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Environmental-Economic Analysis for Decarbonising Ferries Fleets

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Abstract: Several countries heavily depend on their domestic ferries, the decarbonisation of which are required following the prevailing and forthcoming international and national carbon reduction targets. This study aims to conduct an environmental-economic analysis to identify the impact of three decarbonisation measures, specifically, hybridisation, liquified natural gas (LNG) and methanol use, for two ferries of different size of a developing country fleet. The study is based on several methodological steps including the selection of key performance indicators (KPIs), the pre-processing of acquired data to identify representative operating profiles, the environmental and economic KPIs calculation, as well as the comparative appraisal of the investigated measures. The required investments for decarbonising the whole domestic fleet of a case country are subsequently estimated and discussed. All the three investigated measures have the potential to reduce CO_2 emissions, however, not beyond the IMO 2030 carbon emissions reduction target. This study provides insights to the involved stakeholders for supporting their decisions pertinent to the domestic ferries sector decarbonisation.

Keywords: decarbonisation; methanol; LNG; environmental-economic analysis; marine engines

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1. Introduction

Several developing countries strongly depend on maritime transportation for their inter-island connectivity. Domestic ferries play a crucial role in their economic and social development by transporting goods and people between mainland and islands as well as interconnecting islands. However, the operation of these ferries is associated with significant environmental and economic costs, primarily due to their reliance on fossil fuels [1].

Decarbonising the domestic ferry sectors is a crucial step towards achieving these countries' climate and sustainability goals. The International Maritime Organisation (IMO) lists 176 countries as member states and 3 associate members, which have committed to reduce the carbon dioxide (CO_2) emissions per transport work by 40% by 2030, and reach net-zero emissions by 2050, following the Paris Agreement [2]. The domestic ferry sector significantly contributes to the transport related GHG emissions of several countries, hence rendering its decarbonisation efforts of high priority [3]. Worldwide, the shipping industry has been adopting innovative measures to reduce its environmental impact, particularly through decarbonisation practices [4]. The shipping industry is critical for the global trade and commerce, responsible for transporting approximately 80% of the world's goods by volume [5]. However, this industry's growth has also led to increased carbon emissions, thus exhibiting significant environmental impact, including climate change, air pollution, and ocean acidification. To address these issues, several measures have been proposed to promote sustainable practices in the shipping industry. One such measure is the adoption of alternative fuels, such as liquefied natural gas (LNG), methanol, ammonia, or hydrogen, which result in lower emissions compared to traditional marine fuels including heavy fuel oil (HFO) and marine gas oil (MGO) [6].

Hansson et al. [7] studied ammonia as a potential marine fuel demonstrating that the major challenge for its adoption is the higher price per energy content compared to MGO and LNG. Jovanović et al. [8] studied the feasibility of autonomous ships operating with methanol and LNG along with conventional fuels from an environmental perspective, whilst considering the possible emissions effects on global warming, concluding that methanol has significant advantage compared to LNG and MGO. Hovarth et al. [9] demonstrated that renewable based synthetic fuels, such as methanol, are not economically feasible for decarbonising the shipping sector, without the application of emission taxation schemes. The latter is supported by the findings of Trivyza et al. [10] pertinent to the impact of carbon pricing on cruise ships energy systems. Svanberg et al. [11] argued that renewable methanol is a technically viable option to reduce emissions from shipping as it does not introduce major challenges on the fuel supply chains. Korberg et al. [12] studied alternative propulsion systems along with alternative fuels for ferries operation concluding that large ferries can be cost effective with fuels produced by using renewable energy.

Several alternative low and zero-carbon fuels have been proposed for the shipping sector. The use of ammonia, hydrogen, methanol, and biofuels can lead to lower operational carbon footprint, and may be considered carbon neutral when renewable energy is used for their production. Karvounis et al. [13] reported that fossil-based production of hydrogen and ammonia yields significantly higher CO_{2eq} emissions compared to conventional MGO and LNG fuels (as detailed in Table A1). This is attributed to the energy intensive processes required for these fuels production [14,15]. Bio methanol exhibits around 15% less $CO_{2,eq}$ associated with lower fuel production cost; however, its wide adoption is limited by the production location and scalability [16]. Natural gas extraction and processing is accompanied by methane slip and exhibits 25% higher CO_{2eq} emissions compared to MGO [17]. Methanol can be stored under ambient temperature and pressure, and requires less energy compared to LNG and hydrogen, which are stored at cryogenic conditions [18].

Electrification using batteries is accepted as a potential technology for shipping decarbonisation. Hybrid ship power systems integrating both conventional (mechanical) and electrical components (batteries, electric machinery, converters/inverters) can increase the power plant efficiency, reducing the fuel consumption especially in cases with dynamic operations [19]. Previous studies focusing on hybrid power plants for several ship types and employing different battery sizes reported fuel savings in the range 8–17% [20,21]. Law et al. [22] examined several alternative strategies to decarbonise the shipping operations concluding that carbon capture and storage is the most cost-effective pathway, however, no carbon taxation was considered whilst scaling up to fleet was not presented. Percic et al. [23] considered the lifetime emissions and cost of hybrid inland waterway ships, concluding that electrification can reduce both GHG and NOx emissions; however alternative fuels were not investigated. Jang et al. [24] demonstrated that the use of LNG and fuel cells power systems exhibits lower environmental footprint compared to dual fuel gas engines. Kistner et al. [25] argued that the implementation of alternative fuels and fuel cell technologies require extensive investment cost, which cannot be afforded by developing nations' stakeholders. The use of methanol and electrification were identified as potential solutions for short-term decarbonisation of the shipping sector [26], whilst LNG is already employed as low carbon fuel [13,26].

The aim of this study is to conduct an environmental-economic analysis of decarbonising a fleet of domestic ferries, evaluating the costs and benefits of transitioning the sector to low-emission alternatives. This is achieved by: (i) evaluating the environmental and economic indicators of three short- to medium-term solutions with the use of alternative fuels and hybrid power systems for two typical domestic ferries operating in developing countries, considering their entire lifetime; (ii) assessing the investment costs required for the wide implementation of these technologies whilst monetising the carbon emissions considering a reference fleet; (iii) discussing pathways for policymakers and industry stakeholders to facilitate the decarbonisation of the reference domestic ferry fleet.

This study novelty stems from the investigated case study that includes two typical ferries representing the domestic ferries fleet in a developing country as well as the results extrapolations to the whole fleet. The carbon tax as a policy measure is assessed, comparing with the required investment cost. This study provides valuable insights for policymakers and industry stakeholders on the policy and regulatory actions needed to facilitate the decarbonisation of the domestic ferry sector in the short- to long-term.

