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Techno-economic analysis of decarbonization pathways for a deep-sea container vessel

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ABSTRACT
This study identifies a cost-effective decarbonization strategy for a deep-sea container vessel to meet the greenhouse gas emission (GHG) reduction targets set by the International Maritime Organization (IMO) and European Union (EU). For assumed scenarios for technology availability and costs until 2040, we assess the techno-economic viability of selected energy-saving technologies and alternative fuels under regulatory constraints. Our findings indicate that, for the considered vessel type, speed reduction, air lubrication, and hull maintenance are the most cost-efficient measures to reduce GHG emissions through 2030, after which stricter regulatory thresholds make it necessary to shift to clean alternative fuels. Among the alternative fuels evaluated, we identify ammonia as the most cost-effective.

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Container ships; maritime decarbonization; techno-economic analysis; clean technologies; emission reduction; regulations; decarbonization pathway; alternative fuels

1. Introduction

Maritime shipping is a cornerstone of global trade, transporting over 80% of all traded goods by volume (IMO 2020). Between 2025 and 2029, global seaborne trade is projected to grow at an average annual rate of 2.4%, while containerized trade is expected to expand by 2.7% per year (UNCTAD 2024). However, this anticipated growth brings a challenge in terms of an escalating energy demand. Presently, the shipping industry predominantly relies on fossil fuels to meet its energy needs, with heavy fuel oil (HFO) and marine gas oil (MGO) accounting for as much as 95% of total demand (IRENA 2021). This dependency on fossil fuels constitutes a major source of greenhouse gas (GHG) emissions in the sector.

To reduce maritime GHG emissions, in 2023 the IMO adopted a revised GHG reduction strategy, targeting net-zero emissions by around 2050 (MEPC 2023). To achieve this goal, the IMO has introduced several regulations. MEPC (2022c) introduced the Energy Efficiency Existing Ship Index (EEXI), which sets design-based carbon dioxide (CO_2) emission limits (gCO_2/t.nm) for ships above 400 gross tonnage (GT). These limits are verified once per vessel and are typically met through engine power limitation (EPL) or retrofitting (MEPC 2022c). Additionally, MEPC (2021a) introduced the Carbon Intensity Indicator (CII), which measures annual tank-to-wake (T-T-W) carbon intensity. Based on this metric, vessels over 5,000 GT are rated from A to E, with corrective actions required after two consecutive D ratings or one E rating. The indicator aims for a 70% reduction in carbon intensity by 2040 relative to 2008 levels (MEPC 2023). Complementing IMO's efforts, the EU has extended its Emissions Trading System (ETS) to include maritime transport. The EU Emissions Trading System (EU ETS), extended to shipping in 2024, applies to vessels over 5,000 GT and covers 100% of emissions between EU ports and 50% on international legs. Carbon prices are projected to rise from €95/tCO_2 in 2025 to €170/tCO_2 by 2040 (S&P Global Ratings 2022; Brand et al. 2023; IMO 2024). Meanwhile, FuelEU Maritime, effective from 2025, enforces gradually stricter well-to-wake (W-T-W) GHG intensity limits and introduces penalties for non-compliance. Additionally, from 2030, container ships are obliged to use onshore power at EU ports, although its impact is limited for vessels with short port stays (EU 2023a). Figure 1 presents assumed EU ETS costs along with regulatory requirements. Together, these instruments form a complex and overlapping regulatory environment that will influence investment and operational decisions across the global fleet.

The decarbonization of maritime transport has been widely studied, focusing on cost-effectiveness, energy-saving technologies, alternative fuels, and regulatory impacts. Ammar and Seddiek (2020) examined dual-fuel LNG engines, and speed reduction on

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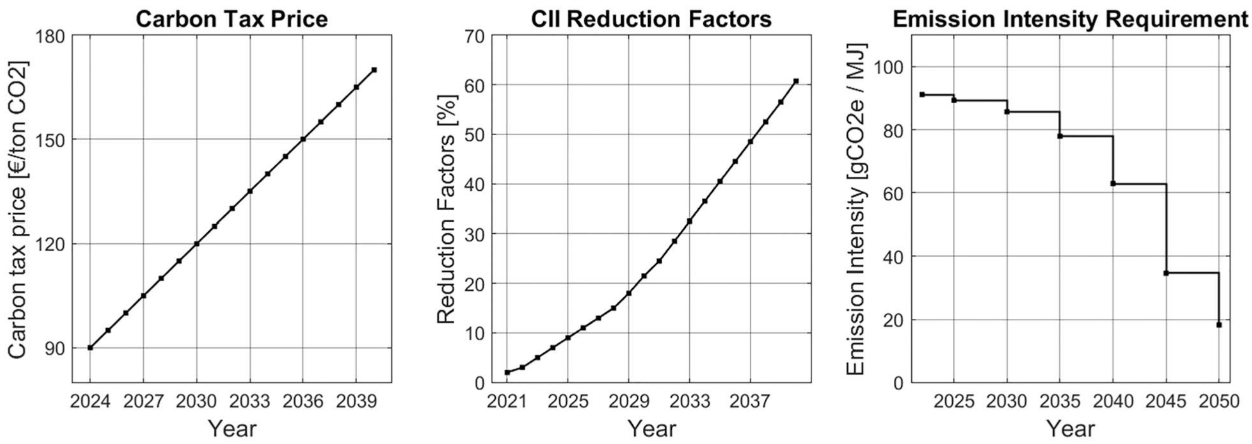

Figure 1. Assumed carbon tax prices, CII reduction factors and FuelEU Maritime intensity requirements till 2040.

container ships, noting strong emissions-reduction potential. Czermański et al. (2022) evaluated alternative fuels and technologies for EEXI compliance, highlighting the lack of a universal solution. Schroer et al. (2022) identified EPL as the most cost-effective measure under EEXI and CII. Balcombe et al. (2019) and Wang et al. (2023) discussed the emissions potential of alternative fuels and associated regulatory challenges. Solakivi et al. (2022) found alternative fuels currently uncompetitive under EU ETS and FuelEU Maritime. Foretich et al. (2021), Gore et al. (2022), and Kouzelis et al. (2022) assessed operational barriers and fuel selection using techno-economic and optimization approaches. Elkafas et al. (2023) examined speed impacts on EEXI/CII under EU ETS. Al-Enazi et al. (2021) and Lagouvardou et al. (2023) explored cleaner fuel alternatives and their cost-effectiveness, while Prussi et al. (2021) emphasized the importance of fuel maturity and safety. DNV (2019) provided an overview of alternative fuel viability. Recent institutional reports have expanded this work including IMO (2024), which modelled mid-term measures shaping fuel transitions, DNV (2024) analyzed multiple pathways emphasizing efficiency and flexibility, and ABS (2024) developed a framework for evaluating technology readiness and regulatory alignment.

Despite extensive research, a clear decarbonization pathway for the maritime sector remains unclear. Given the diversity of vessel types and operational profiles, no single solution can apply across the global fleet. Therefore, developing targeted strategies for specific ship segments is essential. In this context, this study presents a comprehensive, techno-economic decarbonization pathway for Neo-Panamax (~10,000 TEU) container ships, one of the most influential segments in global trade. Unlike broader fleet wide analyses or fuel specific studies, this work integrates energy-saving technologies, fuel options, and regulatory scenarios (IMO and EU) into a single-vessel modelling framework. The analysis extends through 2040 and combines detailed cost modelling, sensitivity analysis, and regulatory compliance assessment, offering a practical, scalable roadmap tailored to a high-impact vessel type.

2. Research approach

This study evaluates decarbonization strategies for a representative deep-sea Neo-Panamax container vessel sailing between Asia and Europe. A typical voyage profile is selected based on common origin–destination pairs, operational frequency, and technical specifications. Key parameters such as distance travelled, cargo capacity, engine type, and fuel consumption are derived from vessel-specific data and used to estimate annual energy use.

The analysis framework compares the additional lifetime cost of implementing technologies, expressed as cost per twenty-foot equivalent unit (TEU)-nautical mile. The economic performance is assessed using the Net Present Value (NPV) method. Cost calculations are based on discounted cash flow modelling using a 5% discount rate. CAPEX is assumed constant over time, with cost reductions offset by inflation. Total cost (TC) is computed using investment and operating parameters, and savings achieved through fuel reduction or regulatory incentives. The formulas for calculating total cost are adopted from IMO (2020), as per Equation (2),

$$C_t = AC_t - FC_t - EC_t - FP_t, \quad (1)$$

$$TC = K + NPV(C_t), \quad (2)$$

where TC is the total additional lifetime cost of technology implementation, K is the CAPEX of technology, AC is the annual maintenance and additional cost of technology, FC is annual fuel cost savings achieved by implementing the technology, EC is annual carbon tax saved, and FP is an annual penalty under FuelEU Maritime saved. Compliance with IMO regulations is assessed in sequence, as shown in Figure 2. Regulatory calculations are implemented in custom-

