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Environmental-economic sustainability of hydrogen and ammonia fuels for short sea shipping operations

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ABSTRACT

Alternative fuels of low or zero carbon content can decarbonise the shipping operations. This study aims at assessing the lifetime environmental-economic sustainability of ammonia and hydrogen, as alternatives to diesel fuel for short sea shipping cargo vessels. A model is employed to calculate key performance indicators representing the lifetime financial sustainability and environmental footprint of the case ship using a realistic operating profile and considering several scenarios with different diesel substitution rates. Scenarios meeting the carbon emissions reduction targets set by the International Maritime Organisation (IMO) for 2030 are identified, whereas policy measures for their implementation including the emissions taxation are discussed. The derived results demonstrate that the future implementation of carbon emissions taxation in the ranges of 136–965 €/t for hydrogen and 356–2647 €/t for ammonia can support these fuels financial sustainability in shipping. This study provides insights for adopting zero-carbon fuels, and as such impacts the de-risking of shipping decarbonisation.

1. Introduction

The shipping sector plays a crucial role in global trade and the economy, contributing significantly to greenhouse gas emissions [1]. In 2020, the sector accounted for 2.76 % of worldwide carbon emissions, and projections forecast a 250 % increase by 2050, reaching 17 % compared to 2012 levels. In response, the International Maritime Organisation (IMO) has implemented regulations in MARPOL Annex VI and set ambitious targets, aiming for a 40 % reduction in carbon emissions by 2030 and net-zero CO_2 emissions by 2050 [2]. To address the environmental impact, alternative fuels such as natural gas, methanol, hydrogen, and ammonia are considered to decarbonise the shipping sector.

Ammonia due to its similar volumetric density to diesel [3] is an attractive alternative fuel. Producing ammonia from renewables improves the overall environmental performance at the expense of higher cost [4]. Hydrogen is also an attractive alternative fuel for the shipping sector. Although its energy content is much higher compared to conventional marine fuels, its density is much lower, thus posing significant challenges for the shipboard storage systems [5]. Ammonia is stored as liquid at atmospheric pressure and 240 K, whereas hydrogen can be stored either at compressed gaseous form (with density around 40 kg/m^3) or liquid state at 21 K (with density around 71 kg/m^3) [6]. Both the hydrogen compression and liquefaction are energy intensive processes deteriorating the overall environmental footprint [7]. Other alternatives include alcohol fuels like methanol, which is considered a transition fuel for the shipping decarbonisation [8]. However, significant challenges pertinent to combustion stability and fuel compatibility must still be addressed [9–12].

Pertinent technoeconomic studies reported that €58 million are required to decarbonise the ferries fleet using natural gas fuel in developing countries, a cost that can incentivised by applying carbon taxation around 50 €/t [13]. The levelised cost of electricity for ammonia fuel cells was estimated around 0.122 $/kWh for the Scotland's ferries fleet, whereas for hybrid propulsion systems, this cost reduces to 0.117 $/kWh [14]. Other propulsion technologies (batteries) were examined, resulting in 7 years return of investment for ferries operating in Adriatic Sea [15]. Elkafas et al. [16] examined the cost for using ammonia and hydrogen among other fuels for short-sea shipping ferries with fuel cells, concluding that the installation of fuel storage systems and fuel cells costed €8.6 million and €8.4 million for ammonia and hydrogen, with the levelised cost of electricity being around 400 €/kWh. Laasma et al. [17] examined the technical readiness for the alternative fuels use in costal ferries demonstrating that marine engines operation with hydrogen would require 2.5 times the CAPEX of the baseline diesel operation. Jafarzadeh et al. [18] proposed that ammonia