2. Materials and Methods

The followed methodology consists of five steps as presented in the flowchart shown in Figure 1. Step 1 involves the selection of the key performance indicators (KPIs) for three categories (technical, environmental, and financial). These KPIs focus on representing the potential technical requirements, such as storage volume or battery weight/volume, as well as to determine the environmental impact and associated costs. An existing lifetime economic-environmental model (LTEEM) is customised to facilitate the calculation of the determined KPIs. Step 2 focuses on the data collection for the selected case ships as well as their pre-processing to estimate the model input parameters, which include the case ships particulars, operating profiles, and fuel consumption datasets. Step 3 investigates four case studies (baseline, hybrid power system, LNG use, methanol use). Step 4 involves the assessment of the environmental, financial, and technical KPIs. Finally, step 5 entails the discussion of this study results facilitating the appraisal of the considered cases feasibility. The presented KPIs did not consider the cost of production and transportation of LNG and methanol fuels whereas, the transport (by ship) costs amount 0.74–1.29 EUR/GJ for LNG and 1.8 EUR/MWh for methanol. However, it is anticipated that those costs are embedded in the fuel price. These factors can be considered in future studies that examine the well-to-wake cost [27,28] as presented in Table A2 of the Appendix A.

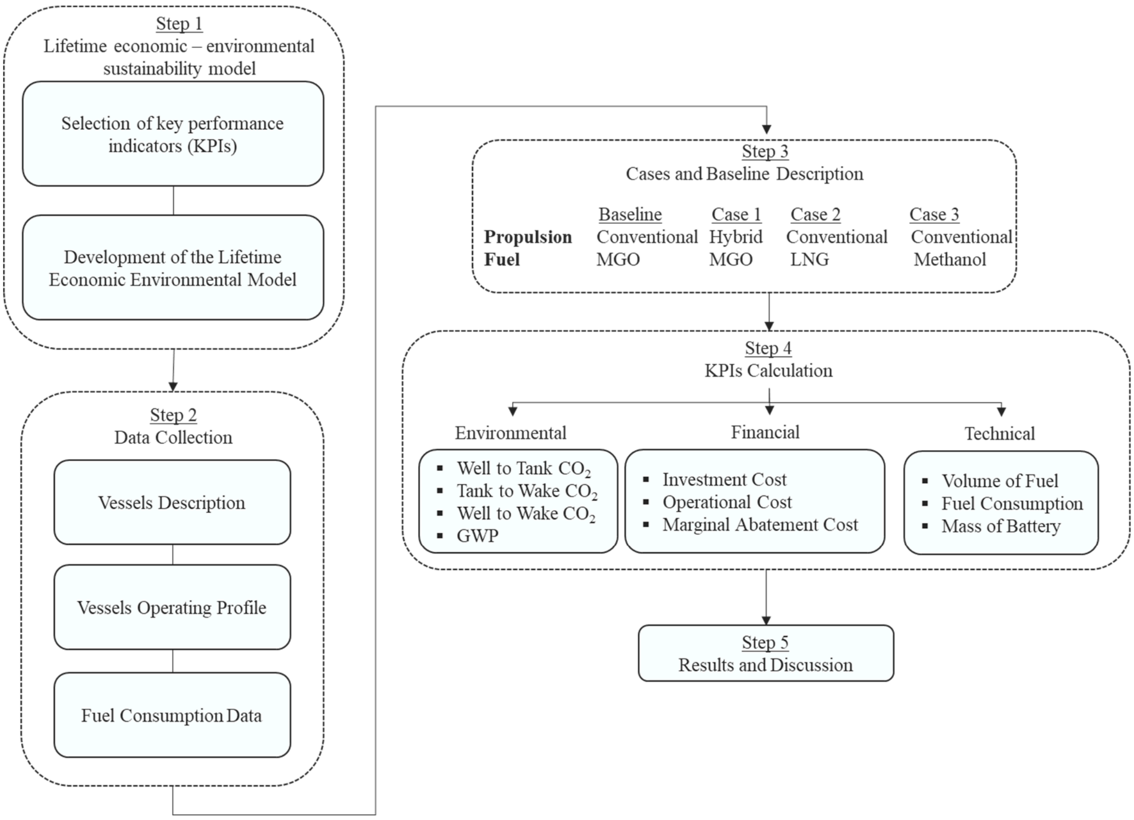


Figure 1. Methodology flowchart.

2.1. Key Performance Indicators

This study employs key performance indicators (KPIs) that are classified in the following groups: environmental, financial, and technical. The environmental KPIs include the CO_2 emissions considering the annual and each voyage timelines, as well as the global warming potential (GWP) that characterises the environmental impact of the considered cases. The CO_2 emissions are considered in a well to tank and tank to wake basis. The financial KPIs include the investment cost (characterising the required capital), the operating expenditure (characterising the operational expenses), and the marginal abatement cost (MAC) that denotes the effectiveness of the emission abatement measures. The technical KPIs include the annual fuel consumption (*FC*), and the fuel required volume, as well as the batteries systems volume and weight, which are required to assess the technical requirements for the investigated cases. The financial KPIs facilitate the appraisal of the potential investment that is essential to accommodate the lower environmental impact power plants.

2.2. Lifetime Economic-Environmental Model

The lifetime economic-environmental model employed in this study is based on Ref. [13]. The model assesses different environmental and economic parameters based on operating profile, employing the typical voyage(s) energy analysis. Since the income streams pertinent to the vessels economic activity are considered the same to the reference ships (with the conventional power plants), they are not used herein. The vessels under consideration can accommodate the alternative fuels storage tanks at free spaces onboard and hence no loss of capital is considered.

The voyage energy analysis is based on the annual fuel consumption, derived from the vessel operating profile, which are estimated based on data received from the ship operators. The determination of the energy required for each voyage is derived by the fuel consumption for each fuel examined by the following equation:

$$E_{trip} = \sum_{f} LHV_f \, FC_i \tag{1}$$

where *LHV* refers to each fuel lower heating value.

The required storage volume for a single voyage is calculated using a storage safety factor (c in Equation (2)) of 20% accounting for the non-used part of the tanks, according to the following equation:

$$V_f = \frac{FC_i}{\rho_f}(1 + \mathrm{c}) \tag{2}$$

where ρ refers to each fuel density.

The investment cost (*CAPEX*) and annual operational expenditure (*OPEX*) are calculated according to the following equations:

$$CAPEX = P_{ME} \, C_E + AT + C_B \tag{3}$$

$$OPEX = AC_{f_i} + AC_{OM} + AC_O \tag{4}$$

where P_{ME} is the nominal power of the ship main engine; C_E, is the engine cost factor (in EUR/kW); *AT* refers to the NOx after-treatment system cost that is essential equipment for all the examined fuels; AC_f is the annual fuel(s) cost; AC_{OM} denotes the maintenance cost factor (EUR/kWh); AC_O refers to any other annual cost considered, for example, carbon taxation; C_B denotes the cost of batteries and requires systems of the hybrid plant (electric machinery, power electronics, DC/AC converters).

The marginal emission abatement cost that characterises the relative investment needed per abated emissions mass is calculated according to the following equations:

$$MAC_{CAPEX} = \frac{\Delta CAPEX}{\Delta CO_{2i}} \tag{5}$$

$$MAC_{OPEX} = \frac{\Delta OPEX}{\Delta CO_{2i}} \tag{6}$$

where i denotes the case study number, and ΔCO_{2i} denotes the difference of the CO_2 emissions from the baseline case study.

