ΔC [EUR] is the cost difference between two operational scenarios,
- Δm_{CO_2} [tCO₂] is the corresponding difference in voyage CO₂ emissions.

The break-even carbon price is estimated from the condition that the two scenarios have equal total voyage cost [23]:

$$P_{CO_2,break-even} = \frac{C_{fuel,B} - C_{fuel,A}}{m_{CO_2,A} - m_{CO_2,B}} \quad (19)$$

where Scenario A represents the lower-cost conventional-fuel case, and Scenario B represents the lower-emission alternative-fuel case.

Equation (19) is applicable to scenarios with identical voyage duration. For scenarios with different operating speeds, the corresponding difference in time-related costs should also be considered.

3.6. Assumptions and Model Boundaries

The model is intended for comparative voyage-level assessment rather than direct operational prediction of measured onboard performance. The main assumptions are:

- constant sailing speed within each scenario;
- seagoing phase only;
- no explicit weather, current, manoeuvring, or port-operation effects;

- fixed cargo mass and voyage distance;
- fuel properties represented by constant LHV and carbon factors;
- auxiliary engines operated on MGO in all scenarios;
- baseline SFOC treated as constant, with low-load correction addressed through sensitivity analysis;
- baseline speed–power exponent fixed at $n = 3$, with $n = 2.8$ – 3.2 tested in sensitivity analysis.

3.7. Case Study Definition and Scenario Setup

The methodology is applied to a representative ageing 5000 TEU post-Panamax container vessel operating on the Rotterdam–Limassol route. This vessel category is relevant because many ships of similar size remain active in regional liner services, while extensive retrofit or alternative-propulsion conversion may be economically constrained near the later stages of commercial service life.

3.7.1. Vessel Characteristics

The principal vessel and propulsion characteristics adopted in the analysis are summarised in Table 2.

Table 2. Principal vessel characteristics.

Parameter	Value
Capacity	5000 TEU
Class	Post-Panamax
Length overall	285 m
Beam	32 m
Draft (scantling)	12.5 m
Deadweight	65,000 t
Design speed	24 knots
Main engine (ME) type	MAN B&W 8K98MC-C (MAN Energy Solutions, Copenhagen, Denmark)
Main engine MCR	46,220 kW [19]
Main engine SFOC	177 g/kWh [19]
Auxiliary engine (AE) type	3 × Wärtsilä 6L32 (Wärtsilä Corporation, Helsinki, Finland)
Auxiliary engine power	~3500 kW (each) [24,25]
Auxiliary engine SFOC	177 g/kWh [24,25]

3.7.2. Route and Operational Parameters

The analysed route corresponds to the Rotterdam–Limassol corridor, with a total sailing distance of approximately 3176 nautical miles based on a representative commercial route through the Mediterranean Sea. The route was selected because it reflects a typical European liner-shipping corridor connecting Northern European and Eastern Mediterranean ports operating under EU ETS and FuelEU Maritime exposure. The transported cargo mass is fixed at 55,000 t, corresponding to approximately 85% of the vessel’s deadweight capacity. This loading condition is consistent with values reported for comparable post-Panamax container vessels in EU Maritime MRV datasets and previous operational studies [10,15].

3.7.3. Analysed Operational Scenarios

Nine operational scenarios were defined by combining three operating speeds, 24, 21, and 19 kn, with three main-engine fuel configurations: HFO, MGO, and B30. The 24 kn condition represents the reference design-speed case at approximately 85% MCR,

while the 21 kn and 19 kn cases represent moderate and deeper slow-steaming operation, corresponding to approximately 57% and 42% MCR, respectively.

For the reference operating condition, the propulsion power at design speed was assumed to be $P_{design} = 39,287$ kW, corresponding to approximately 85% MCR at 24 kn.

The reference main-engine SFOC was used in the baseline calculations. Low-load SFOC deterioration was subsequently evaluated through the correction factor introduced in Equation (5).

MGO was selected as the fossil component of the B30 blend because biodiesel blends are more commonly associated with distillate marine fuels than with HFO.

Auxiliary engines were assumed to operate continuously on MGO in all scenarios, with a total auxiliary demand of approximately 3500 kW. This corresponds to two 3500 kW generators operating at approximately 50% load. Relative to the installed auxiliary-engine capacity of 10,500 kW, the adopted demand represents approximately 33% of the auxiliary plant. A supplementary sensitivity case using 30% of installed auxiliary-engine capacity is provided in Supplementary Materials Section S8.5.

The fuel properties adopted in the analysis are summarised in Table 3. The carbon emission factors are based on representative values reported in international guidelines and marine fuel studies [2], while fuel-consumption differences between fuels were evaluated using an energy-equivalent approach based on lower heating value (LHV) [2,7].

Table 3. Fuel properties adopted in the analysis.

Fuel	Carbon Emission Factor, CF [tCO ₂ /t Fuel]	Lower Heating Value, LHV [MJ/t]
HFO	3.114	40,200
MGO	3.206	42,700
B30	2.70	41,000

For the B30 blend, a TTW carbon emission factor of 2.70 tCO₂/t fuel is used in the main analysis. The corresponding value applicable under EU ETS accounting for biofuels certified under the Renewable Energy Directive (RED) framework is 2.244 tCO₂/t fuel. The RED-certified case is presented separately as Scenario A. A detailed derivation of both values is provided in Supplementary Materials Section S1.

For contextual reference under FuelEU Maritime [4], the 2020 baseline greenhouse-gas intensity is 91.16 gCO₂eq/MJ on a Well-to-Wake (WTW) basis. The TTW-based values calculated in the present study are therefore intended only for comparative operational assessment within the broader FuelEU Maritime regulatory context.

The analysed operational scenarios are summarised in Table 4.

Table 4. Operational scenarios.

Speed	Approx. ME Load	Fuel Types Evaluated	Voyage Duration [Day]
24 knots	85% MCR	HFO, MGO, B30	5.51
21 knots	57% MCR	HFO, MGO, B30	6.30
19 knots	42% MCR	HFO, MGO, B30	6.97

3.7.4. Reference Economic Parameters

The reference economic parameters adopted in the analysis are summarised in Table 5. Fuel prices were selected within representative Rotterdam bunker market ranges [26]. The adopted B30 reference price of 900 USD/t reflects the additional cost premium associated

with marine biofuel blends [27]. A baseline carbon price of 70 EUR/tCO₂ was adopted, consistent with representative EU ETS market conditions during 2024–2025 [28,29]. The influence of carbon-price variability is further examined through the sensitivity analysis presented in Section 4.9.

Table 5. Reference economic parameters adopted in the analysis.

Parameter	Value	Notes
HFO price	500 USD/t	Representative Rotterdam bunker market value [26],
MGO price	750 USD/t	Representative Rotterdam bunker market value [26],
B30 price	850–1050 USD/t (reference value: 900 USD/t)	Representative marine biofuel blend market range and median reference value [27],
Carbon price (EU ETS)	70 EUR/tCO ₂	Representative average value for 2024–2025 market conditions [28,29],
ETS coverage factor (α)	1.0	Full implementation phase (from 2026),
USD/EUR exchange rate	1 USD = 0.92 EUR	Representative ECB average exchange rate for 2024–2025 used for comparative economic assessment [30].

4. Results

This section presents the quantitative results obtained for all nine operational scenarios, including fuel consumption, CO₂ emissions, Energy Efficiency Operational Indicator (EEOI) values, total energy consumption, simplified GHG intensity indicator, fuel costs, and EU ETS costs. A detailed discussion follows in Section 5.

4.1. Operational Benchmarking and Model Robustness

The predicted fuel-consumption values were benchmarked against AIS-derived operational studies, voyage-level slow-steaming analyses, and EU Maritime MRV datasets for comparable post-Panamax container vessels [6,8,9,31,32]. The comparison covered the analysed speed range (19–24 kn) and all investigated fuel configurations (HFO, MGO, and B30). Detailed benchmark ranges are provided in Supplementary Table S1.