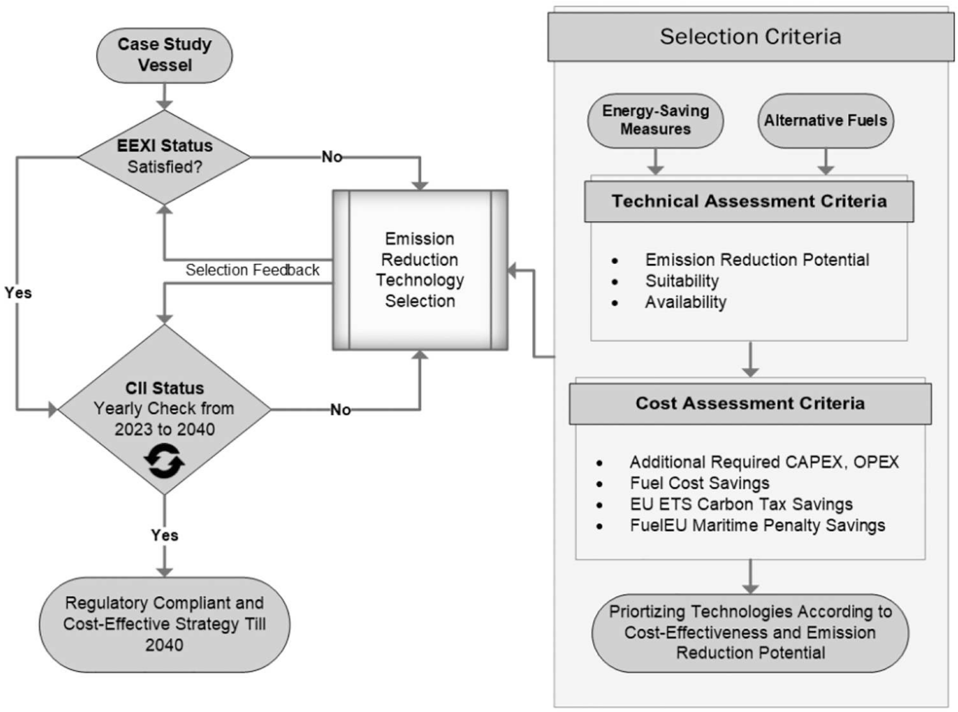

Figure 2. Framework to define a cost-efficient decarbonization strategy.

built MATLAB calculators, benchmarked against validation examples from IACS (2020) and MEPC (2022b).

3. Case study

3.1. Case study vessel description

The case study considers a typical 10,000 TEU container vessel built in 2015. The vessel lifetime is assumed to be 25 years; thus, the vessel is assumed to remain in operation till 2040. Table 1 and Table 2 mention vessel specifications and parameters at service speed.

The vessel's operating profile includes sailing at a service speed, manoeuvering, canal transit, and port modes. HFO is assumed to be used at service speed, while MGO is assumed to be used in emission control areas (ECA). Steam generation and auxiliary heating are assumed to be provided by an exhaust gas boiler (EGB) at service speed, and by an auxiliary boiler (BLR) during manoeuvering, anchorage, and port stays. At service speed a single auxiliary engine (AE) is assumed to be operated at full load using HFO, whereas manoeuvering and canal transit is assumed to require two AEs running on MGO. Port stays are assumed to require a single AE running on MGO (Sontakke 2023). Dependencies between power and speed, as well as between power and specific fuel oil consumption (SFOC) are estimated as per Equation (3) and Equation (4).

Table 3 presents the estimated overall annual fuel consumption for the assumed operating profile. Downtime for dry docking or retrofitting is not included in the analysis.

Table 1. Specifications of the case study vessel (Scheepvaartwest 2016).

Name	Details
Type	Container Vessel
20 ft container capacity	10,000 TEU
Gross Tonnage (GT)	1,13,042 t
Deadweight (DWT)	1,19,359 t
Built year	2015
Length	336.96 m overall 321.78 m between perpendicular
Breadth extreme	48.33 m
Draught	15.52 m
Speed	Max: 23.80 knots Service: 21.00 knots
Main Engine Power	58,116 kW@ 84 RPM
Main Engine SFOC	167 g/kWh (MAN 2012)
Auxiliary Engines	3 × 3300 kW
Auxiliary Engine SFOC	188 g/kWh (DAIHATSU 2023)

Table 2. Operational parameters for a service speed of 21 knots.

Parameters	Values
Service speed	21 Knots
One Voyage (Singapore-Rotterdam)	9,343 nm (Ports 2023)
Annual Voyages	15
Annual Distance	1,39,880 nm
Engine Load	75%
Annual Main Engine (ME) Fuel Consumption	48,241 MT
Total Annual Fuel Consumption	53,566 MT
Total Cargo Carried for one voyage	8,000 TEU
Annual Cargo Carried	1,20,000 TEU

3.1.1. Initial EEXI rating

Attained and required EEXI values are calculated using equations provided in MEPC (2022c) and IMO (2021a) guidelines respectively. Carbon factors on T-T-W basis for fuels are mentioned in Table 4. AE and ME are defined assuming that there are no

Table 3. Estimated annual fuel consumption of the vessel at 21 knots.

	HFO (MT)			MGO (MT)				
Mode	ME	AE	BLR	ME	AE	BLR	Total	Days
At Sea	48,241	2,887	0	0	0	0	51,128	275
Manoeuvering	0	0	0	540	630	120	1,290	30
Canal Transit	0	0	0	120	315	60	495	15
Port	0	0	0	0	472.5	180	652.5	45
Total	48,241	2,887	0	660	1,417	360	53,566	365

Table 4. T-T-W carbon factors (Cf) for different fuel types.

Fuel type	Cf [tCO_2/t-Fuel]	Source
Heavy Fuel Oil (HFO)	3.114	(MEPC 2014)
Marine Gas Oil (MGO)	3.206	(MEPC 2014)
Liquified Natural Gas (LNG)	2.750	(MEPC 2014)
Biofuels (FAME)	2.834	(EU 2023a)
Biofuels (HVO)	3.115	(EU 2023a)
Methanol	1.375	(MEPC 2014)
Ammonia	0	(MEPC 2021b)
Hydrogen	0	(MEPC 2021b)

power take-in system or energy-saving devices. The initial EEXI attained is 13.86 (gCO_2/t.nm), exceeding the required limit of 10.80 (gCO_2/t.nm) as shown in Figure 3. Accordingly, 2023 is taken as the compliance baseline, and the vessel is assumed to adopt energy-saving measures to meet EEXI standards.

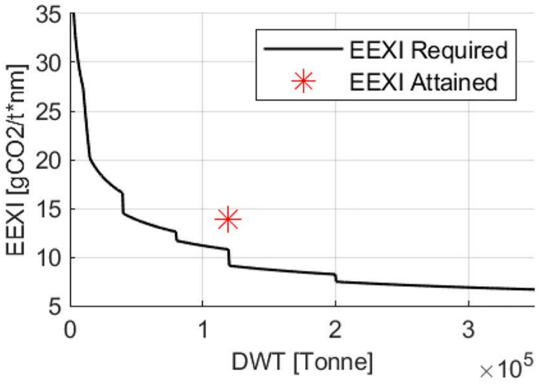

Figure 3. Initial EEXI value.

3.1.2. Initial CII rating

For the initial design (as it was in year 2023), at service speed, the vessel's attained CII is estimated at 10 (gCO_2/t.nm), corresponding to an 'E' rating. To meet regulatory compliance at the time, a minimum 'D' rating is required, implying a 27% reduction. However, operating at a 'D' rating for three consecutive years results in non-compliance (IMO 2021a). Long-term compliance until 2040 requires a 70% reduction, bringing CII down to around 3 (gCO_2/t.nm), as shown in Figure 4. This can be attained either by lowering the annual CO_2 emissions, or by increasing the transport work, e.g. through energy-saving technologies, low-carbon fuels, or operational improvements.

3.2 Implementation – energy-saving measures

3.2.1. Overview

Energy efficiency improvements are critical for early-stage regulatory compliance. In this study we consider the following energy saving measures deemed well suited for the considered vessel: speed reduction with EPL, hull cleaning, hull coating, air lubrication systems (ALS), waste heat recovery systems (WHRS), wind-assisted propulsion system (WASP), trim/draft

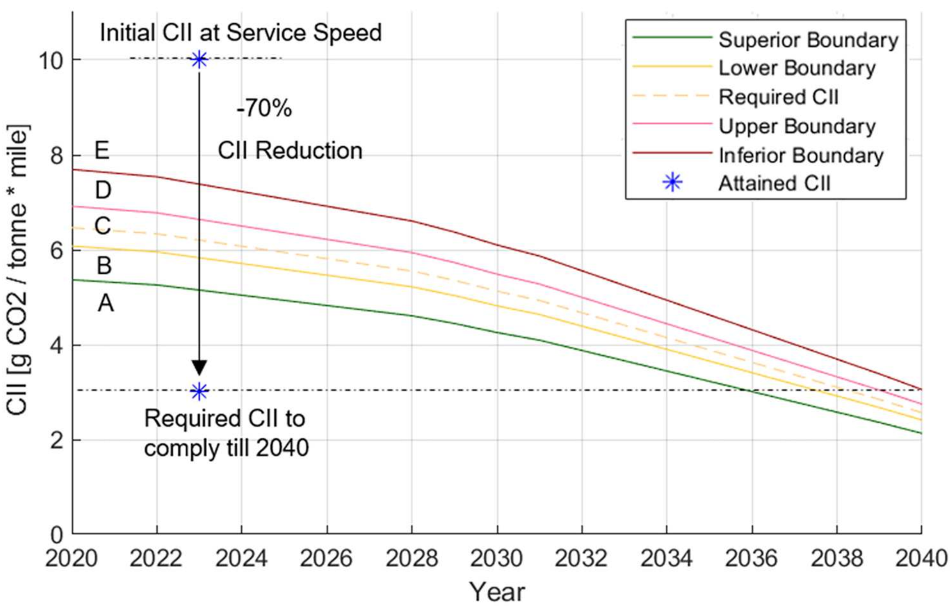

Figure 4. Attained CII index for the vessel in 2023 and pathway to satisfy CII regulation till 2040.

optimization, and auxiliary engine economizers (AEE). Related performance assumptions are drawn from peer-reviewed literature, classification society guidelines and original equipment manufacturer (OEM) data.