The well to tank and tank to wake carbon emissions are calculated as:

$$EM_{CO_2,i} = M_{CO_2,i} EF_{CO_2,i} \tag{7}$$

where M_{CO_2} refers to the mass of CO_2 and EF_{CO_2} to the CO_2 emission factor, whilst the subscript i corresponds to well to tank or tank to wake emissions.

The global warming potential corresponding to 100 years is calculated by the following equation:

$$GWP_{100y} = M_{CO_2} + 36\ M_{CH_4} + 298\ M_{N_2O} \tag{8}$$

3. Case Studies Description

This study investigates two typical RO-PAX ferries of different sizes, representing the fleet of a developing country. The key characteristics of these ferries (termed Vessel 1 and Vessel 2, henceforth) are listed in Table 1. Vessel 1 length is 97.8 m, whilst Vessel 2 has a length of 50 m. Vessel 1 typical voyage is around 27,000 nm, completing three voyages per week, whereas Vessel 2 typical return voyage is 110 nm, running two voyages per day. The investigated ships main particulars for each propulsion engines of Vessels 1 and 2 are listed in Table 2. The rated power of each generator set installed in Vessels 1 and 2 are 350 kWe and 160 kWe, respectively.

Table 1. Characteristics of the case vessels.

Parameter	Vessel-1	Vessel-2
Type	Ro-pax	Ro-pax
Length/breadth/draught [m]	97.8	50
Typical voyage distance [nm]	27,025	110
GT [t]	5145	2682

Table 2. Main engine characteristics.

Component	Vessel-1	Vessel-2
Type	four-stroke	four-stroke
Fuel	MGO	MGO
Rated Power [kW]	2360	1370
Rated Speed [rpm]	750	850
Cylinders	12	12

Four case studies are investigated for both vessels (1 and 2) as follows. The baseline case study (BL) includes the power plant of the existing ships, which include two main engines (each one drives a propeller via a gear box) and three auxiliary generator sets. Both the ship main engines (ME) and auxiliary engines (AE) use marine gas oil (MGO). Case study.

C1 employs a hybrid propulsion system with installed (retrofitted) batteries to generate electric power partially covering the vessels auxiliary and propulsion power demand. Case study C2 considers the BL layout with the LNG use. The MEs and AEs are converted to dual fuel engines operating with natural gas (90% energy fraction) and pilot diesel (10% energy fraction). Case study C3 considers the BL layout with the use of methanol fuel. The MEs and AEs are converted to dual fuel engines operating with methanol as main fuel (90% energy fraction) and diesel pilot fuel (10% energy fraction). The simplified layouts of the investigated case studies are presented in Figure 2, whereas their main characteristics are reported in Table 3.

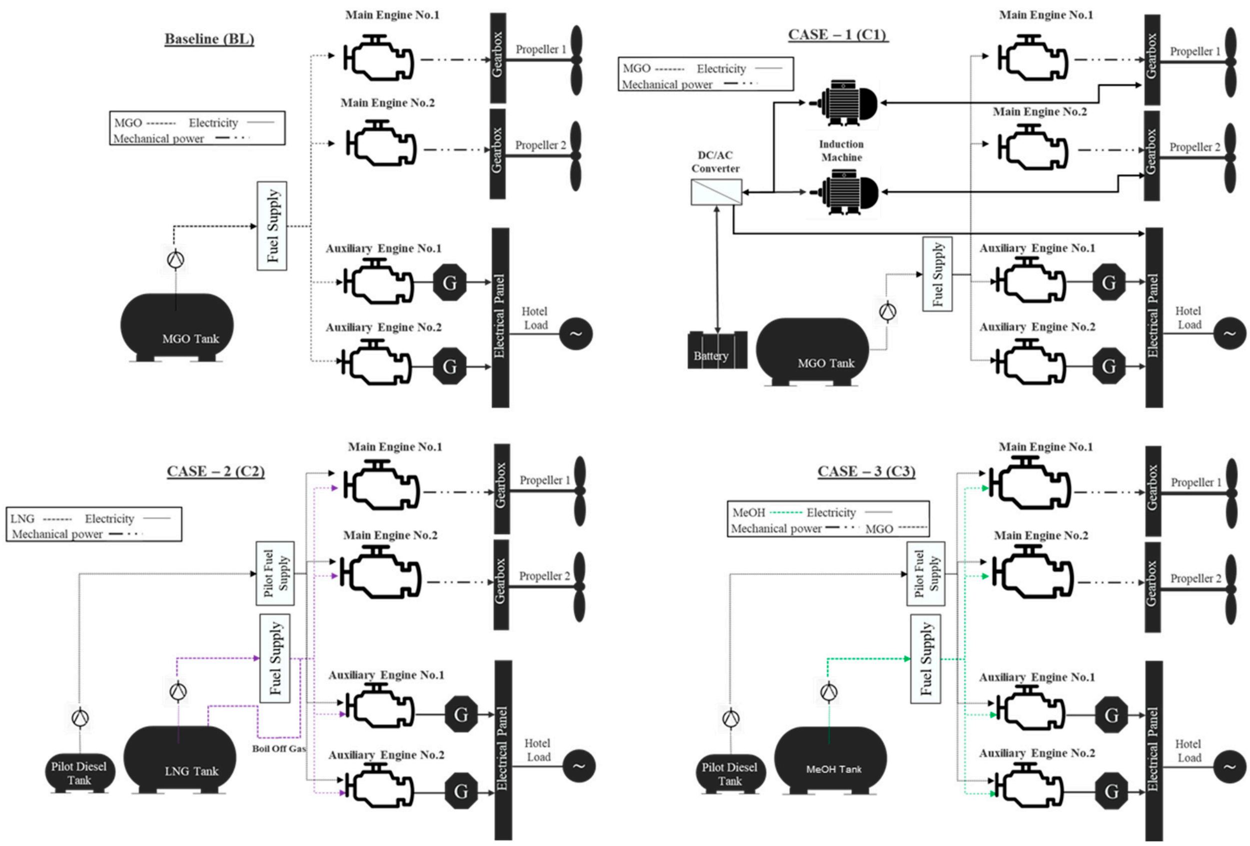


Figure 2. Power plant layouts considered for the four case studies.

Table 3. Main characteristics of the cases studies for each vessel.

Case	Fuels	Main Units	Subsystems
Baseline (BL)	MGO	2 Main diesel engines 2 Auxiliary generator sets	–
CASE—1 (C1)	MGO	2 Main diesel engines 2 Auxiliary generator sets 1 Batteries pack 1 Electric motor/generator	NOx after-treatment unit
CASE—2 (C2)	LNG Pilot diesel	2 Main dual fuel engines 2 Auxiliary dual fuel generator sets	NOx after-treatment unit
CASE—3 (C3)	Methanol Pilot diesel	2 Main dual fuel engines 2 Auxiliary dual fuel generator sets	NOx after-treatment unit

3.1. Input Parameters

For case study C1 (hybrid power system use), the energy storage system consists of a 420 kWh Li-ion battery for Vessel 1 and a 225 kWh Li-ion battery for Vessel 2. These ships power plants include an electric shaft generator, which can be powered by either the battery or by charging the battery through the ship's main engine. The battery sizes were selected by considering batteries capacity of 0.23 kWh per kW of installed power as reported in [26]. According to the same study, hybrid propulsion systems yield an average fuel saving of around 11% with a standard deviation of 3%. In addition to the battery and propulsion system, other components considered in C1 are the DC/AC converter and an electric machine (motor/generator) coupled with the propulsion system gearbox.