For the baseline HFO scenario at 24 kn, the model predicted an average fuel consumption of approximately 182 t/day (main and auxiliary engines combined), consistent with reported operational ranges for comparable 4000–6000 TEU container vessels [9,13]. Relative to the baseline condition, the predicted fuel-consumption reductions were approximately 30% at 21 kn and 46% at 19 kn [10,11].

Relative deviations ranged from 0.41% to 19.78%. Fuel-specific MAPE values were 3.47% (HFO), 7.63% (MGO), and 4.92% (B30), with corresponding RMSE values of 4.52, 9.03, and 9.28 t/day. The largest relative deviation was obtained for the MGO configuration at 19 kn, whereas all model predictions remained within the corresponding literature benchmark ranges. Detailed benchmark comparisons and statistical error metrics are provided in Supplementary Tables S3–S5.

Figure 2 compares the calculated average daily fuel consumption with literature benchmark ranges reported for comparable post-Panamax container vessels (approximately 4500–6000 TEU). Daily fuel consumption was calculated from the voyage fuel consumption and the corresponding voyage duration.

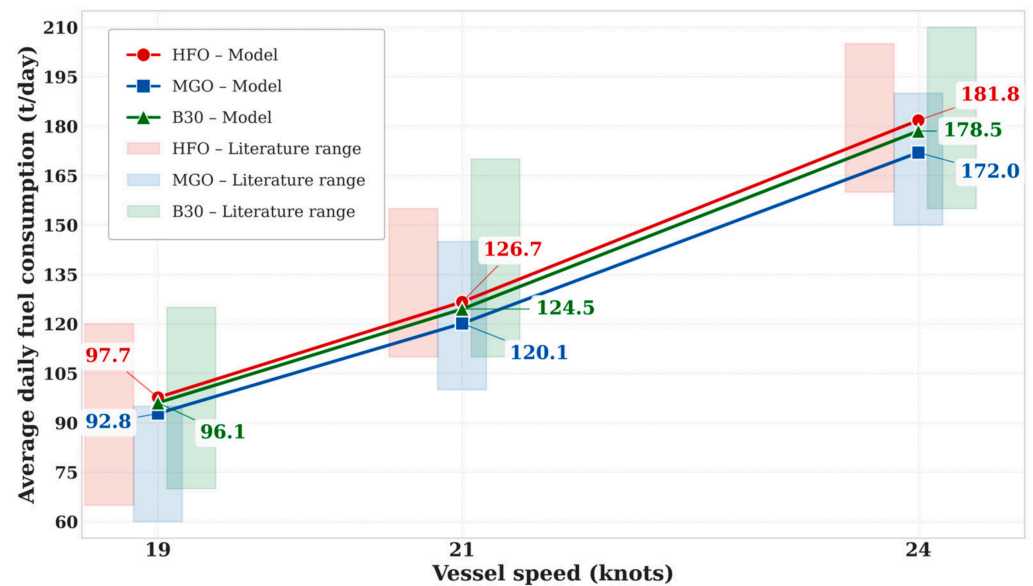


Figure 2. Comparison of calculated average daily fuel consumption with literature benchmark ranges for comparable post-Panamax container vessels. Note: Average daily fuel consumption was calculated by dividing the total voyage fuel consumption reported in Section 4.3. by the corresponding voyage duration. Fuel consumption includes both the main and auxiliary engines.

4.2. Uncertainty and Sensitivity Envelope Assessment

The uncertainty assessment considered variations in main-engine specific fuel oil consumption (SFOC), speed–power exponent, fuel properties, cargo mass, voyage distance, fuel prices, and EU ETS carbon price. Technical and operational parameters were varied within representative ranges relative to the baseline assumptions, as summarised in Table 6.

Table 6. Uncertainty ranges adopted for the sensitivity envelope assessment.

Parameter	Low	Base	High
SFOC, main engine [g/kWh]	142	177	212
Partial-load SFOC correction at 19 kn [%]	0	+10	+15
Emission factor B30 [tCO ₂ /t fuel]	2.24	2.70	3.00
Cargo mass [t]	44,000	55,000	66,000
Voyage distance [nm]	2541	3176	3811
Speed–power exponent (<i>n</i>) [–]	2.8	3.0	3.2
HFO price [USD/t]	400	500	600
MGO price [USD/t]	600	750	900
B30 price [USD/t]	720	900	1080
Carbon price [EUR/tCO ₂]	50	70	90

Note: The selected range for the speed–power exponent ($n = 2.8\text{--}3.2$) reflects representative variability reported for commercial container vessels operating under typical slow steaming and service conditions. The SFOC range represents an uncertainty envelope adopted for sensitivity and Monte Carlo analyses and should not be interpreted as the achievable operating range of the MAN B&W K98MC-C engine.

The adopted SFOC interval was selected to evaluate the robustness of the framework under parameter uncertainty and does not represent the expected operational performance range of the analysed engine.

Additional sensitivity calculations and uncertainty ranges are provided in Supplementary Materials Section S8.

Figure 3 summarises the relative sensitivity of the principal parameters affecting voyage-level CO₂ emissions and total operational cost.

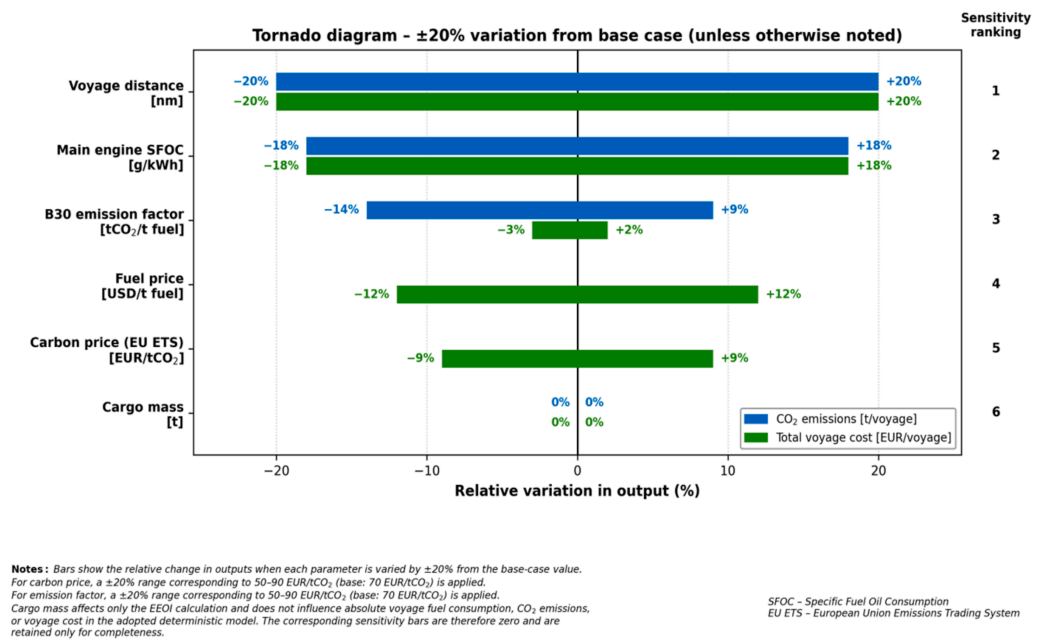


Figure 3. Tornado sensitivity analysis of principal uncertainty parameters affecting voyage-level CO₂ emissions and total operational cost.

4.3. Fuel Consumption per Voyage

Table 7 presents the estimated voyage-level fuel consumption for all analysed operational scenarios, including the combined contribution of the main propulsion engine and auxiliary engines calculated using Equations (1) and (2).

Table 7. Voyage-level fuel consumption for the analysed operational scenarios.