3.2.2. Speed reduction

The required propulsion power is highly dependent on vessel speed. Typically, the correlation between fuel consumption and speed is characterized by an exponential relationship (GloMEEP 2016). On the other hand, the efficiency of a typical ship machinery drops with engine load for loads less than around 80%. To keep a ship manoeuverable in difficult weather conditions, a minimum engine power is needed. Accordingly, we assume that the lowest safe speed of our considered vessel is 12 knots (Bergström et al. 2023). The relationship between speed and power is assumed as per Equation (3) (MEPC 2022c), and engine power and SFOC by Equation (4) (IMO 2020).

$$V_{ref} = (V_{ref,avg} - m_v) \times \left[\frac{\sum P_{ME}}{0.75 \times MCR_{avg}}\right]^{\frac{1}{3}}, \quad (3)$$

where P_{ME} is main engine power [kW], V_{ref} and MCR_{avg} are the statistical mean distribution of ship speeds and maximum continuous ratings (MCR) of main engines, m_v is performance margin, which is 5% of $V_{ref,avg}$ or one knot, whichever is lower.

$$SFC = SFC_{base} \times [(0.455 \times Load^2) - (0.710 \times Load) + 1.280], \quad (4)$$

where SFC is the specific fuel oil consumption of a vessel in g/kWh, SFC_{base} is a baseline of SFOC assumed as 167 g/kWh (MAN 2012), Load is defined as percentage of the main engine power ranging from 0 to 100. Therefore, total fuel consumption for a ship at a particular speed can be estimated using Eq. (5) (Elkafas et al. 2023).

$$FC = P_{ME} \times SFC \times t, \quad (5)$$

Where FC is the fuel consumption of a vessel in tonnes, P_{ME} is engine power at a particular speed in kW, SFC is the specific fuel oil consumption of a vessel t/kWh at a particular speed, t is the duration in hours.

Contrary, reduced speed and consequently reduced engine load can adversely affect engine performance.

Table 5. Operational parameters for a service speed of 15 knots.

Parameters	Values
Speed	15 Knots
One Voyage	9343 nm
Annual Voyages	11.5
Annual Distance travelled	1,06,730 nm
Engine Load	31%
Annual ME Fuel Consumption	20,664 MT
Total Annual Fuel Consumption	25,639 MT
Total Cargo Carried for one voyage	8,000 TEU
Annual Cargo Carried	92,000 TEU

Moreover, lower speed results in more distance travelled and less cargo transported per year. Therefore, the speed was reduced to ensure the vessel achieves at least a ‘C’ CII rating while maintaining a speed above 12 knots and/or the engine load above 28%. Therefore, the vessel’s parameters and fuel consumption for a lower service speed of 15 knots are as per Table 5 and Table 6.

3.2.3. Trim/draft optimization

Trim and draft optimization involves optimizing the trim and/or draft of the ship to reduce hull resistance, which in turn reduces the amount of engine power required and, therefore, fuel consumption. The estimated savings achieved using trim and draft optimization, especially for container vessels are 5% (GloMEEP 2016; IRENA 2021). Depending upon the type of vessel and level of training required for crew members, installation of trim optimization software could cost between USD 15,000 and 75,000 (GloMEEP 2016) without any operational charges.

3.2.4. Hull cleaning

Hull cleaning is an essential aspect of ship’s maintenance and operation to eliminate biological growth or fouling, which, if left unchecked, can increase drag and hence fuel consumption. The fuel-saving potential on main engine fuel consumption by hull cleaning could reach up to 10% (IMO 2011; GloMEEP 2016; HEMPEL 2017) and the cost around USD 55,000 based on a study for the Panamax tanker (IMO 2011; GloMEEP 2016). The frequency of cleaning a ship’s hull depends on several factors, including geographical location, water temperature, water salinity, and the ship’s speed. For this study, we assumed that hull cleaning is carried out annually.

Table 6. Estimated fuel consumption parameters for a speed of 15 knots.

	HFO			MGO				
Mode	ME	AE	BLR	ME	AE	BLR	Total	Days
At Sea	20,664	3,076	0	0	0	0	23,740	293
Manoeuvering	0	0	0	432	504	96	1,032	24
Suez Transit	0	0	0	96	252	48	396	12
Port	0	0	0	0	378	144	522	36
Total	20,664	3,076	0	528	1,134	288	25,690	365

3.2.5. Hull coating

A sub-optimal hull coating may significantly reduce ship's performance, increasing fuel consumption and emissions (IMO 2011). Typically, a ship's hull is coated every five years using high-performance coatings (GloMEEP 2016). Frequent hull cleaning can degrade self-polishing coatings (SPCs), potentially shortening re-application intervals and increasing lifecycle maintenance costs. The fuel saving potential achieved by a newly coated hull is assumed to be 5% (IMO 2011; GloMEEP 2016; IRENA 2021). The fuel-saving potential is assumed to decrease by 1% annually, averaging to 3% over five years. The average cost of hull coating is estimated as USD 70,000 per round as per IMO (2011), HEMPEL (2017) and GloMEEP (2016).

3.2.6. Air lubrication system (ALS)

Air lubrication method involves injecting air bubbles between the hull and seawater to reduce hydrodynamic resistance, thereby lowering propulsion power requirements. ALS is mostly effective for slow-speed vessels (Kim and Steen 2023). The fuel reduction potential for tankers and bulk carriers ranges between 4% to 10% (GloMEEP 2016; ABS 2019; IRENA 2021), whereas for container vessels operating at high speeds, savings could be less (Kim and Steen 2023). Therefore, we estimate that the ALS system would reduce the fuel consumption of the considered container vessel by 5%. The cost of implementing this technology onboard is typically 2-3% of the new building cost for a vessel (IMO 2011; GloMEEP 2016). Therefore, ALS system is assumed to cost approximately USD 2 million. Additionally, the system is assumed to require 3% of total ship's power, i.e. around 0.3 tons (IMO 2011; GloMEEP 2016) of extra fuel for AE per day, which translates into the operational cost of the system for Neo-Panamax container vessel.

3.2.7. Waste heat recovery system (WHRS)

A WHRS captures thermal energy from engine exhaust gases and converts it into electrical power, with additional potential for steam and hot water generation. Such systems can improve energy efficiency by 3–10% on main engines with shaft generators (EC 2015; GloMEEP 2016; Olaniyi and Prause 2020; Schroer et al. 2022). WHRS performance is load-dependent, with reduced effectiveness at lower engine loads. A 10% reduction in main engine fuel consumption is assumed at 100% MCR, which is assumed to decrease proportionally to 7.5% at 75% MCR (Schroer et al. 2022). Actual performance may vary due to factors such as part-load operation, engine condition, and ambient environment, making these assumptions optimistic but consistent with reported values. Installation costs are assumed to range from USD 2 to 10 million for container vessels between 2,500 and 10,500 TEU or with engine power exceeding 25,000 kW, with annual operational costs between USD 25,000 and 30,000 (GloMEEP 2016; Olaniyi and Prause 2020; Schroer et al. 2022). WHRS is applicable to ships with engine power over 10 MW and is particularly suited to long-sea voyages. Similarly, the Auxiliary Engine Economizer (AEE) recovers exhaust heat from the auxiliary engine to generate steam or hot water, reducing fuel consumption by up to 16% during manoeuvering and port operations. (Schroer et al. 2022). However, AEE's relevance is expected to decline after 2030 as shore power becomes mandatory in major EU ports. In this study, AEE is considered only for near-term CII compliance during manoeuvering and berthing, with minimal long-term impact assumed.

3.2.8. Wind-assisted ship propulsion (WASP)

WASP systems lower fuel use by either maintaining speed with less engine power or increasing speed at constant power. Wing sails and Flettner rotors are generally unsuitable for container vessels due to limited deck space and airflow obstructions (GloMEEP 2016) In contrast, kite systems are well-suited for container ships, especially those longer than 30 meters and operating below 16 knots (EC 2015; GloMEEP 2016). These systems use large, remotely controlled kites that harness wind energy to generate forward thrust through a tether line. Kite sails are estimated to be usable for approximately 30% of sailing time, with typical fuel savings ranging from 1 to 5% of main engine consumption (EC 2015; GloMEEP 2016). However, more conservative estimates suggest 1–2% savings for 5,000 TEU container vessels (Wang et al. 2022). Based on this, a 2% fuel reduction is assumed for a 10,000 TEU vessel equipped with a 1,280 m^2 kite system. The installation cost for such a system is assumed as USD 17,55,000 (GloMEEP 2016). Kites and tethers are wear components and may require replacement every few years under continuous use or sooner if damage occurs (Skysails 2024). Due to the absence of specific replacement interval information, maintenance cost is neglected.

3.2.9. Technical analysis of technologies

The study assumes an USD / EUR exchange rate of 0.87 (Macrotrends 2023). The CAPEX range of −20% (optimistic) and +30% (pessimistic), used for sensitivity analysis, reflects typical uncertainties in decarbonization technology costs. It is also assumed that no cargo space is lost due to the installation of these technologies.