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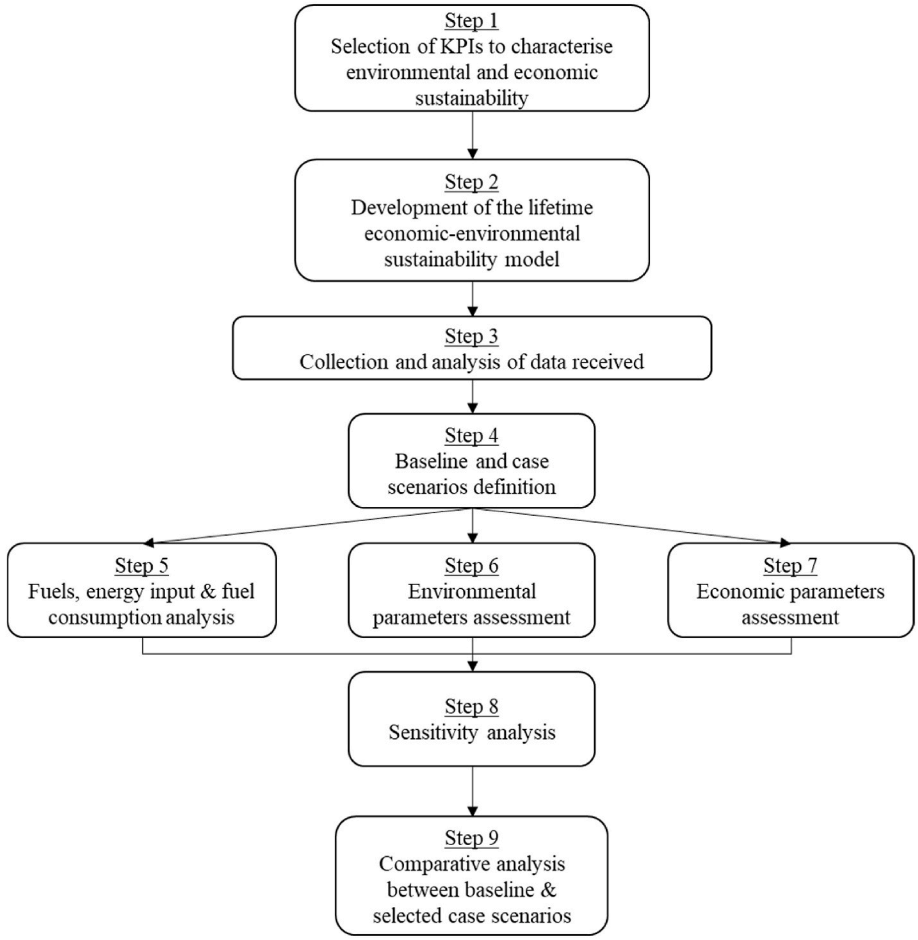

Fig. 1. Methodology flowchart.

fuel cells installed on coastal fishing fleet are expected to exhibit increased capital costs by 65–124 % compared to current diesel systems. Ammonia and methanol use in internal combustion engines were found to be more cost-effective compared to fuel cells systems (that require high CAPEX) for RoPax, tankers and pilot boats [19]. Stolz et al. [20] argued that using ammonia, the total cost of ownership is expected to increase 4–6 times by 2030 to achieve carbon neutral bulk carriers operations.

Hansson et al. [21] studied the potential of ammonia as a marine fuel, identifying a major challenge for its adoption the higher price per energy content compared to marine gas oil (MGO) and liquified natural gas (LNG). Brahim et al. [22] showcased that the ammonia production cost reduction would allow for overcoming potential challenges for its adoption in shipping. Both studies underlined the need for pursuing economic feasibility assessments of potential pathways to increase the profitability and incentivise the ammonia adoption.

Nerheim et al. [23] studied the potential challenges of introducing hydrogen in the maritime sector, highlighting the need to address the shipboard safety implications along with the fuel storage and associated costs. Jovanović et al. [24] studied the feasibility of autonomous ships operating with hydrogen as well as conventional fuels arguing that the required high investment cost impacts the hydrogen fuelled ships development. Atilhan et al. [25] highlighted the different production routes of hydrogen from an environmental perspective, arguing that conventional production methods are economically viable, whereas the liquid hydrogen use achieves significant safety benefits compared to other storage forms. Pericic et al. [26] conducted a technoeconomic analysis on different propulsion methods and fuels for several vessels, concluding that among zero-carbon fuels, ammonia yields better economic performance.