Case	Speed [kn]	Main Engine Fuel	FC _{ME} [t/Voyage]	FC _{AE} (MGO) [t/Voyage]	Total Fuel [t/Voyage]
1	24	HFO	920.2	82.0	1002.2
2	24	MGO	866.3	82.0	948.3
3	24	B30	902.3	82.0	984.2
4	21	HFO	704.5	93.7	798.2
5	21	MGO	663.3	93.7	757.0
6	21	B30	690.8	93.7	784.5
7	19	HFO	576.7	103.6	680.3
8	19	MGO	543.0	103.6	646.5
9	19	B30	565.5	103.6	669.0

Note: Total fuel consumption includes main and auxiliary engines. Auxiliary engines operate on MGO in all cases.

Across all analysed fuel configurations, reducing vessel speed from 24 kn to 19 kn decreased total voyage-level fuel consumption by approximately 32%. Owing to its higher lower heating value, the MGO scenarios consistently produced the lowest mass-based fuel consumption, while the B30 scenarios yielded intermediate values between MGO and HFO, in accordance with the adopted energy-equivalent approach. Auxiliary-engine fuel consumption increased from approximately 82 t/voyage at 24 kn to approximately 104 t/voyage at 19 kn because of the longer voyage duration associated with reduced operating speed.

4.4. CO₂ Emissions

Table 8 presents the estimated voyage-level CO₂ emissions for all analysed scenarios, calculated using the fuel-specific emission factors defined in Section 3.1 and Equations (6)–(8).

Table 8. Voyage-level CO₂ emissions for the analysed operational scenarios.

Case	Speed (kn)	Fuel	CO ₂ Scenario B [t/Voyage]	CO ₂ Scenario A [t/Voyage]
1	24	HFO	3128	-
2	24	MGO	3040	-
3	24	B30	2699	2288
4	21	HFO	2494	-
5	21	MGO	2427	-
6	21	B30	2166	1851
7	19	HFO	2128	-
8	19	MGO	2073	-
9	19	B30	1859	1601

Note: Main-engine emissions depend on the selected fuel, while auxiliary-engine emissions are calculated using the MGO emission factor. Scenario B represents the reference TTW case used throughout the analysis; Scenario A represents the sustainability-certified case under the current Renewable Energy Directive (RED) framework and is included for comparison only.

For the B30 cases, the main analysis applies the conservative Tank-to-Wake (TTW) emission factor defined as Scenario B ($CF_{B30} = 2.70 \text{ tCO}_2/\text{t fuel}$). An additional sustainability-certified biofuel case (Scenario A) is included to evaluate the influence of certification under the current Renewable Energy Directive (RED) framework on CO₂ accounting.

Across all analysed fuel configurations, reducing vessel speed from 24 kn to 19 kn decreased voyage-level CO₂ emissions by approximately 32%. The MGO scenarios produced slightly lower CO₂ emissions than the corresponding HFO cases, whereas the B30 configurations consistently yielded the lowest CO₂ emissions under both Scenario A and Scenario B assumptions.

Under the conservative TTW assumptions adopted in Scenario B, the B30 configuration reduced voyage-level CO₂ emissions by approximately 14% relative to the baseline HFO case at 24 kn.

Figure 4 illustrates the relationship between vessel speed and voyage-level CO₂ emissions for the analysed operational scenarios.

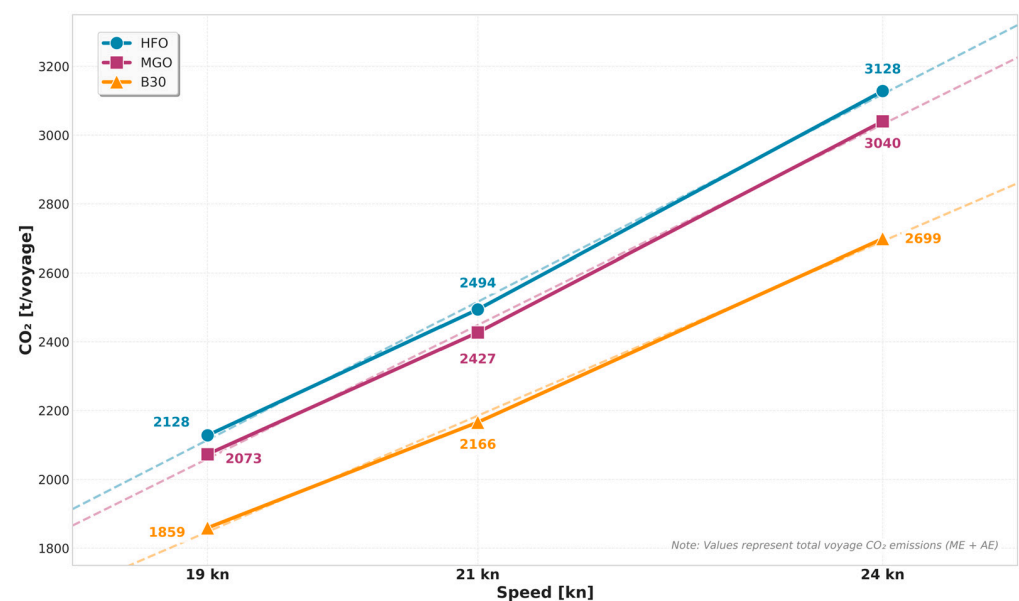


Figure 4. Voyage-level CO₂ emissions for the analysed operational scenarios under TTW accounting. Note: Dashed lines indicate linear regression trends for each fuel configuration (HFO, MGO, B30), color-coded as shown in the legend.

4.5. Energy Efficiency Operational Indicator (EEOI)

Table 9 presents the Energy Efficiency Operational Indicator (EEOI) values calculated using Equation (9). Cargo mass (55,000 t) and voyage distance (3176 nm) were maintained constant across all scenarios so that EEOI variations reflect differences in fuel consumption and fuel-related carbon intensity.

Table 9. Voyage-level EEOI values for the analysed operational scenarios.

Case	Speed (kn)	Fuel	EEOI Scenario B [gCO ₂ /t·nm]	EEOI Scenario A [gCO ₂ /t·nm]
1	24	HFO	17.91	n/a
2	24	MGO	17.41	n/a
3	24	B30	15.45	13.09
4	21	HFO	14.28	n/a
5	21	MGO	13.89	n/a
6	21	B30	12.40	10.59
7	19	HFO	12.18	n/a
8	19	MGO	11.87	n/a
9	19	B30	10.64	9.16

Across all analysed fuel configurations, reducing vessel speed from 24 kn to 19 kn decreased EEOI values by approximately 32%. The MGO scenarios consistently produced slightly lower EEOI values than the corresponding HFO cases, whereas the B30 configurations yielded the lowest EEOI values across all analysed operating speeds under both Scenario A and Scenario B assumptions.

Case 9 (B30, 19 kn) produced the lowest EEOI value among the analysed scenarios, reaching 10.64 gCO₂/t·nm under Scenario B and 9.16 gCO₂/t·nm under Scenario A.

Figure 5 illustrates the variation in EEOI with vessel speed for the analysed fuel configurations.