3.3 Implementation – alternative fuels

3.3.1. Overview

Ammonia and hydrogen offer zero T-T-W CO_2 emissions and are prioritized in regulatory frameworks;

however, their adoption is constrained by low energy density, storage complexity, and integration challenges (DNV 2019; Foretich et al. 2021). Methanol and LNG are treated as transitional options due to improving infrastructure and existing engine compatibility, although their W-T-W emissions vary significantly depending on feedstock and combustion performance (Gore et al. 2022; Solakivi et al. 2022; ABS 2024). Biofuels such as Hydrogenated vegetable oil (HVO) and Fatty acid methyl ester (FAME) offer near-term decarbonization potential and are compatible with conventional engines, but their regulatory treatment is complicated by relatively high T-T-W emissions despite low life-cycle carbon intensity (ICCT 2023). Fuel selection in this analysis is guided by projected availability, compatibility with retrofit or existing engines, emissions intensity, energy density, and anticipated regulatory treatment.

3.3.2. Technical details and analysis

In comparison with HFO, a main advantage of alternative fuels is their lower carbon intensity, as shown in Table 4.

On the downside, due to their lower energy density they require more space, reducing the ship's cargo carrying capacity. Table 7 presents the energy densities of various fuels. It is assumed that LNG, methanol, ammonia, and hydrogen require 5% pilot fuel (MGO) when used in IC engines (DNV 2022a).

Assumed retrofit and capital costs for alternative fuels, including storage and fuel systems are as per Table 8. Annual operational expenses, excluding fuel costs, are estimated at €5 million (Gkonis and Psaraftis 2009), covering crew costs, lubes and stores, maintenance and repair, insurance, and administrative costs. Operational costs are assumed to be the same for engines using HFO, HVO and FAME due to similar maintenance needs. For scenarios involving LNG, methanol, ammonia, and hydrogen as fuel in IC engines, an additional 10% annual cost is assumed for skilled crew and high-quality safety equipment, reflecting the higher risks and lower maturity of these technologies at present (Horvath et al. 2018).

The fuel production cost prediction trends from 2020 to 2040 are mentioned in Table 9. According to the table, the price of e-fuels is expected to decrease significantly by 2040, whereas the price of biofuels is expected to increase slowly. The GHG intensity factors for alternative fuels by their production method are mentioned in Table 9. Additionally, we assume that in case of non-compliance with FuelEU Maritime, the vessel will continue sailing, covering any penalties outlined by the regulation. The carbon tax prices under EU ETS are assumed based on Figure 1. From 2026 onward, EU ETS will include carbon equivalent factors (CO_{2eq}) for other GHGs. However, these factors for biofuels, methanol, hydrogen, and ammonia on a tank-to-wake basis are yet to be decided (EU 2023a). Therefore, only carbon emissions taxes are considered until 2040.

Figure 5 explains the W-T-W emissions of considered alternative fuels and required intensity till

Table 7. Technical characteristics of the considered bunker fuels.

Fuel type	Energy density [MJ/Kg]	Vol Density [MJ/ltr]	Engine Efficiency	Pilot Fuel Required (%)	Boil Off rate per day	Source
HFO	40.9	42.0	50%	0	0	(DNV 2019)
MGO	42.7	35.7	50%	0	0	(DNV 2019)
Biofuels (HVO)	43.0	39.1	50%	0	0	(DNV 2019; Foretich et al. 2021)
Biofuels (FAME)	37.0	33.0	50%	0	0	(DNV 2019; Neste 2020)
LNG	49.0	21.0	52%	5	0.120%	(DNV 2019; Foretich et al. 2021; Gore et al. 2022; Solakivi et al. 2022)
LNG + Storage	25.0	13.0				
Methanol	20.0	14.9	52%	5	0.002%	(DNV 2019; Gore et al. 2022; Solakivi et al. 2022)
Methanol + Storage	17.0	14.0				
Ammonia	18.6	12.7	50%	5	0.040%	(DNV 2019; Gore et al. 2022; Solakivi et al. 2022)
Ammonia + Storage	12.0	11.0				
Hydrogen	120.0	8.5	42%	5	1.060%	(DNV 2019; Foretich et al. 2021; Gore et al. 2022)
Hydrogen + Storage	10.0	5.0				

Table 8. Assumed costs, including storage tanks and fuel systems for different bunker fuels (Lindstad et al. 2021; Lagouvardou et al. 2023).

Fuel type	Capex [€/kW] Optimistic (−20%)	Capex [€/kW] (Base case)	Capex [€/kW] Pessimist (+30%)	Retrofit [€/kW] Optimistic (−20%)	Retrofit [€/kW] (Base case)	Retrofit [€/kW] Pessimistic (+30%)
HFO	480	600	780	0	0	0
HVO/FAME	480	600	780	136	170	220
LNG	960	1200	1560	232	290	380
Methanol	560	700	910	136	170	220
Ammonia	960	1200	1560	232	290	380
Hydrogen	1880	2350	3055	460	575	750

Table 9. W-T-W emissions and cost ranges for different fuel types (IRENA 2021; DNV 2022a; Lagouvardou et al. 2023).

Fuel types	Well-to-wake emissions intensity [gCO_2e/MJ]	Fuel production costs in 2023 [€/ton fuel]	Fuel production cost projections in 2030 [€/ton fuel]	Fuel production cost projections in 2040 [€/ton fuel]	Source
HFO	91.8	257 (206–355)	321 (180–400)	351 (194–577)	(IMO 2020)
MGO	89.0	360 (296–513)	451 (260–847)	493 (279–923)	(ICCT 2023)
HVO	21.0	826 (599–1,174)	1,029 (613–1,444)	1,090 (616–1,563)	(ICCT 2023)
FAME	37.7	942 (840–1,293)	1,356 (940–1,772)	1,539 (1012–2,066)	(ICCT 2023)
Grey – LNG	77.4	215 (183–247)	197 (190–240)	212 (200–430)	(T&E 2023)
Bio – LNG	20.2	1,141 (876–1,459)	1,231 (791–1,670)	1,539 (672–1,419)	(T&E 2023)
E – LNG	28.2	3,256 (2,036–4,055)	2,175 (1,442–2,908)	1,407 (861–1,989)	(T&E 2023)
Grey – Methanol	101.4	401 (189–600)	378 (181–575)	388 (186–589)	(Lagouvardou et al. 2023)
Bio – Methanol	32.1	1,112 (728–1,520)	1,152 (720–1583)	1,143 (695–1591)	(Lagouvardou et al. 2023)
E – Methanol	28.2	3,501 (2,309–4,218)	2,303 (1,617–2,989)	1,628 (1,128–2,163)	(T&E 2023)
Grey – Ammonia	104.9	470 (366–559)	660 (450–650)	660 (500–780)	(IMO 2020; Lagouvardou et al. 2023)
Blue – Ammonia	29.4	680 (385–780)	574 (350–850)	468 (300–570)	(EMSA 2022; Lagouvardou et al. 2023)
E – Ammonia	28.2	2,224 (1,687–2,816)	1,799 (1,473–2,214)	1,060 (873–1,381)	(T&E 2023)
Grey – Hydrogen	109.7	1,740 (1,450–2,300)	2,200 (1,800–3,000)	4,200 (3,000–4,500)	(Hydrohub 2019; Lagouvardou et al. 2023)
E – Hydrogen	28.2	2,617(1,985–3,313)	2,117 (1,733–2,605)	1,116 (919–1,454)	(T&E 2023)

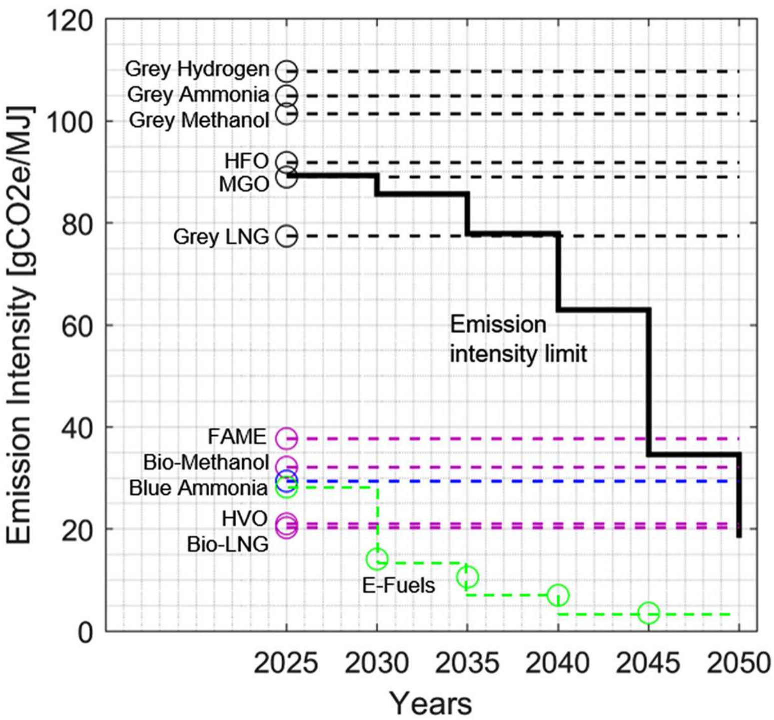

Figure 5. FuelEU maritime status as per Table 9 for different alternative fuels compared to the required value.