Korberg et al. [27] analysed the potential of electro-fuels use for different propulsion systems, highlighting the fuel cost as a major factor for ensuring financial feasibility. Fuel cells were proposed for short sea shipping operations, whilst ammonia and hydrogen, were found to be the least cost-effective solutions for both bulk carriers and container ships. Horvath et al. [28] studied the financial feasibility of different fuels including liquid hydrogen for short sea and ocean-going vessels benchmarking against other fossil-based fuels including diesel, LNG, and methanol. Considering a fixed cost of carbon, hydrogen use was found to be the most cost-effective case to achieve the IMO decarbonisation targets for 2030 and 2050.

The preceding literature review highlights the following research gaps: (a) there is a lack of studies assessing the feasibility of alternative fuels use in marine engines, especially for short sea shipping vessels; (b) comprehensive lifetime economic-environmental analysis of hydrogen and ammonia use as marine fuels are scarce; (c) the implications of emissions taxation as policy measures to accelerate zero-carbon fuels adoption requires further studies.

The aim of this study is to appraise the sustainability of hydrogen and ammonia fuels for a short sea shipping cargo vessel. To that extend, the lifetime economic and environmental assessments along with sensitivity studies on the fuels price and emissions taxation are employed to quantify key performance indicators and provide decision support for plausible policy measures that can support the incentivisation of these fuels adoption.

The novelty of this study stems from: (a) the use of realistic operating profiles of medium sized cargo vessels of short sea shipping; (b) the simultaneous consideration of economic and environmental parameters along with emissions taxation scenarios; (c) development of financial sustainability maps for supporting decisions on incentivisation policy measures.

2. Methodology

This study employs a methodology of nine steps, as shown in Fig. 1. Step 1 deals with the selection of the key performance indicators (KPIs) pertinent to the lifetime environmental and economic parameters that characterise the sustainability of the investigated vessel operations considering the conventional fuel partially substitution with hydrogen or ammonia. Step 2 focuses on the development of the model to calculate these KPIs along with the required input parameters and assumptions. Step 3 involves the collection and pre-processing of the model input parameters. Step 4 determines the baseline (reference) scenario as well as the case scenarios including the hydrogen and ammonia fuels energy fractions, and the decarbonisation targets for the auxiliary and propulsion power system. Step 5 includes the calculation of the energy demand and the required fuel consumption for these scenarios. Step 6 deals with the calculation the environmental KPIs. Step 7 focuses on the calculation of the lifetime economic KPIs. The results from Steps 6 and 7 assess the environmental and economic sustainability of the considered vessel as well as determines the most attractive scenarios for further study. Step 8 deals with the sensitivity studies considering the emissions taxation and fuels prices, developing financial sustainability maps. Step 9 provides decision support highlighting the main directions and policy measures for the future adoption of hydrogen and ammonia for short sea shipping cargo vessels.

2.1. Key performance indicators

The considered key performance indicators (KPIs) to assess the financial and environmental aspects of the investigated scenarios are classified in the following groups: generic (annual fuel consumption, energy demand, fuel storage volume), economic (Net Present Value, payback period, Capital Expenditure, Operational Expenditure, Marginal Emissions Abatement Cost), and environmental (annual CO2 and NOx emissions, Carbon Intensity Indicator, Global Warming Potential, Acidification Potential, Aerosol Formation Potential, Eutrophication Potential).

2.2. Lifetime economic-environmental sustainability model

This study only focuses on the ship operational phase, whereas the fuel production phase is considered out of this study's scope. For the economic KPIs calculation, the ship operation income is assumed unchanged regardless of the employed fuels (these income streams are not considered. The equations for the KPIs calculation are reported in the supplementary material (Appendix A), whereas KPIs presented in the results are introduced below.