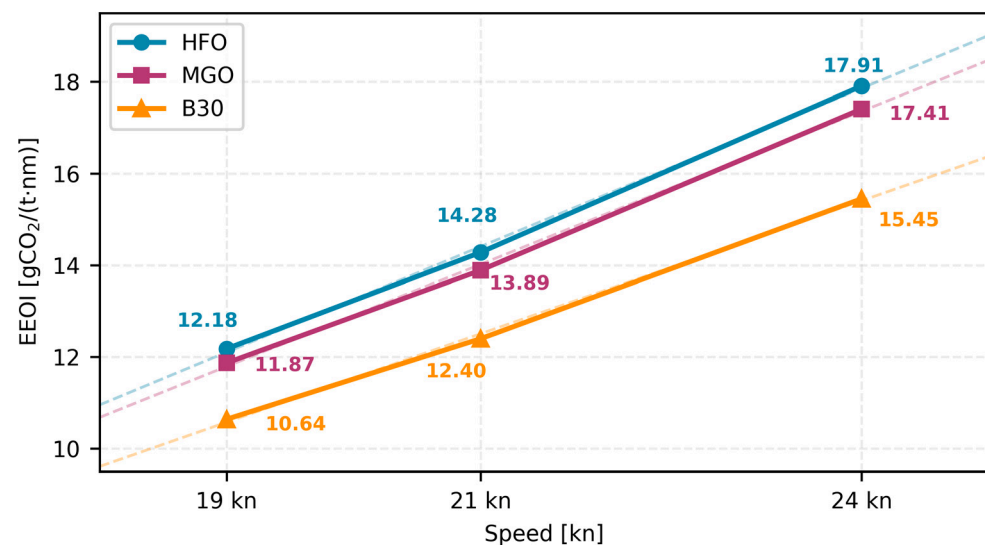


Figure 5. Variation in voyage-level EEOI across the analysed speed and fuel scenarios. Note: Dashed lines indicate linear regression trends for each fuel configuration (HFO, MGO, B30), color-coded as shown in the legend.

4.6. Total Energy Consumption and Simplified GHG Intensity Indicator

Table 10 presents the total voyage-level energy consumption values calculated according to Equations (10) and (11), together with the simplified Tank-to-Wake (TTW) GHG-intensity indicator calculated using Equation (13).

Table 10. Total energy consumption and TTW GHG-intensity indicator.

Case	Speed [kn]	Fuel	E_{total} [GJ/Voyage]	$GHG_{intensity}$ [gCO ₂ /MJ]
1	24	HFO	40,493	77.26
2	24	MGO	40,493	75.08
3	24	B30	40,493	66.65
4	21	HFO	32,323	77.17
5	21	MGO	32,323	75.08
6	21	B30	32,323	67
7	19	HFO	27,607	77.08
8	19	MGO	27,607	75.08
9	19	B30	27,607	67.33

Note: Total energy consumption includes main and auxiliary engines. GHG-intensity values are calculated on a simplified TTW basis, assuming MGO operation for auxiliary engines in all scenarios.

Across all analysed fuel configurations, reducing vessel speed from 24 kn to 19 kn decreased total voyage-level energy consumption by approximately 32%. Because the analysis was based on an energy-equivalent approach, the total voyage energy consumption remained essentially identical for the three fuel configurations operating at the same speed.

The HFO scenarios produced TTW GHG-intensity values of approximately 77.1–77.3 gCO₂/MJ across the analysed speed range, while the MGO scenarios remained close to 75.1 gCO₂/MJ. The B30 configurations produced the lowest TTW GHG-intensity values, ranging from approximately 66.7 to 67.3 gCO₂/MJ.

4.7. Fuel Cost

Table 11 presents the estimated fuel cost for all analysed scenarios. The calculations are based on the fuel-consumption values reported in Table 7 and the reference fuel prices defined in Section 3.7.4 (HFO: 500 USD/t, MGO: 750 USD/t, B30: 900 USD/t).

Table 11. Estimated fuel cost per voyage.

Case	Speed (kn)	Fuel	Fuel Cost [USD/Voyage]
1	24	HFO	521,595
2	24	MGO	711,242
3	24	B30	873,523
4	21	HFO	422,540
5	21	MGO	567,739
6	21	B30	691,985
7	19	HFO	366,033
8	19	MGO	484,892
9	19	B30	586,599

Note: Fuel costs include main and auxiliary engines. Auxiliary-engine consumption is calculated using MGO in all scenarios. Fuel prices correspond to the reference values defined in Section 3.7.4.

Across all analysed fuel configurations, reducing vessel speed from 24 kn to 19 kn reduced voyage-level fuel cost by approximately 30–33%. Among the analysed scenarios, Case 7 (HFO, 19 kn) produced the lowest fuel cost (366,033 USD/voyage), whereas Case 3 (B30, 24 kn) resulted in the highest fuel cost (873,523 USD/voyage).

The higher cost of the B30 scenarios was primarily associated with the assumed biofuel market price despite the lower operational emissions intensity.

4.8. EU ETS Cost

Table 12 presents the estimated EU ETS cost for all analysed scenarios, calculated using the CO₂ emissions reported in Table 8 and the baseline carbon price of 70 EUR/tCO₂ defined in Section 3.7.4.

Table 12. Estimated EU ETS cost per voyage.

Case	Speed (kn)	Fuel	CO ₂ [t/Voyage]	ETS Cost [EUR/Voyage]
1	24	HFO	3128	218,987
2	24	MGO	3040	212,823
3	24	B30	2699	188,926
4	21	HFO	2494	174,603
5	21	MGO	2427	169,883
6	21	B30	2166	151,587
7	19	HFO	2128	148,956
8	19	MGO	2073	145,093
9	19	B30	1859	130,116

Across all analysed fuel configurations, reducing vessel speed from 24 kn to 19 kn reduced EU ETS cost by approximately 31–32%. The B30 configurations consistently produced the lowest EU ETS costs because of their lower TTW CO₂ emissions, whereas Case 1 (HFO, 24 kn) resulted in the highest carbon-cost exposure.

The lowest EU ETS cost was obtained for the B30 19 kn scenario (Case 9).

4.9. Economic Performance and Pareto Trade-Off Analysis

The economic assessment was performed using the voyage-cost formulation and Pareto trade-off methodology defined in Sections 3.4 and 3.5. In addition to the baseline fuel-cost and EU ETS evaluation, a simplified time-cost sensitivity term was included to account for the influence of increased voyage duration under slow-steaming conditions.

4.9.1. Pareto Frontier Identification

The Pareto frontier was identified using two minimisation objectives: total operational cost and voyage-level CO₂ emissions. A scenario was considered dominated when another configuration achieved both lower cost and lower emissions.

Table 13 presents the Pareto dominance assessment for all analysed operational scenarios.

The Pareto analysis identified three non-dominated operational configurations:

- Case 7 (HFO, 19 kn)—minimum-cost configuration;
- Case 8 (MGO, 19 kn)—intermediate operational trade-off;
- Case 9 (B30, 19 kn)—minimum-emission configuration.

All remaining scenarios were classified as dominated because at least one alternative configuration achieved both lower operational cost and lower CO₂ emissions.

Table 13. Pareto dominance assessment for the analysed operational scenarios.

Case	Scenario	Voyage-Level Operational Cost [EUR/Voyage]	CO ₂ [t/Voyage]	Pareto Status
1	HFO, 24 kn	698,855	3128	Dominated
2	MGO, 24 kn	867,165	3040	Dominated
3	B30, 24 kn	992,567	2699	Dominated
4	HFO, 21 kn	563,340	2494	Dominated (by 7)
5	MGO, 21 kn	692,203	2427	Dominated
6	B30, 21 kn	788,213	2166	Dominated
7	HFO, 19 kn	485,707	2128	Non-dominated (min cost)
8	MGO, 19 kn	591,193	2073	Non-dominated
9	B30, 19 kn	669,787	1859	Non-dominated (min emissions)

Note: Operational cost = Fuel cost (converted to EUR) + EU ETS cost.

4.9.2. Marginal Decarbonisation Trade-Off

Applying the marginal decarbonisation methodology defined in Section 3.5 to the two Pareto-optimal operational configurations (Cases 7 and 9) provides an estimate of the additional economic cost associated with further voyage-level CO₂-emission reduction.

Transitioning from the HFO low-speed configuration (Case 7) to the B30 low-speed configuration (Case 9) reduced voyage-level CO₂ emissions by approximately 269 tCO₂/voyage while increasing voyage-level operational cost by approximately 184,000 EUR/voyage.

The resulting marginal decarbonisation cost was approximately 684 EUR/tCO₂ avoided. Detailed calculation steps are provided in Supplementary Materials Section S10.

Figure 6 illustrates the cost–emissions relationship for all analysed scenarios and identifies the Pareto frontier.