2050 as per FuelEU Maritime regulation. The biofuels, e-fuels, and blue ammonia satisfy the FuelEU Maritime criteria until 2040. Therefore, if the vessel were to keep operating on HFO or grey variants of alternative fuels, it would incur annual penalties, assuming it maintains the same operational profile.

4. Results

4.1. Initial cost analysis

To comply with upcoming IMO and EU regulations, an initial comparison of energy-saving technologies and alternative fuels is conducted based on their

Table 10. Assumed Capex and recurring expenses related to technologies implemented onboard the vessel.

Technology	CAPEX [€] Optimistic (−20%)	CAPEX [€] Baseline	CAPEX [€] Pessimistic (+30%)	Annual costs [€]	Source
Trim/Draft Optimization	40,000	50,000	65,000	-	(GloMEEP 2016)
Hull Cleaning	44,000	55,000	72,000	-	(IMO 2011; GloMEEP 2016)
Hull Coating	200,000	250,000	325,000	-	(IMO 2011)
ALS	1,600,000	2,000,000	2,600,000	110 t HFO	(IMO 2011)
WHRS	6,500,000	8,000,000	10,500,000	30,000	(Schroer et al. 2022)
WASP	1,350,000	1,700,000	2,250,000	-	(GloMEEP 2016)
AEE	72,000	90,000	117,000	10,000	(Schroer et al. 2022)

Table 11. Estimated annual fuel reduction potential by ESD and their effect on vessel at service speed.

Technology	Fuel reduction Potential (Pessimistic)	Fuel reduction Potential (Base case)	Fuel reduction Potential (Optimistic)	Source
Trim/Draft Optimization	0.5% of ME	3.0% of ME	5.0% of ME	(GloMEEP 2016; IRENA 2021)
Hull Cleaning	1.0% of ME	5.0% of ME	10.0% of ME	(IMO 2011; GloMEEP 2016; IRENA 2021)
Hull Coating	1.0% of ME	3.0% of ME	5.0% of ME	(IMO 2011; GloMEEP 2016; IRENA 2021)
Air Lubrication System (ALS)	2.0% of ME	5.0% of ME	10.0% of ME	(ABS 2019; IRENA 2021; Kim and Steen 2023)
Waste Heat Recovery System (WHRS)	3.0% of ME	7.5% of ME	10.0% of ME	(EC 2015; GloMEEP 2016; Olaniyi and Prause 2020; Schroer et al. 2022)
Wind Assisted Ship Propulsion (WASP)	1.0% of ME	2.0% of ME	5.0% of ME	(EC 2015; GloMEEP 2016; Wang et al. 2023)
Auxiliary Engine Economizer (AEE)	1.0% of AE	16.0% of AE	20.0% of AE	(GloMEEP 2016; Schroer et al. 2022)

cost-effectiveness, measured as the additional cost per container per nautical mile (€/TEU-NM) over the technology's lifetime. The assumed CAPEX and annual costs are shown in Table 10 and Table 8, while fuel savings are taken from Table 11. Fuel prices through 2040 and their W-T-W emissions are listed in Table 9, and emission factors used to calculate annual emissions are provided in Table 4. Carbon taxes under the EU ETS are applied from 2024, accounting for 50% of emissions on Asia–Europe routes. Similarly, FuelEU Maritime penalties are included from 2025, based on 50% of annual energy use. All calculations are performed using base case values as defined in Equation (2).

As per Figure 6, retrofitting the vessel with energy-saving measures is initially more cost-effective than adopting alternative fuels. Negative values reflect cost savings, while positive values indicate additional expenses. Speed reduction offers the greatest fuel savings, followed by hull cleaning, ALS, WHRS, and hull coating. In contrast, AEE and WASP provide lower efficiency gains, as detailed in Table 11. WHRS and

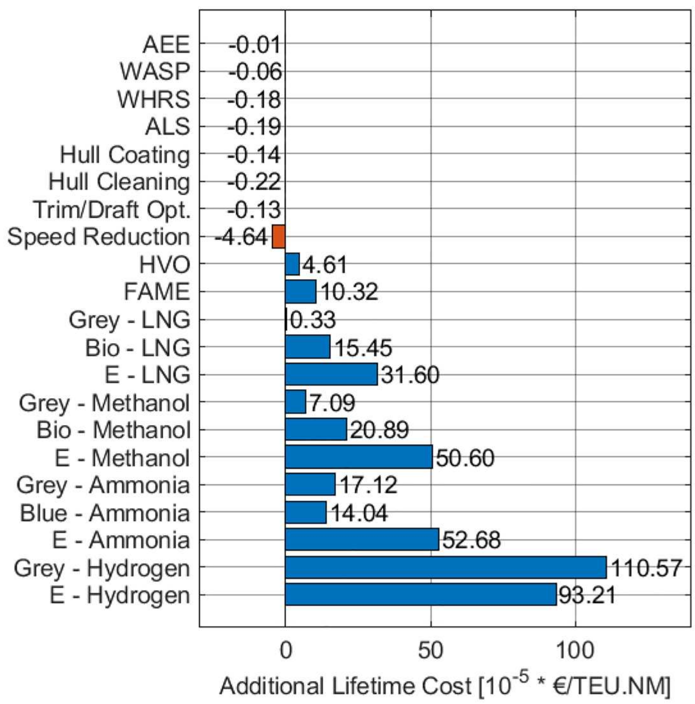

Figure 6. Comparison of total additional cost per 10^{-5} * TEU.nm for emission reduction technologies in 2023.

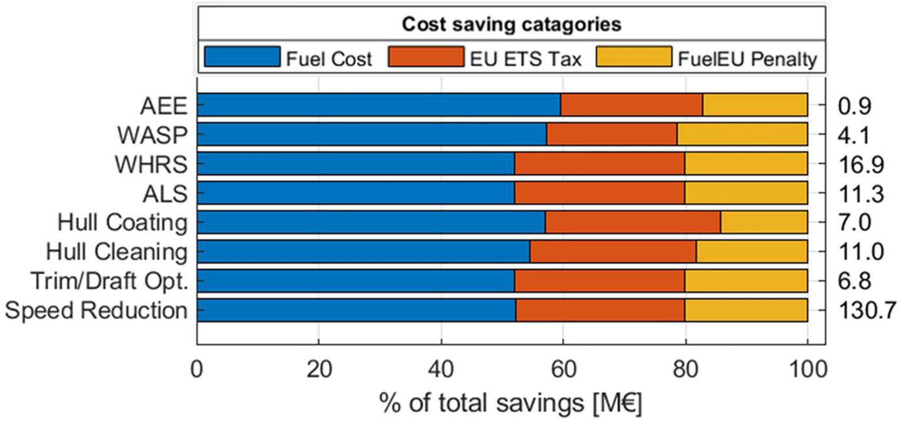

Figure 7. Lifetime Cost savings on EU ETS tax, FuelEU Maritime penalty and Fuel cost achieved by implementing various energy saving technologies in 2023.

speed reduction are incompatible with each other, since WHRS performance declines with reduced engine power (Schroer et al. 2022). ALS is particularly effective at lower speeds (GloMEEP 2016).

Figure 7 shows, speed reduction yields the highest savings in fuel costs, EU ETS taxes, and FuelEU Maritime penalties among all technologies. Of the total cost savings from installing energy-saving technologies in 2023, fuel savings account for roughly 50%, with carbon tax and FuelEU Maritime penalty savings contributing 30% and 20%, respectively. Since ammonia and hydrogen engines are not expected to reach technological maturity before 2030 (DNV 2022a), the vessel is initially assumed to adopt speed reduction, ALS, hull cleaning, and hull coating. Due to uncertainty of the combined energy saving potential, a total of 10% annual fuel saving was assumed from ALS, hull coating, and hull cleaning on top of speed reduction (DNV 2025).

4.2. Outcome of technology implementations

Reducing the vessel's speed from 21 knots to 15 knots (28.5% reduction), the vessel's CII rating is reduced from 10 to 6.23 (gCO_2/t.nm) (37% reduction), improving band from 'E' to 'C' as per Figure 9. Additionally, the total fuel consumption of the example vessel is reduced by around 48%. However, due to reduced speed, the vessel's annual transport capacity falls by 24%.

By applying EPL, reducing the engine power by 40% to 34,870 kW, an EEXI of 10.77 (gCO_2/t.nm) is achieved, meeting regulatory requirements. However, this limitation restricts the vessel's speed to 19.6 knots. Given the vessel's operational speed is already reduced to 15 knots, limiting engine power to 60% satisfies EEXI regulation, as illustrated in Figure 8. Notably, once EEXI requirements are met, no further verification is necessary (DNV 2023a).

Installing ALS and carrying out hull cleaning and hull coating results in an additional 5% CII reduction.

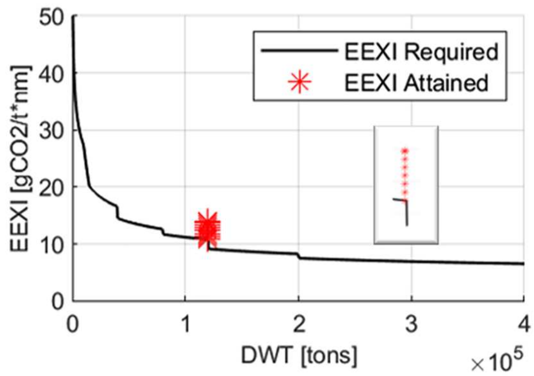

Figure 8. EEXI Status after reducing the vessel's speed and limiting power to 60%.