Table 4 lists the model input parameters, which include the fuels prices, the emission factors, as well as the cost factors of the marine engines and machinery systems. The emission factor for NG methane slip was adapted from Balcombe et al. [29]. It is worth mentioning that significant progress has been made in recent years to reduce methane slip, with reductions of up to 50% achieved in low-pressure two-stroke gas engines [30]. The cost factors for LNG storage refer to C-type tanks, which are typically employed in maritime applications [31].

Table 4. Model input parameters; adapted from Refs. [8,32–36].

Parameter		Value
Marine Methanol engine cost factor	EUR/kW	780 [1]
Marine LNG engine cost factor [1]	EUR/kW	554
Marine Diesel engine cost factor	EUR/kW	493
Maintenance cost factor	EUR/kWh	0.012
After-treatment unit cost factor	EUR/kW	40
Battery cost factor	EUR/kWh	800
Methanol fuel supply system	M EUR	1.2
MGO CO_2 EF [2]	kg CO_2/kg fuel	3.02
NG CO_2 EF	kg CO_2/kg fuel	2.75
Methanol CO_2 EF	kg CO_2/kg fuel	1.37
MGO CH_4 EF	kg CH_4/kg fuel	0.006
NG CH_4 EF	kg CH_4/kg fuel	0.041
Methanol CH_4 EF	kg CH_4/kg fuel	0
MGO N_2O EF [3]	kg N_2O /kg fuel	1.4×10^{-4}
NG N_2O EF	kg N_2O /kg fuel	0.71×10^{-4}
Methanol N_2O EF	kg N_2O /kg fuel	0.71×10^{-4}
MGO Price [5]	EUR /t	674
LNG Price [4]	EUR /t	1400
Methanol Price [4]	EUR /t	1000
Methanol storage cost	EUR /m^3	3000
LNG storage cost	EUR /m^3	2000

[1] Four stroke gas engine is considered, [2] Provided by industrial sources, [3] Uncertainty regarding the N_2O emission factors is noted, [4] Fuel costs refer to conventional fuel production methods. [5] year average as of 2023 is used for the fuel price of MGO according to [37].

The main properties of the MGO, LNG and methanol fuels are summarised in Table 5. Due to its lower energy content compared to MGO fuel, methanol requires a larger amount of fuel storage to meet the same energy demand. Specifically, the energy content of methanol is less than half of that of MGO fuel [38]. However, LNG would as well require higher storage volume comparing to MGO due to its lower density [39]. The efficiency of the case ships engines when operating with LNG and methanol, is assumed same with the diesel mode, as supported by the data provided in [40].

Table 5. Fuel properties, adapted from [26,41].

Property	MGO	LNG	Methanol
LHV [MJ/kg]	42.7	48.6	20.1
Fuel Density [kg/m^3]	838	428	791
Volumetric Energy Density [MJ/L]	34	22	16
Gross Storage System Size Factor	×1	×2.4	×1.7

The considered ferries fleet characteristics are presented in Table 6. The total gross tonnage of the fleet is 981,500 GT. The examined vessels belong to the category of above

400 GT. These ships can accommodate the batteries and alternative fuels storage tanks at free spaces without loss of payload; hence, no loss of capital is considered.

Table 6. Ferries fleet characteristics.

GT	Number of Vessels
0–100	67
100–399	135
Above 400	160

3.2. Emissions Taxation

Emissions taxation is identified as a potential measure to incentivise the ferries fleet decarbonisation. According to the World Energy Outlook [42], the carbon emissions tax is estimated at 40–50 EUR/t and 100–110 EUR/t for the 2030 and 2040, respectively, for emerging markets and developing countries with net zero targets. Those values are also applied for the energy production sector. Hence, it is assumed that similar values are expected for the shipping industry for the considered developing country.

4. Results

At this section, the derived results are presented and discussed. The following subsections provide the environmental, the financial, and technical KPIs.

4.1. Environmental KPIs

Figure 3 provides the well to tank, tank to wake and their total, annual CO_2 emissions for the four investigated case studies (BL, C1, C2 and C3), for the two vessels. In the case of methanol, fossil (C3-F) and renewable (C3-R) production methods are considered. The former (C3-F) includes the methanol production from natural gas by employing the following processes: steam reforming to produce syngas, methanol synthesis reaction, and methanol purification. The latter (C3-R) considers the use of biomass feedstock and gasification process to produce methanol, whereas the electric energy demand is covered by renewable energy sources. The horizontal lines correspond to 40% Well to Wake CO_2 emissions reduction (compared to the baseline), which aligned with the IMO 2030 targets. For the tank to wake, the presented results demonstrate that the CO_2 emissions can reduce by about 11%, 33% and 8% for the case studies C1, C2 and C3 respectively compared to BL. The methanol use (C3) results in the lowest CO_2 emissions reduction (8%), which is attributed to the methanol lower heating value ratio (compared to the LNG and MGO), leading to higher methanol consumption. However, it is inferred that the three alternative case studies (C1, C2, and C3) cannot achieve the IMO 2030 targets.

Given the well to tank CO_2 emissions for the four cases calculated using the values for the well to tank CO_2 emissions factors listed in Table A1. For BL, the well to tank CO_2 emissions are 864 t CO_2 and 452 t CO_2 for vessels 1 and 2, respectively. Batteries production even when using 15–20% renewable energy mix exhibits significantly lower emission factors [43] Hence, case C1 exhibits better environmental performance (considering the well to tank phase) compared to the other cases. For LNG (case C2), higher well to tank emissions (compared to BL) were estimated, specifically 1161 t CO_2 and 608 t CO_2 for the selected vessels. This is attributed to the increased CO_{2eq} emission factor for the methane slip associated to natural gas extraction. Methanol production using energy from fossil fuels (C3-F) is associated with lower emission factors compared to LNG, and slightly higher compared to MGO. However, the increased methanol consumption yields similar well to tank emissions to the BL case (834 t CO_2 and 437 t CO_2 for vessels 1 and 2, respectively). For methanol produced from biomass feedstock using renewable energy (C3-R), which exhibits potential in developing countries, the well to tank emissions can considerably reduce (709 t CO_2 and 371 t CO_2 for vessels 1 and 2, respectively). The well to tank and corresponds to 26%, 27%, 45%, 27% and 23% of the tank to wake emissions for cases BL, C1, C2, C3-fossil, and C3-renewables, respectively. Cases C1 and C2 exhibit almost similar well to wake CO_2 emissions (lower by 11% and 10% respectively compared to BL), whereas case 3 exhibits well to wake CO_2 emissions 7% (for fossil based production) and 9% (for biomass based production) lower that the BL and 5% higher than C1.