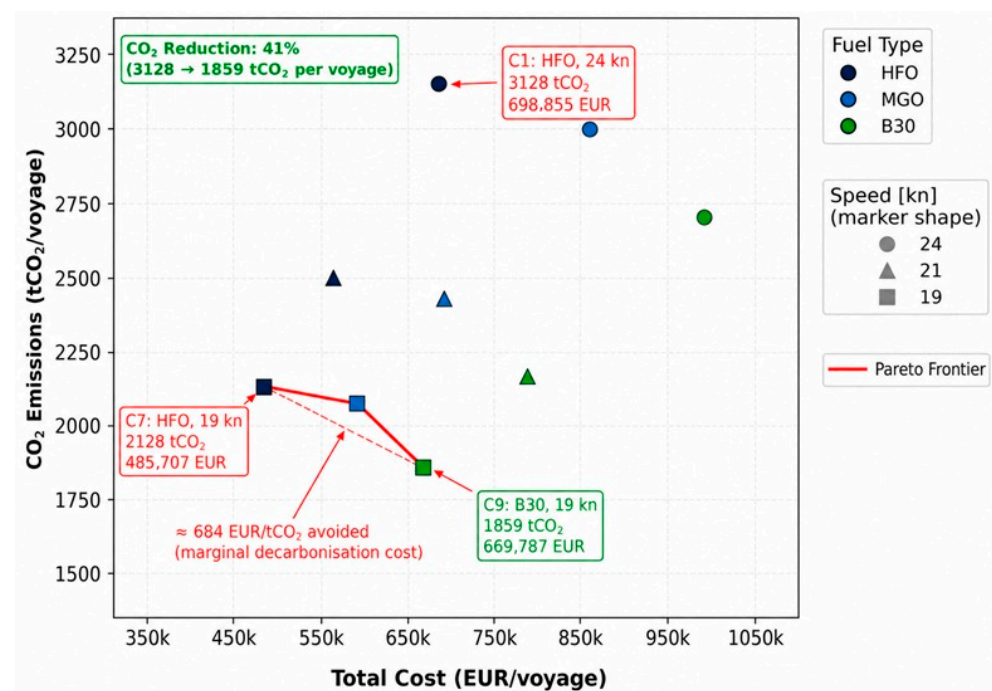


Figure 6. Pareto relationship between voyage-level operational cost and CO₂ emissions for the investigated fuel-speed operational configurations. Note: Marker colours indicate fuel type. Marker shapes indicate operational speed. The Pareto frontier connects Cases 7, 8, and 9 (all at 19 kn). The frontier line identifies non-dominated operational scenarios.

4.9.3. Operational Decarbonisation Frontier

The Pareto frontier identified three non-dominated low-speed operational configurations corresponding to the 19 kn operating condition: Case 7 (HFO), Case 8 (MGO), and Case 9 (B30).

Within the analysed operational space, the HFO configuration represented the minimum-cost solution, while the B30 configuration represented the minimum-emission solution. The MGO configuration provided an intermediate trade-off between operational cost and emissions reduction.

4.10. Economic Sensitivity and Break-Even Carbon Price Analysis

The economic sensitivity assessment examined the influence of fuel-price volatility and EU ETS carbon-price variation on total voyage cost.

Table 14 summarises the corresponding cost changes under $\pm 20\%$ fuel-price variation and carbon-price scenarios of 50, 70, 90, and 150 EUR/tCO₂.

Table 14. Sensitivity of operational cost to fuel-price and carbon-price variation.

Case	Scenario	Base Case	Fuel Price −20%	Fuel Price +20%	50 EUR/tCO ₂	90 EUR/tCO ₂	150 EUR/tCO ₂
C1	HFO, 24 kn	698,855	602,881	794,828	636,287	761,423	949,126
C7	HFO, 19 kn	485,707	418,357	553,057	443,148	528,266	655,942
C9	B30, 19 kn	669,787	561,852	777,721	632,611	706,963	818,490

Note: Base case: 70 EUR/tCO₂ and reference fuel prices from Section 3.7.4. All values in EUR/voyage.

The results indicate that fuel-price variation had a larger influence on total operational cost than moderate EU ETS carbon-price fluctuations within the analysed range. The additional time-cost effect associated with slow steaming is reported separately in Supplementary Materials Section S11.

Using Equation (19) and the fuel-cost difference between Cases 7 and 9, both corresponding to the same voyage duration (19 kn operation), the estimated break-even carbon price is:

$$P_{\text{CO}_2, \text{break-even}} \approx 754 \frac{\text{EUR}}{\text{tCO}_2}$$

Table 15 summarises the sensitivity of the estimated break-even EU ETS carbon price to alternative B30 fuel-price assumptions.

Table 15. Sensitivity of break-even carbon price to B30 fuel price.

B30 Price [USD/t]	Break-Even Carbon Price [EUR/tCO ₂]
720	406
810	580
900	754
1080	1102

An additional break-even assessment was performed for the biofuel case certified under the current Renewable Energy Directive (RED) framework (Scenario A). Under this accounting approach, voyage-level CO₂ emissions for Case 9 decrease from 1858.8 to 1600.9 tCO₂/voyage, while the voyage-level operational cost remains unchanged. Relative to the HFO reference case (Case 7), the corresponding CO₂-emission reduction increases from approximately 269 to 527 tCO₂/voyage.

Using the same fuel-cost difference between Cases 7 and 9, the estimated break-even carbon price decreases from approximately 754 EUR/tCO₂ to approximately 385 EUR/tCO₂. This result highlights the economic importance of sustainability certification and demonstrates the strong influence of the adopted carbon-accounting framework on the economic competitiveness of certified biofuel blends.

The corresponding results are summarised in Table 16.

Table 16. Effect of sustainability certification on break-even carbon price.

Scenario	ΔCO_2 Relative to Case 7 [tCO ₂ /Voyage]	Break-Even Carbon Price [EUR/tCO ₂]
Scenario B	269.2	754
Scenario A	527.0	385

Note: Both scenarios use the same voyage-level fuel-cost difference between Cases 7 and 9. The difference arises exclusively from the adopted carbon-accounting approach and the resulting CO₂ reduction.

Figure 7 illustrates the break-even carbon-price relationship between the two representative low-speed operational configurations identified in the Pareto trade-off analysis.

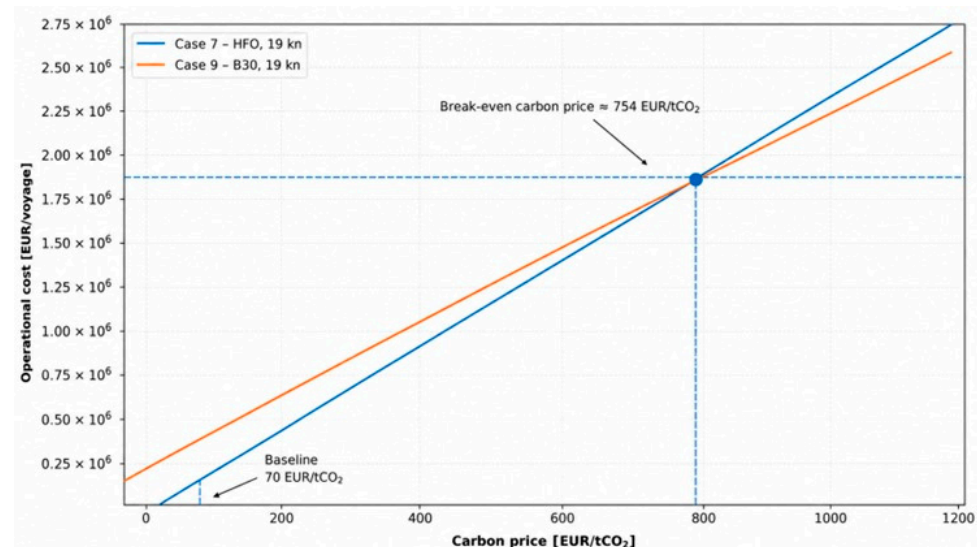


Figure 7. Break-even carbon-price analysis for the Pareto-optimal scenarios (Case 7: HFO, 19 kn; Case 9: B30, 19 kn). Note: The intersection point indicates economic equivalence between Cases 7 and 9.