The net present value (NPV) is calculated according to the following equation [31]:

$$NPV_i = \frac{CAPEX + OPEX}{(1+dr)^t} \quad (1)$$

where subscript i refers to the investigated scenario, dr is the discount rate, and t is the ship lifetime.

The payback period of the required investments for hydrogen and ammonia is calculated as:

$$PBP = \frac{CAPEX}{IF} \quad (2)$$

where, IF is the inflow of cash stemming from the emissions taxation.

The emissions taxation for rendering the investment break-even is calculated according to Nocera & Cavallaro [32] considering the target NPV from the baseline case and the emissions difference as:

$$E_{i,j_{tax}} = \frac{\Delta NPV}{E_{i,j}} \quad (3)$$

where, $E_{i,j}$ refers to the emissions of scenario i; subscript j refers to the CO_2 and NOx emissions; ΔNPV refers to the difference of NPV values of scenario i, from the baseline.

The carbon intensity indicator (CII) is calculated based on IMO guidelines (MEPC 76/15 Annex 10) according to the following equation:

$$CII_i = \frac{\sum_{j=1}^{n_e} FC_{i,j}\, EF_{CO_2\, i,j}}{dwt\ \ d} \left[\frac{kg_{CO_2}}{t\ nm}\right] \quad (4)$$

where FC refers to the fuel consumption of the ship engines; EF_{CO2} is the CO_2 emission factor; d is the ship's voyage distance in nm; dwt is the vessel deadweight in tonnes; and n_e is the number of engines; subscript j indicates the considered engine.

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

$$MEAC = \frac{NPV_i}{\Delta E_i} \quad (5)$$

where i index designates the scenario number, and ΔE denotes the difference of the CO_2 or NOx emissions from the baseline case.

This study considers the following environmental KPIs: (a) Global Warming Potential (GWP) is used to compare the energy absorbed by the emissions of 1 ton of CO_2 over a specified time period (typically 100 years); (b) Acidification Potential (AP) refers to the emissions that cause acid rain [33]; (c) Aerosol Formation Potential (AFP) exhibits the PM, SOx, and NOx emissions relative to the 2.5 particulate matter equivalent over a lifetime [34]; and (d) Eutrophication Potential (EP) presents the potential to cause over-fertilisation of the water and soil resulting to growth of biomass and affecting costal ecosystems [35]. The equations for these KPIs are provided in Appendix A of the supplementary material.

The N_2O emissions factor is calculated according to the following equation:

$$EF_{N_2O}\left(\frac{g_{N_2O}}{g_{fuel}}\right) = \frac{bsEF_{N_2O}\left(\frac{g_{N_2O}}{kWh}\right)}{bsfc\left(\frac{g_{fuel}}{kWh}\right)} \quad (6)$$

where $bsEF$ denotes the brake specific emission factor for N_2O.

This study employs the following assumptions:

- The environmental assessment is performed considering the GWP, AP, AFP, and EP indicators, which are calculated by employing the lifetime CO_2, NOx, CH_4, N_2O, PM, and SOx emissions. The latter were estimated considering the emission factors reported in the pertinent literature and ISO 14067:2018. Ammonia slip may also affect the final environmental indicators; however, its estimation was considered out of this study scope, as it requires further experimental investigations [36].
- The shipboard use of hydrogen and ammonia fuels requires dedicated storage, safety and feeding systems. Safety assurance procedures as well as rules and regulations for hydrogen and ammonia have been under development [37]. The required approvals and certification are associated with a cost, which, however, was not considered herein.
- Pilot diesel fuel energy fractions in the range 3–10 % were reported for dual-fuel engines operating with diesel–ammonia and diesel–hydrogen [38–40]. This study assumes 10 % energy fraction for the pilot diesel fuel in both the cases of ammonia and hydrogen.