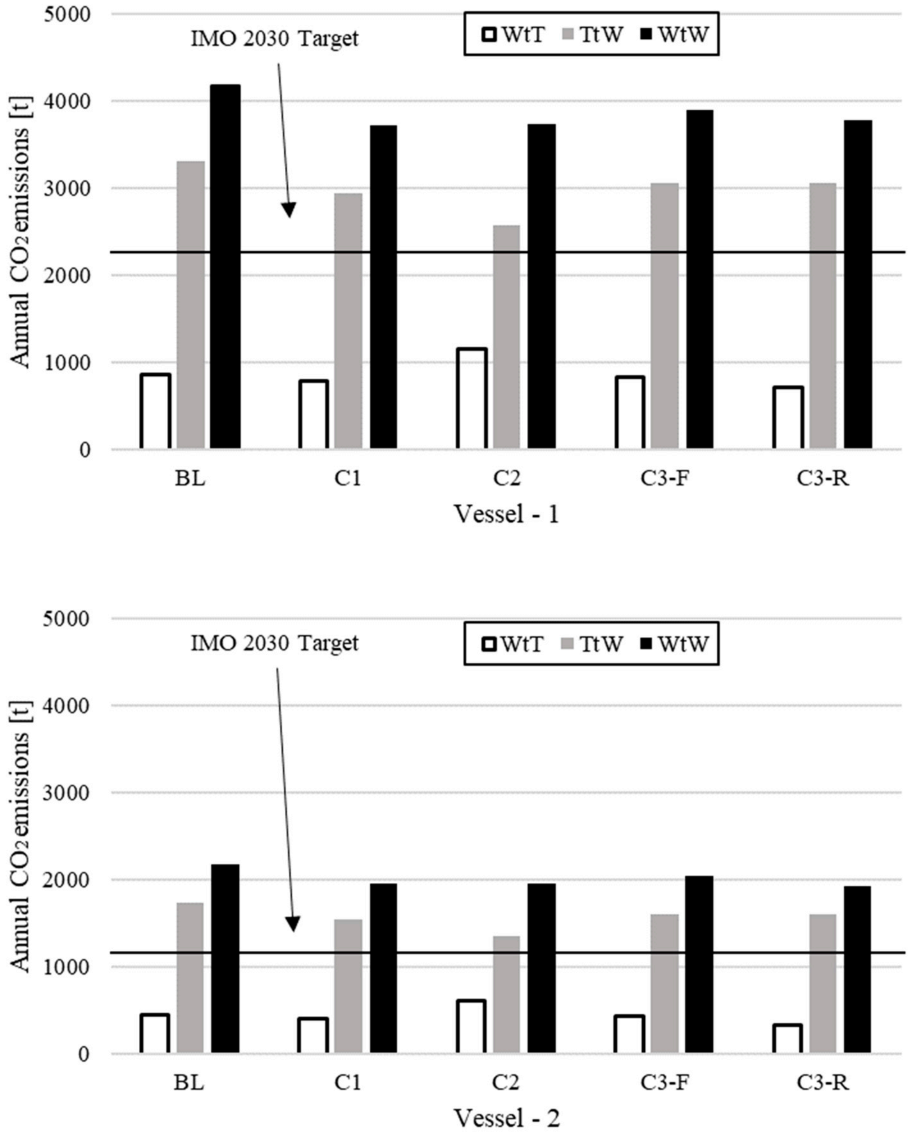


Figure 3. Well to tank, tank to wake and total CO_2 emissions, for vessel-1 (**top**) and vessel-2 (**bottom**) and the considered cases.

Figure 4 illustrates the global warming potential (*GWP*) in CO_2-equivalent emissions of the investigated case studies during the vessels' lifetime. It must be noted that a lifecycle approach considering the fuel production and ship building phases would be more inclusive, hence it is proposed for future studies. However, the lifetime *GWP* is an indicator for the investigated vessels environmental footprint. Case study C3 (methanol use) provides the lowest *GWP*, approximately 22% lower than that of BL, which is attributed to the almost zero N_2O and CH_4 emissions. Case study 2 (LNG use) exhibits 8% higher *GWP* compared to the baseline (BL), due to the significant contribution of N_2O and CH_4 emissions. However, recent advancements in marine gas and dual fuel engines technology have effectively mitigated the methane slip [44,45]. Case study C1 (hybrid system) is also associated with slightly reduced *GWP*, due the lower fuel consumption and corresponding reduction of the CO_2, N_2O and CH_4 emissions.

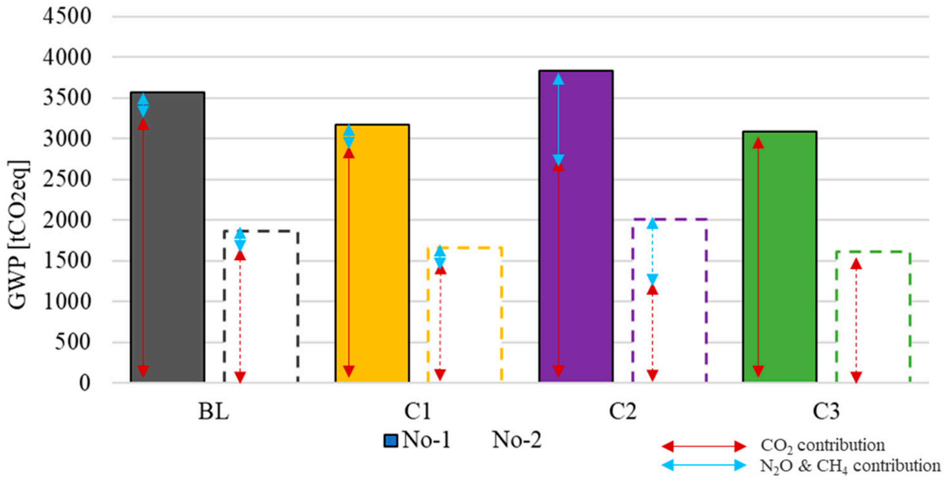
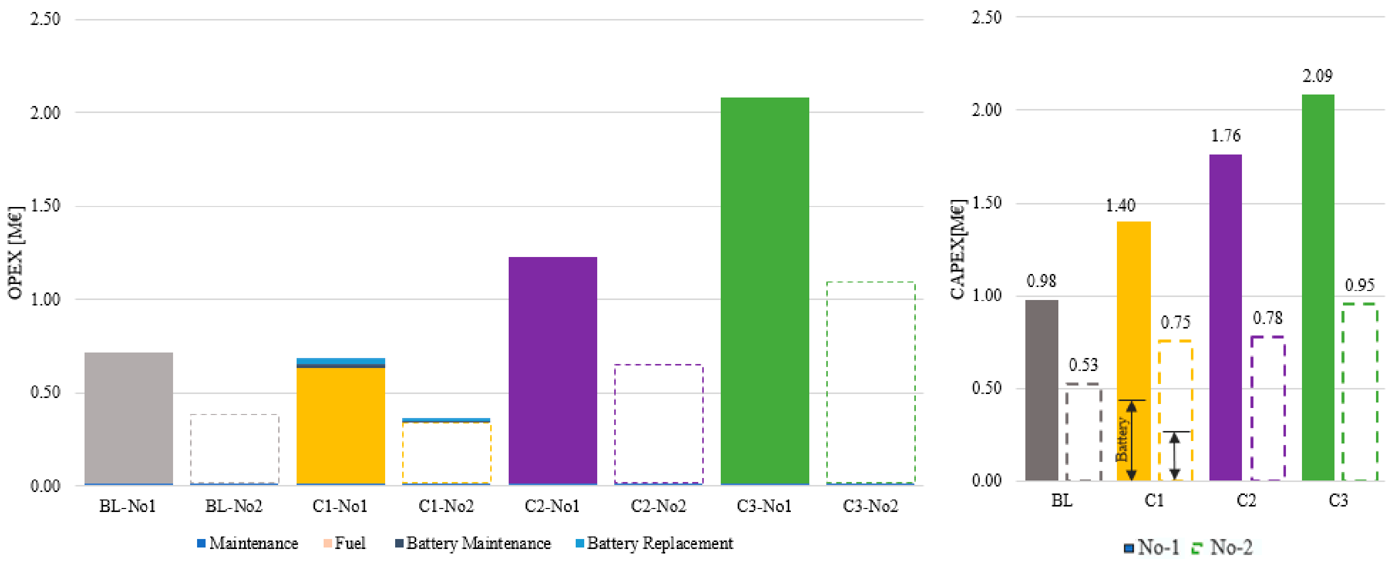