The marginal decarbonisation cost was approximately 684 EUR/tCO₂ avoided, while the corresponding break-even carbon price was approximately 754 EUR/tCO₂.

Monte Carlo Uncertainty Assessment

A supplementary Monte Carlo assessment (10,000 iterations) was performed for the Pareto-optimal low-speed operational configurations (Cases 7 and 9) in order to evaluate the influence of combined operational and market uncertainty.

The simulation considered simultaneous variation in SFOC, speed–power exponent, fuel prices, and EU ETS carbon price within the ranges defined in Table 6.

The stochastic assessment is intended to provide comparative uncertainty ranges rather than probabilistic forecasting of future market behaviour.

The median marginal abatement cost was approximately 685 EUR/tCO₂ avoided (5th percentile: 416 EUR/tCO₂; 95th percentile: 954 EUR/tCO₂), while the median break-even carbon price was approximately 756 EUR/tCO₂ (5th percentile: 487 EUR/tCO₂; 95th percentile: 1023 EUR/tCO₂).

Figures 8 and 9 illustrate the resulting probability distributions for MAC and break-even carbon price, respectively. Detailed statistical assumptions and supplementary results are provided in Supplementary Materials Section S9.

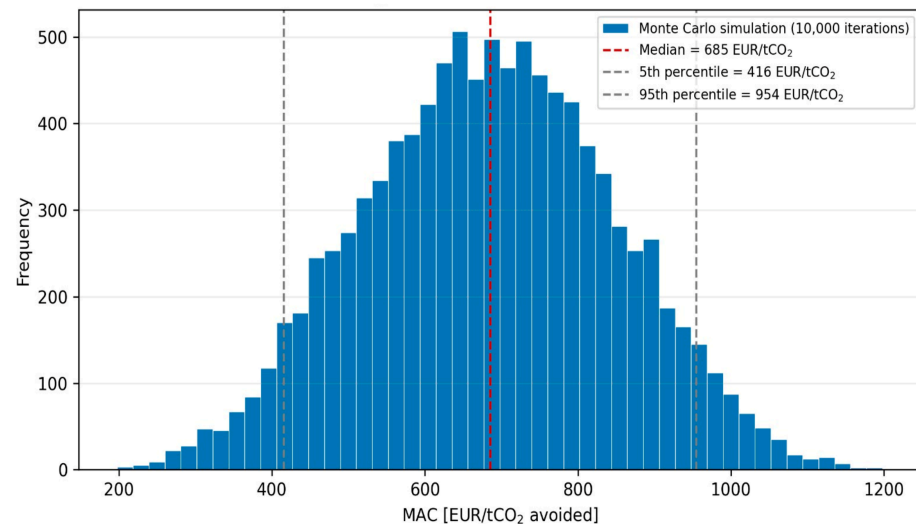


Figure 8. Monte Carlo distribution of marginal abatement cost (MAC) for the Pareto-optimal low-speed operational configurations (Cases 7 and 9).

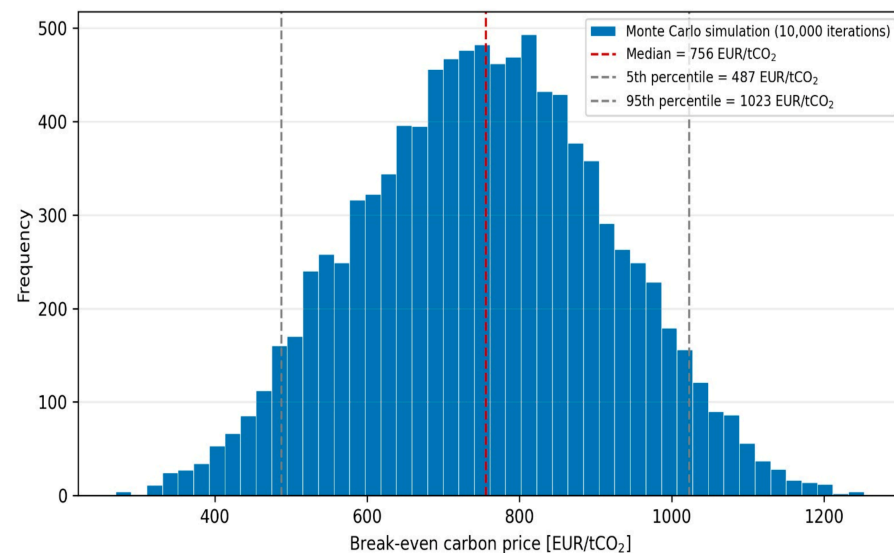


Figure 9. Monte Carlo distribution of break-even carbon price for the Pareto-optimal low-speed operational configurations (Cases 7 and 9).

5. Discussion

The results provide a quantitative basis for evaluating the environmental and economic performance of operational decarbonisation strategies for existing container vessels. This section interprets the main trade-offs associated with operational speed reduction, fuel switching, and regulatory carbon exposure.

5.1. Operational Implications of Slow Steaming

Reducing vessel speed from 24 kn to 19 kn produced the largest decrease in voyage-level fuel consumption, CO₂ emissions, and EU ETS exposure across all analysed operational scenarios. Total fuel consumption decreased by approximately 32%, confirming that operating speed remained the dominant parameter affecting voyage-level energy performance [10,14,15]. At lower speeds, auxiliary-engine fuel consumption increased because of longer voyage duration, partially moderating the reduction in EEOI values.

Benchmarking against AIS-derived studies and EU Maritime MRV datasets for comparable 4000–6000 TEU post-Panamax container vessels showed satisfactory agreement between the simplified voyage-level framework and published operational data [9,10,13,15]. Relative deviations ranged from 0.41% to 19.78%, with fuel-specific MAPE values of 3.47% (HFO), 7.63% (MGO), and 4.92% (B30).

The sensitivity analysis showed that the operational advantages of slow steaming remained significant even under representative low-load engine penalties. Applying partial-load SFOC correction factors of +10–15% at approximately 42% MCR reduced the predicted fuel-consumption benefit at 19 kn from about 32% to approximately 24–26%. Nevertheless, the reduced-speed scenarios continued to produce the lowest fuel consumption and CO₂ emissions among the analysed cases.

Variations in the speed–power exponent between $n = 2.8$ and $n = 3.2$ modified predicted fuel consumption by approximately $\pm 4\%$ relative to the baseline assumption of $n = 3.0$, without changing the comparative ranking of the analysed operational scenarios. This indicates that the relative environmental and economic advantages associated with reduced operating speed remain robust under representative propulsion-model uncertainty.

These findings are particularly relevant for ageing container vessels, where propulsion retrofits or alternative-fuel conversion may be economically difficult to justify [6,8]. Under such conditions, slow steaming remains one of the few immediately applicable operational measures capable of reducing fuel consumption, emissions, and regulatory carbon exposure without major propulsion-system modification.

The analysed 19–21 kn operating conditions correspond to commercially realistic slow-steaming regimes already observed within parts of the European container fleet [10,15]. However, reduced operating speed also increases voyage duration and may affect schedule flexibility within liner services operating under fixed timetable constraints. On the Rotterdam–Limassol route, reducing speed from 24 kn to 19 kn increased voyage duration by approximately 1.46 days, partially offsetting the direct fuel cost and EU ETS savings associated with lower fuel consumption.

Overall, the results indicate that slow steaming currently represents the most practical short-term operational decarbonisation measure for ageing container vessels operating under European environmental regulation. Its economic attractiveness nevertheless remains dependent on route structure, schedule constraints, vessel-utilisation costs, and wider liner-shipping market conditions.