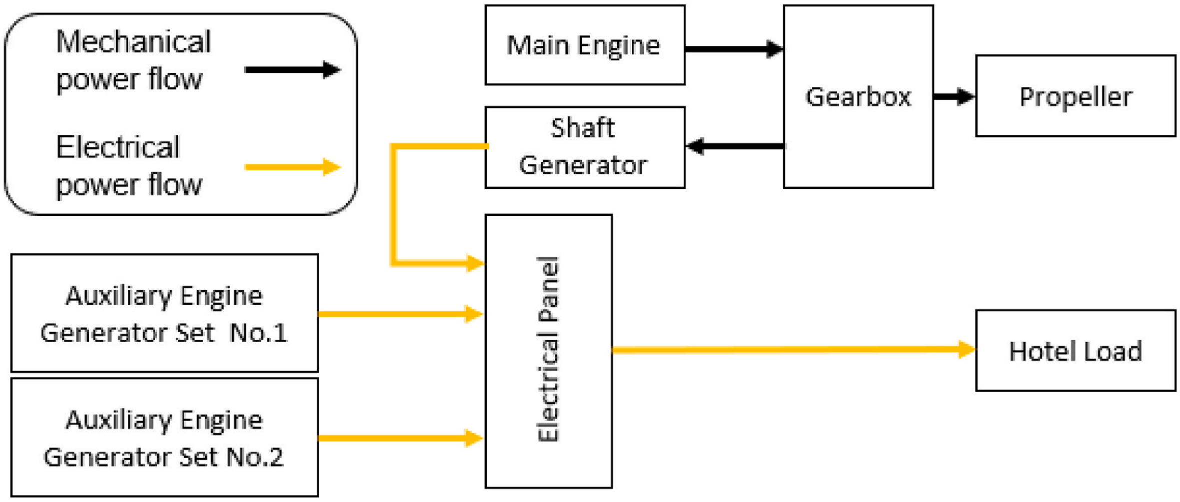

Fig. 2. Case ship power plant configuration.

Table 1
Case ship power plant main components specifications.

Component	Auxiliary Engine	Main Engine	Power take-out electric generator
Type	Four-stroke high speed	Four-stroke medium speed	AC
Fuel	MGO*	MGO	–
Rated power (kW)	182	1900	1900
Rated speed (rpm)	1800	750	
Cylinder No. (−)	6	6	–

*MGO: marine gas oil.

- Lubricant consumption remains constant in the investigated scenarios.
- Installation costs were included in the capital cost.
- For all scenarios, the shipping route, the engine type, and the maintenance cost were considered the same.
- The cost of the required strengthening for the fuel storage tank(s) and corresponding ship structure was not considered.
- The ship energy demand profile was considered the same as the baseline case.
- Financial sustainability implies that the same NPV (for a scenario) is achieved as the baseline scenario. Adopting alternative fuels is associated with a need for investment, thus higher NPV, which however will be investigated in further studies.
- The operation of the vessel with installed ammonia and hydrogen fuel cells instead of retrofitted engines, is out of the scope of this study; however, fuel cells use is discussed in Refs. [41,42].
- The tank to wake emissions were calculated, which represent the vessel operation. The fuels production and transportation costs are included in the fuel prices. Hydrogen and ammonia production using conventional fossils was considered.

2.3. System and scenarios description

The investigated ship (case ship henceforth) is a short sea shipping cargo vessel with 6000 DWT and 106 m length. This vessel engine room includes one main marine four-stroke diesel engine (ME), two auxiliary diesel engine-generator sets (AE), one power take-out electric generator, and an emergency diesel engine. The ship power plant configuration is presented in Fig. 2, whereas the main specifications of its main components are listed in Table 1.

Table 2
Investigated scenarios for the case ship operation.