As per Figure 9, the combination of these energy-saving measures reduces the vessel's CII rating from 'E' to 'B' based on 2023 operating conditions. If the vessel continues operating with the same profile, it would meet the CII requirements till 2030.

4.3. Implementation of alternative fuels in 2031

Beyond 2031, the exponential increase in reduction factors make energy-saving measures inadequate to meet CII requirements until 2040. Thus, alternative fuels become crucial from 2031 onwards. Figure 10 compares the additional costs of installing alternative fuels in 2031. All cost calculations are done as per Equation (2). Accounting for additional lifetime costs, grey LNG and HVO emerge as the most favourable options. Conversely, installing a hydrogen fuel system appear the least attractive, with grey hydrogen costs approximately four times higher than e-ammonia and green hydrogen being around twice as costly.

Figure 11 shows the lifetime cost savings in EU ETS taxes and FuelEU Maritime penalties resulting from implementing alternative fuels onboard, compared to the vessel solely using HFO and MGO till 2040. Negative values for penalties with grey-methanol, grey-

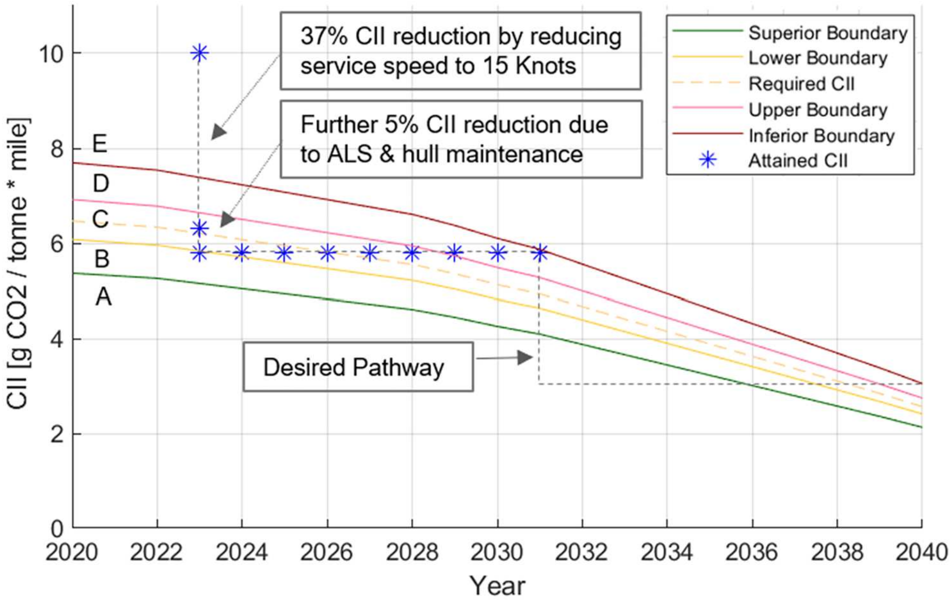

Figure 9. CII rating development till 2030.

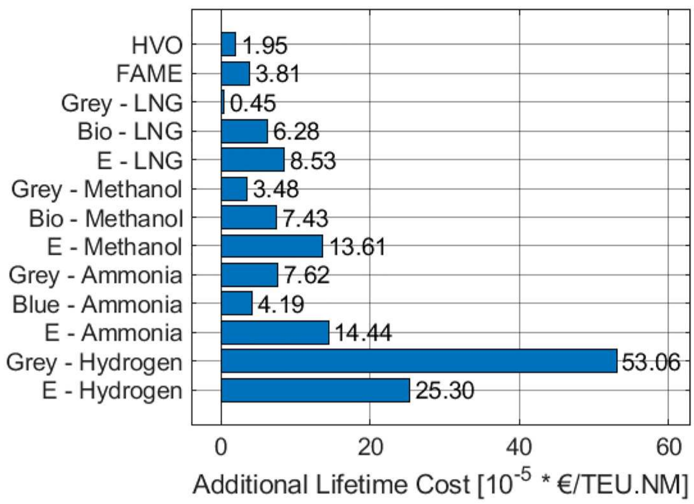

Figure 10. Comparison of additional lifetime cost per 10^5*TEU.nm for installing alternative fuels onboard in 2031.

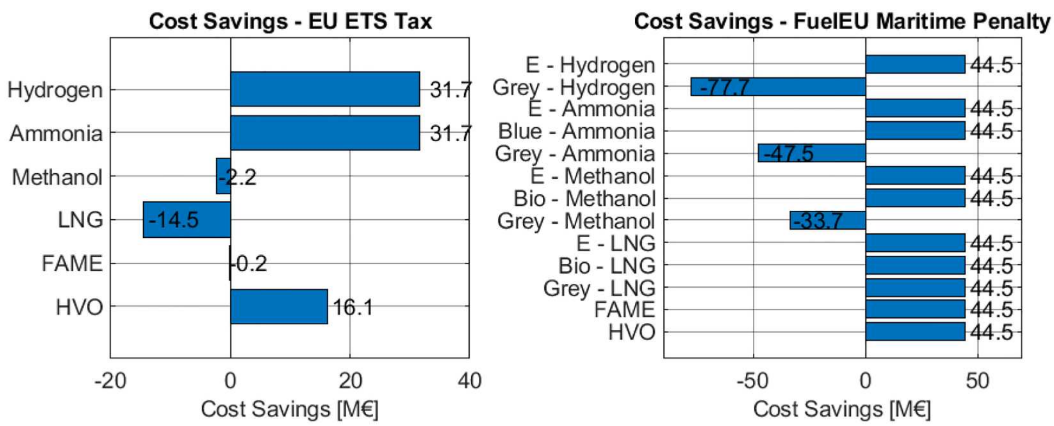

Figure 11. Lifetime Cost savings on EU ETS tax and FuelEU Maritime penalty achieved by implementing alternative fuels in 2031.

Table 12. Fuel types and their effect on tank volumes and lost cargo carrying capacity at service speed.

Fuel type	Fuel Volume Relative to HFO	Fuel Weight Relative to HFO	Lost Capacity Per Voyage (TEU)	% of annual cargo Carrying Capacity lost
HFO & MGO	1.0	1.0	0	0.0%
HVO	1.0	0.9	7	0.1%
FAME	1.2	1.1	28	0.3%
LNG	1.9	0.8	97	1.2%
LNG + Storage	3.0	1.5	221	2.8%
Methanol	2.7	2.0	180	2.2%
Methanol + Storage	2.9	2.3	198	2.4%
Ammonia	3.3	2.2	242	3.0%
Ammonia + Storage	3.8	3.4	295	3.7%
Hydrogen	5.6	0.4	489	6.1%
Hydrogen + Storage	9.5	4.7	905	11.3%

ammonia, and grey-hydrogen signify additional costs due to their higher GHG content on a WT-W basis. Despite having LNG's negative savings on carbon taxes due to its higher T-T-W carbon content and lower energy density, grey LNG is the most cost-effective option in 2031 due to lower production costs.

4.4. Technical analysis of alternative fuels

It is assumed that both ME and AE are converted to use alternative fuels, with engine efficiencies and boil-off rates based on Table 7. Fuel tank and system conversions are considered sufficient to support operations at service speed. Table 12 summarizes the impact of alternative fuels on weight, volume, and annual cargo capacity. Due to lower energy densities, additional storage volume is required to match the travel range of HFO, reducing container space. This is estimated using a standard 20-foot container volume of 33 m^3 (ISO 2020). Hydrogen requires nearly 10 times more space than HFO, resulting in an 11% annual cargo loss. LNG and methanol require three times more volume, ammonia four times, and ammonia and hydrogen are 3.5 and 5 times heavier than HFO, respectively. In contrast, FAME and HVO have similar volume and weight to HFO, causing minimal cargo loss.

4.5. Outcome of technology implementations in 2031

Figure 12 displays the comparison of CII ratings achieved with alternative fuels onboard in 2031. LNG, methanol, and HVO do not meet CII targets beyond 2031 due to higher fuel consumption from lower energy density, despite having lower carbon factors than HFO. Only ammonia and hydrogen ensure compliance through 2040, with ammonia emerging as the more cost-effective option. Among its variants, blue ammonia is the least expensive in 2031.

Therefore, one of the pathways to decarbonize a 10,000 TEU container vessel involves implementing speed reduction along with ALS, hull cleaning and, hull coating initially, followed by adopting alternative fuels from 2031. Among the available options, ammonia emerges as the most cost-effective and regulatory compliant alternative fuel (Figure 13).