5.2. Role of Alternative Fuels Under EU ETS and FuelEU Maritime

The analysed MGO and B30 configurations reproduced operational behaviour consistent with previously reported marine-fuel studies [9,31]. Because the assessment was based on an energy-equivalent approach, total voyage-level energy consumption remained broadly similar between fuels operating at the same speed, while the principal differences between scenarios were reflected in CO₂ emissions, EEOI, and TTW GHG-intensity values. The MGO cases produced slightly lower mass-based fuel consumption and GHG-intensity values than the corresponding HFO configurations because of the higher lower heating

value of distillate fuels. The B30 blend produced the lowest TTW GHG-intensity and emissions values because of the lower effective carbon intensity of the biogenic fuel fraction.

The analysed B30 scenarios indicate that partial biofuel substitution can reduce voyage-level CO₂ emissions without requiring major propulsion-system modifications, making biofuel blends a potentially attractive transitional option for ageing container vessels operating under tightening European environmental regulation [6,7]. Compared with operational measures such as slow steaming, fuel substitution affects emissions intensity more directly than transport efficiency, highlighting the complementary relationship between operational optimisation and lower-carbon fuel strategies.

The economic attractiveness of biofuel use nevertheless remains strongly dependent on fuel prices and carbon-cost levels. Under the adopted market assumptions, the lower bunker price of HFO continued to provide a substantial economic advantage relative to the analysed MGO and B30 configurations. Although the lower-carbon fuel scenarios reduced voyage-level CO₂ emissions and EU ETS exposure, the associated reduction in carbon cost was insufficient to offset the higher operational cost associated with marine biofuel blends at current fuel-price and carbon-price levels.

The results also illustrate the increasing importance of lifecycle-based emissions accounting within European maritime regulation. Whereas the EU ETS monetises direct onboard CO₂ emissions, FuelEU Maritime increasingly favours fuels with lower lifecycle greenhouse-gas intensity. Consequently, sustainability certification and upstream fuel-production pathways become important factors influencing the long-term regulatory attractiveness of alternative marine fuels.

The comparison between the conservative TTW-based B30 scenario and the certification-based scenario under the current RED framework further illustrates the sensitivity of emissions assessment to the adopted accounting methodology. When the biogenic fraction is recognised under the current RED framework, additional reductions in voyage-level CO₂ emissions are obtained relative to the conservative TTW assumptions adopted in the main analysis. These differences highlight the influence of sustainability certification and regulatory accounting assumptions on the resulting emissions indicators. However, the reported TTW GHG-intensity values should not be interpreted as direct FuelEU Maritime compliance values, since the present assessment does not include full WTW lifecycle accounting.

For liner operators on routes similar to Rotterdam–Limassol, the results suggest that biofuel blends may become progressively more attractive under higher carbon prices, improved fuel availability, and stronger lifecycle-based regulatory incentives. However, the analysis does not account for fuel-supply limitations, regional bunker availability, or long-term procurement constraints associated with large-scale biofuel deployment.

5.3. Economic Feasibility and Carbon Pricing

The Pareto assessment identified three representative non-dominated low-speed operational configurations: Case 7 (HFO, 19 kn), representing the minimum-cost solution; Case 8 (MGO, 19 kn), representing an intermediate operational trade-off; and Case 9 (B30, 19 kn), representing the minimum-emission solution. All remaining operational scenarios were classified as dominated because at least one alternative configuration achieved both lower operational cost and lower voyage-level CO₂ emissions.

The results indicate that reduced vessel speed remained the dominant factor for simultaneously lowering both operational cost and voyage-level CO₂ emissions. All non-dominated configurations corresponded to the lowest analysed operating speed (19 kn), confirming the strong influence of slow steaming on propulsion energy demand and EU ETS exposure. Within the low-speed operating conditions, progressive substitution from

HFO to MGO and subsequently to B30 reduced emissions while increasing operational cost, illustrating the economic trade-off associated with incremental decarbonisation.

The economic attractiveness of slow steaming nevertheless depends partly on the additional voyage time associated with reduced operating speed. On the Rotterdam–Limassol route, reducing speed from 24 kn to 19 kn increased voyage duration by approximately 1.46 days, introducing additional vessel-utilisation costs that partially offset the fuel-cost and EU ETS savings obtained through lower fuel consumption. However, under the analysed charter-rate assumptions, the reduction in fuel consumption and carbon exposure remained sufficient to compensate for the additional time-related penalty.

The analysis also showed that the comparatively low bunker price of HFO continued to provide a substantial economic advantage relative to the analysed MGO and B30 configurations. Although the lower-carbon fuel scenarios reduced voyage-level CO₂ emissions and EU ETS exposure, the associated reduction in carbon cost remained insufficient to offset the higher operational cost associated with marine biofuel blends under the analysed market conditions.

The break-even assessment demonstrated that the carbon price required for the low-speed B30 configuration to achieve cost parity with the corresponding HFO case remained substantially above EU ETS allowance prices observed during 2024–2025 [28,29]. The marginal decarbonisation assessment produced a corresponding abatement cost of approximately 684 EUR/tCO₂ avoided when transitioning from the minimum-cost HFO configuration to the minimum-emission B30 configuration. When the biofuel pathway is considered under the certification-based scenario defined within the current RED framework, the break-even carbon price decreases substantially. This result indicates that sustainability certification may significantly improve the economic attractiveness of biofuel-based decarbonisation strategies.

The sensitivity analysis further showed that the economic competitiveness of the B30 configuration remained strongly dependent on the marine-biofuel price. Lower biofuel prices substantially reduced the break-even carbon price required for economic competitiveness, indicating that future reductions in biofuel production cost and improved fuel availability may influence operational feasibility more strongly than moderate variation in EU ETS allowance prices alone.

Overall, the results indicate that slow steaming currently represents the most economically accessible short-term decarbonisation measure for ageing container vessels operating under European environmental regulation. Wider adoption of marine biofuels would likely require either substantially higher carbon prices or improved biofuel-market competitiveness supported by larger production scale and stronger lifecycle-based regulatory incentives.

5.4. Operational Trade-Offs Under European Maritime Regulation

The Pareto analysis illustrates the operational trade-off between short-term economic performance and voyage-level emissions reduction for existing container vessels operating under European environmental regulation. Within the analysed operational space, the low-speed HFO configuration represented the minimum-cost solution, whereas the low-speed B30 configuration produced the lowest CO₂ emissions.

The results suggest that operational optimisation alone may not be sufficient to achieve deeper long-term decarbonisation targets, particularly under increasingly stringent lifecycle-based regulatory frameworks. At the same time, practical liner-shipping decisions remain influenced by additional operational constraints such as schedule reliability, cargo-delivery commitments, port coordination, and regional fuel availability [33].

For routes similar to Rotterdam–Limassol, hybrid strategies combining moderate speed reduction with partial fuel substitution may become progressively more attractive under higher carbon prices and stronger lifecycle-based regulation. The relative competitiveness of these strategies will nevertheless remain dependent on fuel-market conditions and operational flexibility within individual liner networks.

5.5. Methodological Limitations

The proposed framework is based on a simplified deterministic voyage-level methodology for comparative assessment of operational decarbonisation strategies for existing container vessels operating under European environmental regulation.

The environmental assessment is based primarily on Tank-to-Wake (TTW) emissions accounting rather than the complete Well-to-Wake (WTW) methodology applied under FuelEU Maritime [4]. Consequently, the reported GHG-intensity values reflect onboard operational emissions only and should not be interpreted as direct FuelEU Maritime compliance values. The relative environmental performance of the analysed fuels may vary depending on feedstock origin, upstream production emissions, fuel-production pathway, and sustainability certification [17].

The present assessment does not include pathway-specific WTW GHG-intensity calculations or FuelEU Maritime compliance-balance evaluation. These elements depend on certified fuel-pathway data and corresponding WTT emission values.