Figure 4. Global warming potential for the operational phase of the examined vessels and different cases (solid lines denote Vessel 1; dashed lines denote Vessel 2).

4.2. Financial KPIs

Figure 5a provides the annual operating expenditure for vessels 1 and 2 (large and small). It is evident that in all case studies the fuel cost amounts more than 95% of the operating costs. For Vessel 1, case studies C2 (LNG use) and C3 (methanol use) correspond to increases of the annual operational expenditure by M EUR 0.52 (42%) and M EUR 1.37 (66%) respectively compared to BL. For Vessel 2, case studies C2 (LNG use) and C3 (methanol use) correspond to increases of the annual operational expenditure by M EUR 0.27 (41%) and M EUR 0.72 (65%) respectively compared to BL. On the contrary, case study C1 (hybrid power plant) reduces the annual operational expenditure by M EUR 0.03 (−4%) and M EUR 0.02 (−4%) for the large and small vessels respectively compared to BL, which is attributed to the considerable fuel savings. Figure 5b provides the investment costs for the four case studies. For the large vessel and cases C1, C2, and C3, the required additional investment costs (compared to the BL investment) amount of M EUR 0.42 (30%), M EUR 0.78 (45%) and M EUR 1.1 (53%) respectively. For the small vessel, the extra investment costs (compared to the BL investment) were found M EUR0.23 (30%), M EUR 0.25 (33%), and M EUR 0.43 (45%) for C1, C2, and C3, respectively. The required investment is greater for the alternative fuel technologies, attributed to the cost required for the retrofitted solutions, storage and feeding systems, safety systems and equipment (Figure 5b). Particularly for methanol use, the higher investment cost is attributed to the considerably higher cost of methanol fuelled marine engines as also indicated by the respective cost factors listed in Table 4.

Table 7 provides the marginal CO_2 emissions abatement costs (MAC) for case studies C1, C2, and to C3 (compared to the BL) considering the required investment cost (MAC_{CAPEX}) and operating cost (MAC_{OPEX}). Considering the investment cost, lower MAC_{CAPEX} denotes more significant contribution of each monetary unit spent for decarbonisation. Hence, for the three case studies, the most significant environmental value for money is attributed to C2 (LNG use), as the CO_2 emissions reduction is higher compared to other case studies. Regarding the carbon benefit based on the operating costs (MAC_{OPEX}), the negative sign of the C1 case denotes that there exist financial benefits along with the carbon emissions reduction, attributed to the fuel consumption reduction, rendering C1 financially most attractive than the others. The overall marginal abatement cost for Vessel-1 and Vessel-2 is calculated as 0.49 M EUR/t CO_2 and 0.84 M EUR/t CO_2 for C1, 6.79 M EUR/t CO_2 and 3.65 M EUR/t CO_2 for C2 and 50.08 M EUR/t CO_2 and 27.19 M EUR/t CO_2 for C3.



(a) (b)

Figure 5. (**a**) *OPEX*, and (**b**) CAPEX for the four investigated studies and the two considered vessels. Solid bars denote Vessel-1; Dashed bars denote Vessel-2.

Table 7. Marginal abatement cost.

Cases	Vessel 1	Vessel 2
	MAC_{CAPEX} [M EUR/t CO_2]	
C1	1.16×10^{-3}	1.19×10^{-3}
C2	1.08×10^{-3}	0.66×10^{-3}
C3	4.58×10^{-3}	3.39×10^{-3}
	MAC_{OPEX} [M EUR/t CO_2]	
C1	-0.67×10^{-3}	-0.35×10^{-3}
C2	5.71×10^{-3}	2.99×10^{-3}
C3	45.5×10^{-3}	23.8×10^{-3}

4.3. Technical KPIs

Figure 6a provides the annual fuel consumption, whereas Figure 5b presents the required fuel volume per voyage (the characteristics of the fuels were listed in Section 3.2) for the four case studies and the two vessels. It must be noted that the presented results in Figure 6b do not account for the battery volume as well as the volume of the fuel storage and feeding systems. Table 8 provides the batteries volume and mass for the case vessels.

Table 8. Mass and volume of batteries considered in case study 2 [13].

Parameter	Vessel 1	Vessel 2
Batteries volume [m^3]	8000	4300
Batteries Mass [t]	4.6	2.5

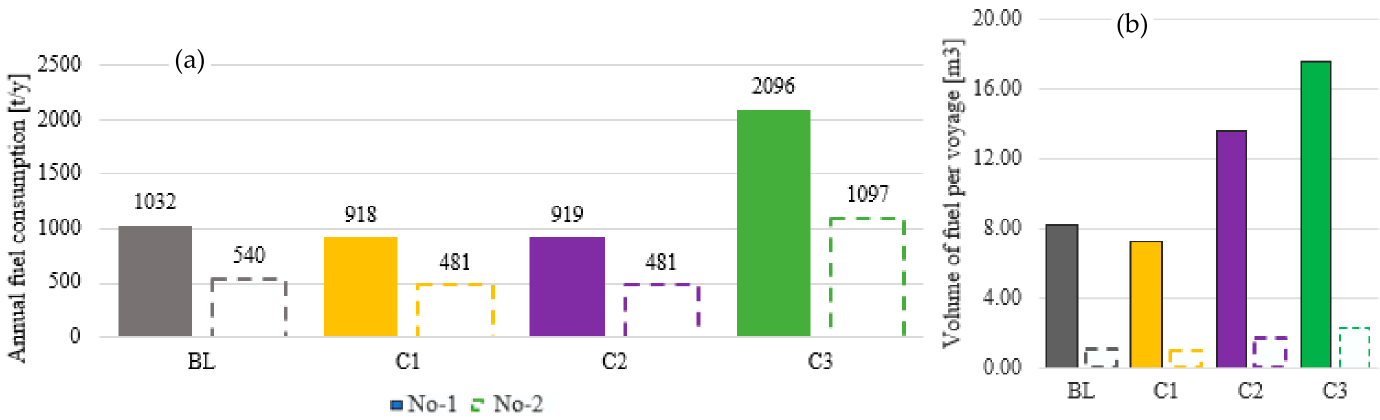


Figure 6. (**a**) Annual fuel consumption, and (**b**) fuel volume for each voyage. Solid bars denote vessel-1; dashed bars denote vessel-2.