5. Sensitivity analysis

The sensitivity analysis is conducted using both optimistic and pessimistic scenarios. In the optimistic case, energy-saving potential is higher, while CAPEX and fuel prices are lower. Conversely, the pessimistic scenario assumes reduced energy savings and

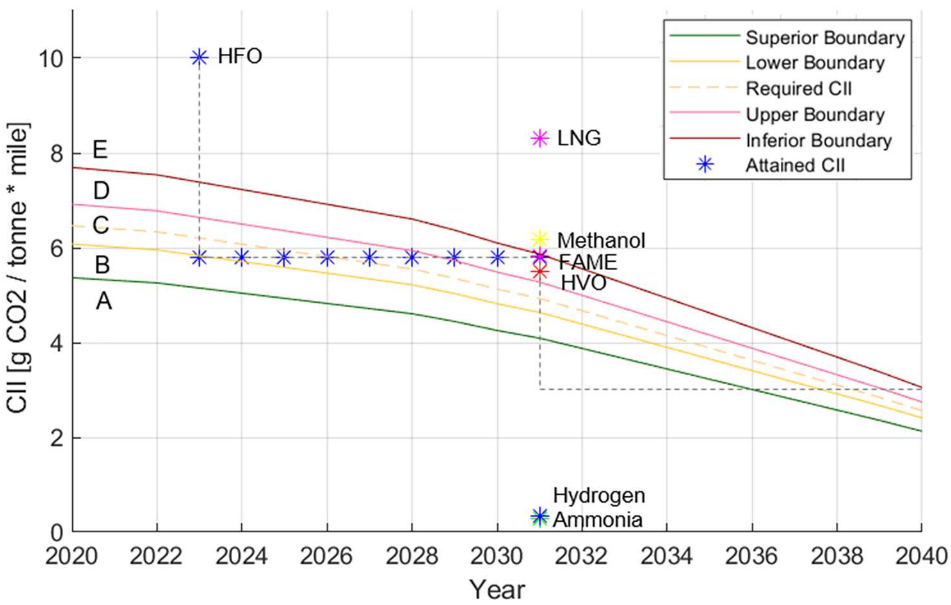

Figure 12. CII ratings attained by implementing different alternative fuels in 2031 onboard vessel sailing at 15 knots.

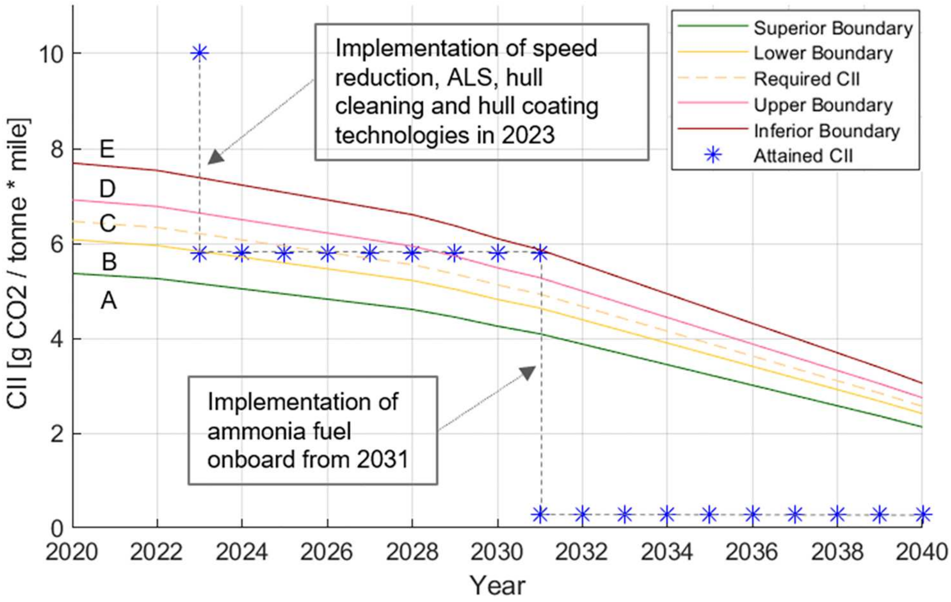

Figure 13. Proposed pathway for cost-effective CII compliance until 2040.

increased CAPEX and fuel costs. Relevant data on energy-saving potential, CAPEX, and fuel prices are shown in Table 11, Table 10, Table 8 and Table 9. As shown in Figure 14 and Figure 15, the cost impacts of these measures vary significantly by scenario, highlighting the sensitivity of these technologies to economic conditions.

For technologies assumed to be implemented in 2023, most energy-saving measures deliver lifetime cost savings across all scenarios, with speed reduction emerging as the most cost-effective option. Under optimistic conditions, lower costs and higher efficiencies further amplify these savings, while under pessimistic conditions, the margins narrow but the cost benefits remain intact. Notably, in the pessimistic scenario, trim/draft optimization becomes a comparable alternative to ALS. While ALS still provides slightly greater savings, the difference is less pronounced, highlighting the increased uncertainty in comparative performance under less favourable conditions. This suggests that in challenging economic environments, multiple technologies may offer similarly viable pathways, reinforcing the importance of adaptable strategies tailored to vessel-specific characteristics and shifting market or regulatory contexts.

Both in 2023 and 2031 model years, all e-fuels, except e-LNG, show significant variability between the optimistic and pessimistic scenarios. This variability suggests that their costs are highly sensitive to external factors, particularly fuel prices and the cost

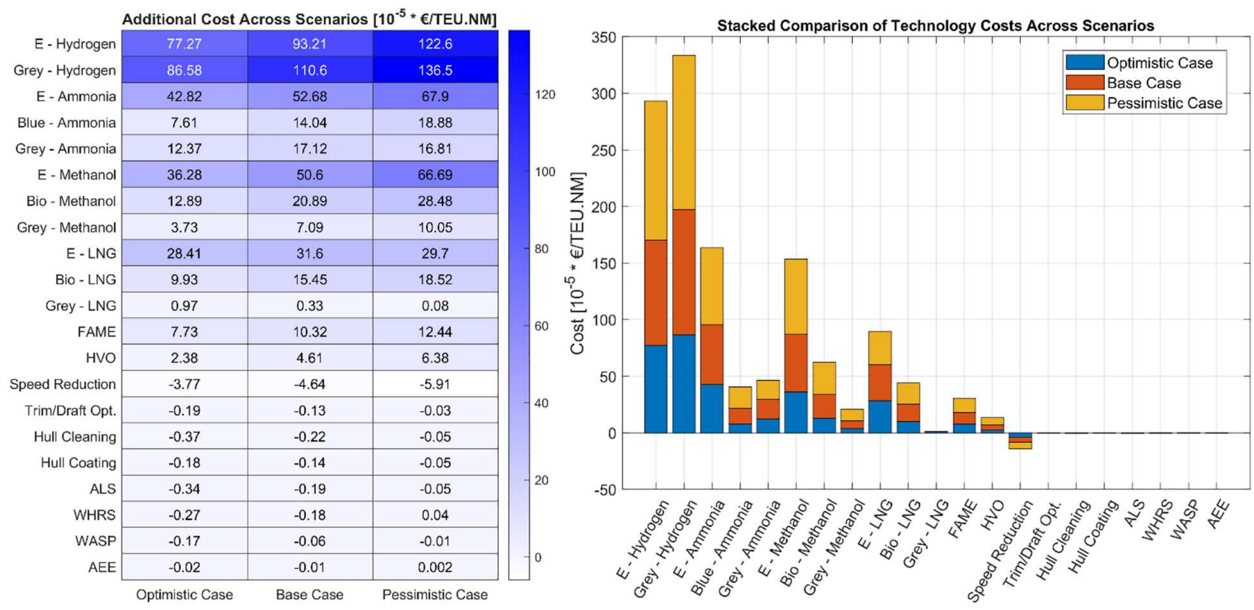

Figure 14. Sensitivity analysis for technology implementation costs in 2023.

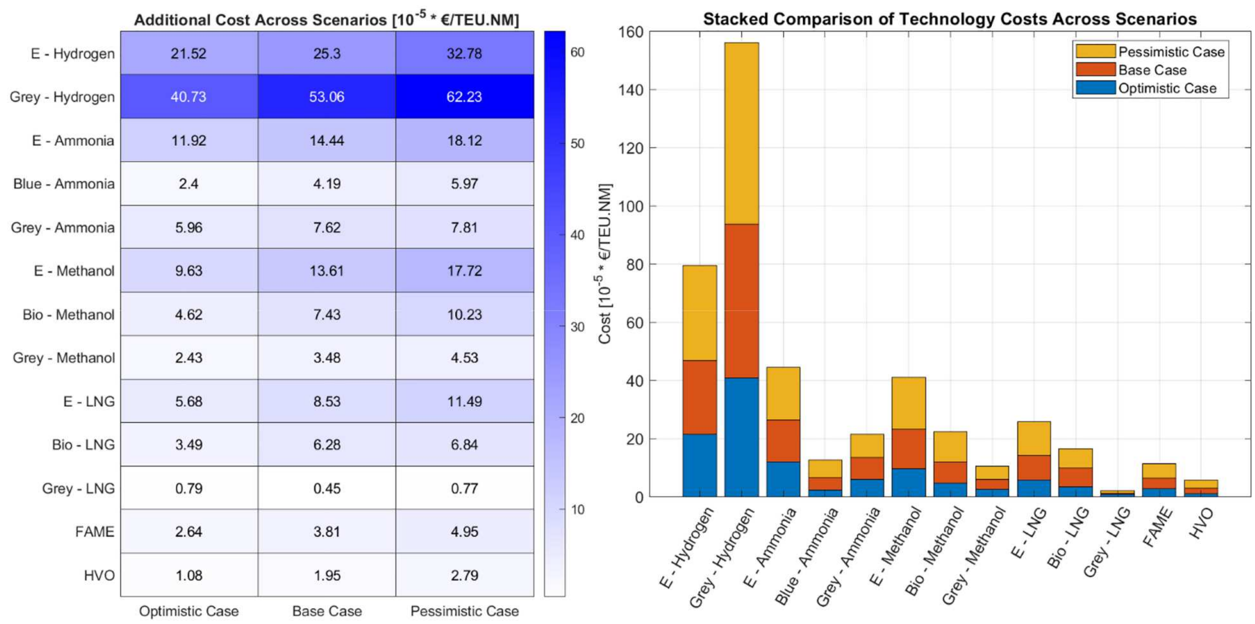

Figure 15. Sensitivity analysis for technology implementation costs in 2031.

of HFO with which they are being compared. In the pessimistic scenario, the WHRS implementation incur additional costs, rather than the cost savings observed in the base and optimistic cases. Notably, the speed reduction measure is less cost-effective in the optimistic scenario, yielding more savings in the pessimistic case. This highlights the measure's sensitivity to HFO prices, as it becomes more effective when HFO prices are high.