The modelling framework assumes steady-state operating conditions characterised by constant vessel speed, engine load, and environmental conditions throughout each voyage. In practical operation, fuel consumption and emissions are additionally influenced by weather conditions, sea state, routing decisions, hull fouling, manoeuvring operations, and port congestion [6,18].

The propulsion model further assumes constant main-engine specific fuel oil consumption (SFOC) together with a fixed speed–power relationship based on the adopted cubic approximation. Although representative low-load SFOC correction factors were included through sensitivity analysis, engine operation near 40–45% MCR may increase SFOC under deep slow-steaming conditions [14,15]. Similarly, variation in the adopted speed–power exponent ($n = 2.8\text{--}3.2$) modified predicted fuel consumption by approximately $\pm 4\%$ relative to the baseline assumption.

The environmental performance of the B30 scenarios also depends on the adopted emission factors and certification assumptions. In practice, the lifecycle greenhouse-gas performance of marine biofuels may vary according to feedstock origin, upstream processing, transport pathway, and sustainability certification requirements [4,17].

The analysis further assumes identical auxiliary-engine operation in all scenarios, with auxiliary generators continuously operating on MGO regardless of the selected propulsion fuel. In practical operation, auxiliary-engine fuel switching could further reduce voyage-level CO₂ emissions within the lower-carbon fuel scenarios.

The economic assessment does not explicitly represent factors such as long-term fuel procurement agreements, freight-market variability, fleet deployment constraints, schedule-recovery costs, or regional fuel availability. In addition, the Pareto assessment was based on a limited number of discrete operational scenarios rather than continuous optimisation of vessel speed and fuel-blend ratio.

A supplementary Monte Carlo assessment was included to evaluate the combined influence of technical and economic uncertainty on marginal decarbonisation cost and break-even carbon-price variability.

Nevertheless, the framework remains suitable for comparative evaluation of operational decarbonisation pathways for existing container vessels operating under evolving European maritime regulation. Future work should focus on dynamic voyage modelling, lifecycle-based WTW assessment, weather-routing integration, and expanded stochastic treatment of fuel-price and carbon-market uncertainty.

5.6. Policy and Operational Implications

The results indicate that current European maritime regulation increasingly links operational decision-making to both carbon pricing and lifecycle-based emissions performance. Whereas the EU ETS directly increases the cost associated with onboard CO₂ emissions, FuelEU Maritime progressively favours fuels with lower lifecycle greenhouse-gas intensity.

Under the analysed operating and market conditions, slow steaming remained the most economically accessible short-term measure for reducing fuel consumption and EU ETS exposure for ageing container vessels operating on established liner services. For the investigated operational scenarios, reducing operating speed to 19 kn decreased fuel cost by approximately 30–33% and reduced voyage-level CO₂ emissions and EU ETS exposure by approximately 31–32%.

By comparison, wider adoption of lower-carbon fuels remained constrained by fuel price, fuel availability, sustainability certification, and carbon-market conditions. The results further indicate that operational decarbonisation strategies cannot be evaluated solely through fuel cost or emissions reduction because practical liner-shipping decisions remain influenced by schedule reliability, port rotation, cargo-delivery commitments, and regional bunker availability.

The results indicate that operational optimisation and partial fuel substitution can provide meaningful short-term emissions reduction for existing container vessels, whereas long-term alignment with international climate targets will likely require broader deployment of alternative fuels, lifecycle-based regulation, technological development, and gradual fleet renewal [1,34,35].

5.7. Policy Implications for EU Regulators

The results suggest that current EU ETS carbon price levels (50–80 EUR/tCO₂) provide limited direct incentive for biofuel adoption in container shipping, absent additional mechanisms. FuelEU Maritime's lifecycle-based approach may complement carbon pricing by penalising high-WTW-intensity fuels regardless of price. Policymakers may consider: (i) separate compliance credits for certified sustainable biofuels [36], (ii) targeted subsidies or co-funding mechanisms for biofuel trials, or (iii) higher carbon price floors in the maritime ETS sector. However, detailed policy design is beyond the scope of this study.

6. Conclusions

Reducing operating speed from 24 kn to 19 kn decreased voyage-level fuel consumption and CO₂ emissions by approximately 32% across all analysed operational scenarios, confirming slow steaming as the most effective short-term decarbonisation measure for the investigated 5000 TEU container vessel. Even after applying representative low-load SFOC corrections, the reduced-speed configurations continued to produce the lowest fuel consumption and EU ETS exposure among the analysed cases.

Combining slow steaming with lower-carbon fuels further reduced voyage-level emissions and TTW GHG-intensity values [37,38]. However, under the adopted market assumptions, the analysed B30 configurations remained economically disadvantaged relative to the corresponding HFO cases because the reduction in EU ETS cost did not offset the higher biofuel price. The estimated break-even carbon price for the low-speed B30

configuration (approximately 754 EUR/tCO₂) remained substantially above current EU ETS allowance levels.

The results indicate that operational decarbonisation strategies for existing container vessels are increasingly shaped by the combined influence of EU ETS carbon pricing and FuelEU Maritime lifecycle-based regulation [39]. Under current market conditions, operational optimisation provides the most immediately applicable emissions-reduction measure for ageing vessels, whereas wider adoption of lower-carbon fuels remains dependent on fuel-market competitiveness, sustainability certification [40] and future carbon-price evolution.

The proposed framework integrates voyage-level fuel-consumption modelling, TTW emissions assessment, EU ETS exposure estimation [41], operational benchmarking, and Pareto-based trade-off analysis within a unified comparative methodology. The analysis nevertheless remains subject to several limitations, including simplified steady-state operating conditions, TTW-based environmental assessment, and the exclusion of weather variability, dynamic routing, and port-congestion effects. Future work should focus on integrating lifecycle-based WTW assessment, FuelEU Maritime compliance-balance evaluation, dynamic voyage modelling, operational liner-service constraints, and real-time operational data within more advanced stochastic decarbonisation frameworks.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/jmse14141296/s1>, Table S1: Carbon emission factor of B30 blend; Table S2: Literature benchmark data by fuel type and speed; Table S3: Statistical error metrics (AE, RE, MAPE, RMSE); Table S4: Speed-reduction trend validation; Table S5: Model consistency with benchmark ranges; Figures S1–S3: Validation plots for HFO, MGO, and B30 fuel-consumption trends versus vessel speed; Table S6: Fuel properties and theoretical energy-equivalent SFOC values used for the fuel-consumption correction; Table S7: Comparison between IMO-type load correction and adopted sensitivity cases; Table S8: Sensitivity of auxiliary-engine fuel consumption to the adopted auxiliary-load assumption; Table S9: Statistical summary of Monte Carlo uncertainty assessment for Cases 7 and 9; Table S10: Time-cost sensitivity associated with slow steaming-induced voyage extension.

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Abbreviations

The following abbreviations are used in this manuscript:

AE	Auxiliary Engine
B30	Biofuel blend (30% FAME, 70% fossil fuel)
CF	Carbon emission factor
CO ₂	Carbon dioxide
DCS	Data Collection System
EEOI	Energy Efficiency Operational Indicator
EU	European Union
EU ETS	European Union Emissions Trading System
FAME	Fatty Acid Methyl Ester
GCMD	Global Centre for Maritime Decarbonization
GHG	Greenhouse Gas
HFO	Heavy Fuel Oil
IMO	International Maritime Organisation
LHV	Lower Heating Value
MAPE	Mean Absolute Percentage Error
MCR	Maximum Continuous Rating
ME	Main Engine
MGO	Marine Gas Oil
MRV	Monitoring, Reporting and Verification
nm	Nautical miles
RE	Relative errors
RED	Renewable Energy Directive framework (RED II and RED III)
RMSE	Root Mean Square Error
SFOC	Specific Fuel Oil Consumption
TEU	Twenty-foot Equivalent Unit
TTW	Tank-to-Wake
WTW	Well-to-Wake

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