Case study C1 (hybrid system) results in fuel reductions of 12% and 11% for the large and small vessels, respectively. This is attributed to the achieved fuel savings by the energy storage system (batteries) use. These reductions correspond to respective reductions of the fuel volume per voyage (as the ships main engines operate with MGO). The batteries systems volume is estimated to 8000 m^3 and 4300 m^3 for large and smaller vessels, respectively. This volume can be accommodated in the case vessels, whereas the estimated batteries weight (4.6 t and 2.5 t respectively) is not expected to impact the ship strength and stability. The industry has accumulated adequate experience to appropriately address the batteries and hybrid systems safety, as such systems are extensively employed commercially the last decade.

Case study C2 (LNG use) for both vessels resulted in a similar fuel reduction (11%) as case study C1, which however is attributed to the higher heating value of the natural gas compared to the diesel. The required LNG volume per voyage increases by 74%. Considering the LNG storage and feeding systems, the required shipboard volume is expected to further increase as reported in [41], However, the derived volume increase is in alignment with the figures reported in [46] for the LNG fuel use. It was found based on the case ships general arrangement drawings that the required LNG along with the associated storage and feeding systems can be accommodated by using tank layouts as reported in [47], whereas the use of LNG is not expected to cause any potential safety implications, due to the existing regulatory framework and extensive industry expertise.

Case study C3 (methanol use) resulted in 103% increase of the fuel consumption compared to BL, which is due to the methanol lower heating value. The required methanol volume for each voyage increases by 113%, (more than double the MGO volume of case study BL) for both vessels, which also aligns with the figures reported in [48] for methanol use. Moreover, methanol use is not expected to cause safety implications, due to the existing regulatory framework and methanol ships operation since 2016 [41].

4.4. Fleet Decarbonisation

From the preceding discussion, the cases C1 and C2 are chosen for further analysis due availability of LNG fuel and the required technologies in the considered area as well as lower storage requirements and cost pertinent to methanol. For the decarbonisation of the whole fleet, cost-effective measures for emissions reduction must be identified. This section elaborates on the cost implications for the implementation of the investigated solutions for the Ro-Pax ferries power plans hybridisation (based on case study C1) and the LNG use (case study C2) that contributes to the CO_2 reduction despite the increased *GWP*. These solutions are considered appropriate for the decarbonisation of the ferries fleet in the short-term. The estimated costs (characterising the required investments) for the two investigated ferries are provided in Figure 4.

Based on these values and the gross tonnage of each ferry, the ratio of cost difference to the GT is calculated and presented in Table 9. The cost difference between the BL case and the cases C1, C2 are used for the examined vessels. The results for case study C1 (hybrid power plant) are employed to identify the trade-off in the whole GT range of the considered fleet (from 100 t to 30,000 t). To address the uncertainty due to the limited number of the investigated ferries (only 2), three trendlines types are considered, namely, linear, exponential, and power.

Table 9. Cost difference to gross tonnage ratio for the two investigated ships considering the hybrid power plan (case study C1) and the LNG use (case study C2).

	Ro-Pax Ferry		**C1**	**C2**	**C1**	**C2**
	Length [m]	**GT**	**ΔCost [M EUR]**	**ΔCost [M EUR]**	$\frac{\Delta\text{Cost}}{\text{GT}}\left[\frac{\text{EUR}}{\text{GT}}\right]$	$\frac{\Delta\text{Cost}}{\text{GT}}\left[\frac{\text{EUR}}{\text{GT}}\right]$
Vessel 2	50	2682	0.23	0.35	85.76	130.5
Vessel 1	100	5145	0.42	0.96	81.63	186.5

For the LNG use (case study C2), the pertinent investments cost exhibits greater uncertainty. Therefore, the average of the calculated values for the two ferries are employed to subsequently estimate the investment cost for the fleet. The estimated investment costs for the considered fleet for the hybridisation (C1) and LNG use (C2) are presented in Table 10. The hybridisation of the Ro-Pax ferries fleet is estimated to M EUR 28.1, whereas the LNG use in this fleet is more expensive with the pertinent estimated cost amounting at around M EUR 58.

Table 10. Total investment cost for the hybridisation and the use of LNG fuel for the of Ro-Pax ferries fleet.

C1—Ro-Pax hybrid powerplant				
Total IC	Linear	Power	Exponential	Average
M EUR	26.5	30.6	27.3	28.1
C2—Ro-Pax LNG fuel use				
Total IC		Average		
M EUR		58.04		

To compare the estimated investment costs, the monetisation of the estimated annual carbon emissions for the considered ferries fleet (amounting to 981,500 GT as reported previously) was carried out by employing a carbon tax based on the ranges discussed in the previous sections. The estimated annual tax is reported in Table 11. Considering a carbon tax of EUR 50 per tonne of CO_2, the annual tax amounts to M EUR 49. It is apparent that the introduction of a carbon tax policy can be used for funding investments for the decarbonisation of the ferries fleet. However, vigilant, and well-planned strategies are needed to avoid disruptions in the ferries sector and ensure that the cost will not pass to the passengers by increasing the fares. To promote decarbonisation initiatives in developing countries, subsidisation or financial support must be sought by national or international authorities. It is recommended that the decarbonisation initiatives are combined with initiatives for the new designs to simultaneously address the safety and cost-effectiveness perspectives. However, this is recommended for future studies.

Table 11. Monetisation of the annual carbon emissions.

Carbon Tax [EUR/t]	**Annual Tax Revenues [M EUR]**
50	49.08
100	98.15

5. Discussion

This study aims to investigate near-term strategies for mitigating carbon emissions within ferry fleets operating in developing countries. It must be noted that the domestic ferries fleets of these countries subject to national regulations (and not IMOs regulations). This study findings based on the estimated lifetime (tank to wake) and lifecycle (well to wake) parameters are summarised as follows.

From a lifetime perspective, hybrid power plants with MGO as fuel, allow for 12% fuel consumption reduction and hence smaller carbon footprint associated with fuel savings.

For deeper decarbonisation, LNG allows for 11% fuel consumption and 23% tank to wake CO_2 emissions reduction. LNG, despite its advantages as a marine fuel, shows increased well-to-tank emissions due to methane slip associated with natural gas extraction. However, it seems to be one the most effective solutions considering the well to wake emissions.