Overall, the analysis reveals the robustness of most measures, particularly energy efficiency improvements, biofuels, and LNG variants, across all scenarios. However, it also highlights the significant cost risks associated with alternative fuels, particularly under pessimistic scenarios. Therefore, the conclusions drawn from the base case remain valid, supporting the same strategic pathway even under different economic conditions.

6. Discussion and future work

The shipping industry is in urgent need of technical solutions to curb emissions and achieve the IMO's 2050 carbon neutrality target. However, the path forward is complex due to evolving regulations and uncertainty around future technology, among other factors. Ship operators must either reduce onboard energy use or switch to low-carbon fuels to remain compliant. This study's cost analysis reveals that energy-saving measures offer long-term economic benefits. Implementing these measures help the 10,000 TEU container vessel meet CII criteria through 2030. Among them, speed reduction emerges as the most cost-effective option due to low capital costs and significant fuel savings. However, reducing speed from 21 to 15 knots results in a 24% annual cargo capacity loss. To maintain cargo throughput, operators would need to deploy one additional vessel for every four operating under slow steaming. This introduces additional costs and cradle-to-grave emissions, which must be assessed to fully understand the fleet-wide impact. Furthermore, long-term slow steaming may require modifications to engine units, turbochargers, and associated systems to ensure reliable performance.

Waste heat recovery systems (WHRS) are currently limited to main and auxiliary engines, but advances in energy converters could enable their expansion to recover waste heat from other machinery. Air lubrication systems (ALS) involve higher upfront costs but offer notable fuel savings. In contrast, kite sails remain less cost-effective for deep-sea container vessels due to high implementation costs and modest fuel reduction. However, ongoing research and pilot projects suggest that wind-assisted propulsion may play a more prominent role in the future. Implementing multiple energy-saving technologies simultaneously could deliver cumulative benefits, though their combined impact remains uncertain and is likely to vary depending on vessel-specific characteristics.

This study applies Net Present Value (NPV) to assess investment performance, as it captures the time value of money and long-term cost-effectiveness. While metrics like payback period and internal rate of return (IRR) are commonly used, NPV is regarded as the better way to rank investments due to its ability to handle scenarios with fluctuating cash flows with a pre-defined, and if needed diverse, discount rate that reflects the time value of money. The break-even time charter (T/C) rate, though common in shipping, does not fully reflect the financial impact of long-term investments. In contrast, NPV offers a more stable and policyaligned framework, consistent with its use in multiple IMO assessments to evaluate decarbonization measures (IMO 2011, 2020).

FuelEU Maritime regulation requires ship operators to adopt lower GHG fuels to avoid penalties driven by tightening reduction factors. Further research is needed to improve fuel production methods and reduce GHG content. Emissions pooling under FuelEU Maritime allows HFO fuelled vessels to offset penalties by grouping with e-fuel-powered ships, potentially reducing compliance costs. Although this study models a single-vessel fleet, exploring pooling strategies could offer additional savings and support wider e-fuel adoption. The regulation also mandates shore power use for container ships at port from 2030. However, since shore power is expected to offset only about 1% of total fuel use in this case, it is excluded from the analysis. Vessels with longer port stays are likely to benefit more from this requirement.

Both CII and EU ETS apply T-T-W carbon factors, which can differ significantly from W-T-W values for the same fuel. For example, ammonia and hydrogen emit zero T-T-W CO_2 and meet CII targets through 2040, yet their grey variants have higher W-T-W emissions than HFO, resulting in substantial FuelEU Maritime penalties. Conversely, biofuels, despite their lower W-T-W emissions, are penalized under both regulations due to their higher T-T-W emissions. Incentives linked to a CII rating of B or higher may encourage alternative fuel use, though implementation details remain uncertain. In the absence of CII and related incentives, a phased approach of using fuel oil with penalties until 2030, then transitioning to bio-blends and ultimately to bio/e-methanol or blue/e-ammonia appears most viable.

Our analysis identifies blue ammonia as the most cost-effective and regulatory compliant fuel for deep-sea container vessels post-2030. This finding is strongly supported by scenario based studies from UMAS (2025), T&E (2023), and IMO (2024), which show blue ammonia as the lowest-cost compliance option between 2036 and 2044. These results align with our staged approach: implementing energy-saving measures first, followed by a fuel transition around 2031. Broader projections from MMMCZCS (2023), DNV (2023b) and LR (2023a) further support blue ammonia as a scalable and near-term transitional fuel at least until 2040. However, the literature also points to key uncertainties. These include reliance on permanent CO_2 storage, evolving GHG accounting rules, and potential regulatory shifts that may limit blue ammonia's eligibility under future 'near-zero' fuel definitions. Operational safety and crew training are also recognized challenges (Baldauf et al. 2013; Baumler et al. 2014). Nevertheless, investing in ammonia capable engines remains a strategically sound decision. Regardless of whether blue or e-ammonia dominates in the long term, the ability to switch between them allows ship operators to respond flexibly to changes in fuel availability, cost, and policy. This flexibility reinforces the value of ammonia as a future ready solution, even amid short term uncertainty.

Limitations and uncertainties

While this study provides a detailed vessel-level techno-economic assessment, it has several limitations. Most of the considered decarbonization measures, including speed reduction and the use of alternative fuels, would have a negative impact on the ship's transport capacity, potentially requiring additional vessels to maintain trade volume. This may increase fleet-level emissions, infrastructure demand, and capital costs, partially offsetting per-vessel efficiency gains. Future studies should adopt a system-level perspective considering such factors.

Furthermore, the speed–power relationship is modelled using a cubic approximation, which is reliable for the design speed range. However, studies such as Berthelsen and Nielsen (2021) show that, this model may slightly underestimate the power demand at low speed, and hence overestimate fuel savings from speed reduction. Nevertheless, as this study focuses on typical container vessel speeds (15–22 knots), the cubic law is assumed a valid simplification.

Methodologically, the study is limited to a single vessel type and does not capture variability across fleet characteristics or operational strategies. Assumptions on fuel prices, carbon costs, and retrofit expenses are based on projections and subject to uncertainty. While performance data are sourced from literature and vendors, real-world variation may occur. The model also excludes downtime, port infrastructure constraints, and logistic disruptions. Broader economic impacts such as freight rate shifts, operator responses, and global fuel demand are beyond scope but highlight opportunities for future research in fleet-scale and policy-responsive modelling.

7. Conclusion

This study aims to identify cost-effective decarbonization strategy for a deep-sea container vessel in line with IMO and EU emission regulations. It evaluates viable technologies, reviews regulatory frameworks, and assesses technically feasible decarbonization pathways using projected trends in renewable fuel and green technology costs. A comprehensive literature review supports the selection of suitable energy-saving technologies, including speed reduction, hull maintenance, air lubrication systems, waste heat recovery, and wind-assisted propulsion and trim/draft optimization. The analysis also covers low-carbon fuel options such as LNG, HVO, FAME, methanol, ammonia, and hydrogen. Regulatory frameworks such as EEXI, CII, EU ETS, and FuelEU Maritime are examined in the context of a 10,000 TEU container vessel. Initial findings show non-compliance with EEXI and CII, requiring the implementation of corrective measures.

A cost analysis is conducted to evaluate the additional lifetime cost of each technology per TEU.nm. By model year 2023, all energy-saving technologies are found to be more cost-effective than alternative fuels in €/TEU.nm terms, with speed reduction from 21 to 15 knots emerging as the most cost-efficient option. However, this results in a 24% reduction in cargo capacity. To meet CII requirements until 2030, the vessel is assumed to adopt a combination of measures, including speed reduction, air lubrication systems, hull cleaning, and hull coating. EEXI compliance is achieved through speed reduction and reducing engine power by 40%.

Energy-saving technologies are found sufficient to meet CII requirements until 2030, but stricter regulations force alternative fuels adoption later. By 2031, ammonia, particularly blue or e-ammonia, is identified as the most cost-effective and regulatory compliant option through 2040. Although hydrogen also meets regulatory criteria, its higher cost and lower energy density make it less viable for long-haul operations. In summary, we conclude that a viable decarbonization pathway for a deep-sea container vessel involve implementing energy-saving measures till 2030 such as speed reduction, air lubrication systems, and hull maintenance, followed by a transition to alternative fuels after 2030, with ammonia offering the most practical long-term solution.

Authorship contribution statement

Ishan Sontakke: Conceptualization, Methodology, Investigation, Writing – Original Draft.
Martin Bergström: Review & Editing, Supervision.
Vaidehi Gosala: Review & Editing, Supervision.
Michael Baldauf: Review & Editing, Supervision.
Sören Ehlers: Review & Editing, Supervision.

Disclosure statement

No potential conflict of interest was reported by the author(s).

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