Methanol exhibits the worse financial performance (considering *CAPEX* and *OPEX*) due to its low energy content (that yields increased fuel consumption), which renders its feasibility questionable. From a well to tank perspective, use of locally sourced biomass-based methanol can contribute to the lifecycle CO_2 emissions reduction.

Considering the whole fleet, hybrid power plants would lead to significant savings in fuel costs and a substantial decrease in carbon emissions. However, the reduction in emissions might not be as significant as other alternatives in a well-to-tank perspective. The availability of technology and infrastructure for the hybrid system may influence the feasibility of implementing this solution across the whole fleet.

Contrary, LNG as a fuel for the whole fleet would result in similar fuel consumption reduction, fuel cost savings and reduced emissions combined with established technology and infrastructure, making it a practical choice for fleet-wide adoption especially if advancements in technology continue to mitigate methane slip issues. Fleet-wide adoption of fossil–based methanol would not be financially or environmentally effective, as the increased fuel consumption results to only 7% well to wake CO_2 emissions reduction.

Potential introduction of emission taxation schemes from developing countries is expected to be a key driver towards the adoption of alternative propulsion technologies and fuels. However, associated challenges and measures for not transferring this cost to the end users must be thoroughly investigated in future studies.

This study offers invaluable insights to ferry operators and policymakers of developing counties, to curtail carbon emissions within their fleets. The adoption of short-term measures can facilitate the transition towards decarbonised shipping operations. However, achieving ambitious emissions targets may necessitate the use of synergies and several measures combinations. Furthermore, this study assesses the impact from several measures, contributing towards the enhancement of shipping sustainability.

6. Conclusions

This study examined different short- to medium-term solutions for the Ro-Pax ferry fleet decarbonisation in developing countries. The solutions of power plant hybridisation, LNG fuel use and methanol use were considered for two representative vessels (large and small). A lifetime economic-environmental analysis was carried out to estimate technical, environmental, and economic key performance indicators. The derived results were subsequently employed to comparatively assess these three solutions, whereas the financial impact on the whole fleet was discussed. The study main findings are summarised as follows.

- Hybridised power plants align with a short- to medium-term cost-effective strategy for reducing emissions in ferry operations, as they can yield approximately 11% fuel consumption reduction, leading to proportional emissions reductions.
- The required storage volume for LNG and methanol is expected to increase by 74% and 113% respectively compared to the baseline diesel fuel.

- The hybrid power system is the most cost-effective way to curtail CO_2 emissions, however achieved decarbonisation does not meet the 2030 targets.
- LNG power plants can achieve a 22% reduction in CO_2 emissions, although their *GWP* increases by 8%. Combining LNG use and hybrid power plants can meet the 2030 emission targets.
- The required investments for decarbonising, using LNG, larger and smaller vessels amount to approximately M EUR 0.78 and M EUR 0.25, respectively.
- The use of methanol results in reductions in both CO_2 emissions and *GWP*, but requires substantial investments due to the considerably higher cost of methanol-fuelled marine engines, amounting to M EUR 1.1 and M EUR 0.42 for large and small vessels, respectively.
- From a well to wake perspective the cases C1 and C2 exhibit 11% and 10% lower CO_2 emissions respectively pertinent to BL, whereas C3 exhibits reduction of 7% for fossil-based and 9% for biomass-based production that the BL.
- Considering the RoPax ferries fleet, the total investments required for hybrid propulsion and LNG fuel amount to M EUR 28 and M EUR 58, respectively.
- The introduction of a carbon tax in the range of 50–100 EUR/t CO_2 could be explored as a policy measure to incentivise decarbonisation in this sector. However, financial support for implementing such investments is required to prevent additional costs for end-users.

The limitations of this study are associated with the data uncertainties pertinent to the emission factors and scarcity of data for methanol fuelled marine engines. Given the significance of CO_2 emissions and their impact on the environment, it is crucial to evaluate the overall environmental footprint associated with the use of different fuels. Future studies may employ updated emission factors considering significant developments in marine engine technologies and zero-carbon fuels operations along with the lifecycle assessments.

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Nomenclature

AC	Annual Cost (EUR)
CAPEX	Capital Expenditure (EUR)
C_i	Cost factor (EUR /kW)
DWT	Dead Weight Tonnage (mt)
FC	Fuel Consumption (t)
GT	Gross Tonnage (−)
GWP	Global Warming Potential (t $CO_{2\text{-eq}}$)
MAC	Marginal Abatement Cost (EUR/t CO_2)
OPEX	Operational Expenditure (EUR)
P	Engine Power Output (kW)
V_f	Volume of Fuel (t)

Abbreviation

AT	After Treatment
GHG	Greenhouse Gas
IMO	International Maritime Organisation
KPI	Key Performance Indicator
LNG	Liquified Natural Gas
LTEEM	Lifetime Economic Environmental Model
MGO	Marine Gas Oil

Appendix A

Table A1 lists the characteristics of several fuels including well—to—Tank Emissions factors, shipboard storage conditions, cost factors, and technical maturity. Table A2 provides cost factors associated with the transportation of methanol and LNG.

Table A1. Characteristics of different alternative fuels for the shipping sector [26].

Fuel	Well—to—Tank Emissions Factors				Shipboard Storage Conditions	Cost Factor (EUR/MJ)	Technical Maturity
	CO_2 (g/MJ)	N_2O (g/MJ)	$CO_{2.eq}$ (g/MJ)	NOx (g/MJ)			
Brown NH_3	64.8	4.5×10^{-4}	64.9	4.4×10^{-2}	T: 240–290 K P: 8–10 bar State: liquid	1.8×10^{-2}	Low
Green NH_3	18.5	4.5×10^{-4}	18.6	4.4×10^{-2}		2.7×10^{-2}	Low
Brown H_2 (liquid)	77.9	2.5×10^{-4}–2.5×10^{-3}	77.9–78.4	3.4×10^{-2}	T: 20 K P: 12.7 bar State: Cryogenic liquid	1.7×10^{-2}	Low
Green H_2 (liquid)	7.9	4.1×10^{-4}	7.98	3×10^{-2}		4.3×10^{-2}	Low
CH_3OH—NG based	20	2.9×10^{-4}	20	4.6×10^{-2}	T: 293 K P: 1 bar State: liquid	2×10^{-2}	Medium
CH_3OH—biomass based	17	2.2×10^{-4}	17	5.6×10^{-2}		0.8×10^{-2}	Medium
LNG—Fossil based	26	1.6×10^{-4}	26	6×10^{-2}	T: 134 K P: up to 7 bar State: Cryogenic liquid	2.9×10^{-2}	High
MGO	19.6	5.4×10^{-4}	19.7	23×10^{-2}	T: 293 K P: 1 bar State: liquid	1.9×10^{-2}	High

Table A2. Cost factors for transportation of methanol and LNG.

Fuel	Cost Factor	Transportation Method
Methanol	1.8 EUR /MWh	Ship
	0.16 EUR/t-mile [1]	Truck
	0.071 EUR/t-mile [1]	Rail
LNG	0.74–1.29 EUR/GJ	Ship

[1] Data retrieved by de Fournas et al. [49].

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