Scenario code	AEs MGO substitution percentage (energy basis)	ME MGO substitution percentage (energy basis)	Fuels
BL	0	0	AEs: MGO ME: MGO
$1H_2$	0	90	AEs: MGO ME: Hydrogen & pilot MGO
$2H_2$	0	40	AEs: MGO ME: Hydrogen & MGO
$3H_2$	0	50	AEs: MGO ME: Hydrogen & MGO
$1NH_3$	0	90	AEs: MGO ME: Ammonia & pilot MGO
$2NH_3$	0	40	AEs: MGO ME: Ammonia & MGO
3NH3	0	50	AEs: MGO ME: Hydrogen & MGO

The case ship typically operates in short routes transporting containers. The operating modes include sailing, manoeuvring, anchorage, and port, whereas different power plant components operate in each mode. Operating data providing the component load fraction versus operating hours for a period of 33 days were available and presented in Figure C1 of the supplementary material. The typical ship operation considers a maintenance period equal to 1.2 % of the total annual time (8760 h). The engines brake specific fuel consumption (bsfc) and the specific NOx emissions are presented in Figure C2 of the supplementary material (Appendix C).

The baseline scenario (BL) involves ship ME and AEs operating with MGO, following the considered operating profile. The investigated MGO substitution scenarios for the ship ME are listed in Table 2. For 90 % MGO substitution, the remaining 10 % comes from pilot diesel for combustion initiation. For 40 % and 50 % substitution, MGO is directly injected into engine cylinders, while hydrogen or ammonia is injected in cylinder ports and burned using the premixed-combustion concept. Scenarios $1H_2$ and $1NH_3$ explore deep decarbonisation pathways, while scenarios starting with numbers 2 and 3 consider 40 % and 50 % reduction, respectively. Table 3 lists input parameters for KPIs, with hydrogen and ammonia engines using after-treatment systems to

Table 3
Model input parameters.

	Input parameter	Value/Unit	Reference
General	Discount rate	12 %	Assumption
	Service life	30 y	Assumption
	Annual operating time	8760 h/y	Operator Data
	Annual maintenance time	105 h/y	Operator Data
Financial	After-treatment unit capital cost factor	40 €/kW	Operator Data
	Maintenance cost factor	0.012 €/kWh	[49]
	Retrofit Cost	20 % of CAPEX	[49]
	Alternative fuels systems cost	€700,000	[29]
	Alternative fuels additional maintenance cost factor	5.2 €/kWh	[50]
	Alternative fuels storage system cost factor	112 €/kW	[51]
	Brake specific fuel consumption	from Figure C3	Operator Data
	Capital cost factor for marine four-stroke diesel engines (MGO operation)	493 €/kW	[52]

Table 4
Emission factors.

Fuel	CO_2 emissions factor (kg CO_2/kg fuel)	NOx emission factor (kg NOx/kg fuel)[f]	N_2O emission factor (kg N_2O/kg fuel)
MGO	3.02	according to Fig. 4	0.00016[a]
Hydrogen	0	0.009[b]	0.0004[c]
Ammonia	0	0.003[d]	0.000158[e]

[a] Calculated by eq. (6) Karvounis et al. [45].
[b] According to Shadidi et al. [46].
[c] Calculated by eq. (6) and $bsEF_{N_2O}$ from Shadidi et al. [46].
[d] From Dimitriou & Javaid [47].
[e] From Maersk Mc-Kinney Moller Center [53].
[f] Includes NO and NO_2.

Table 5
Considered fuel prices for the sensitivity study.

	Sensitivity study code		
Fuel	A	B	C
Hydrogen	700 €/t	2000 €/t	3500 €/t
Ammonia	350 €/t	690 €/t	1300 €/t

mitigate NOx emissions and ammonia slip. CAPEX includes these systems cost. Prices for MGO, hydrogen, and ammonia are based on the last five years' averages, as reported in World Bunkers [43] and Karvounis et al. [44,45].

Emission factors for CO_2 and NOx are listed in Table 4. Their values depend on the engine type, size, and operating conditions. However, due to the lack of information in the pertinent literature, this study employs the values for diesel-ammonia and diesel-hydrogen dual-fuel engines with high diesel substitution rates reported in Shadidi et al. [46] for hydrogen, and Dimitriou and Javid [47] for ammonia. Further experimental and numerical studies are needed [48] to accurately estimate emission factors for hydrogen and ammonia fuelled engines.

CO_2 and NOx emissions taxation can incentivise zero-carbon fuels adoption in shipping. Evaluation of existing policies in various sectors and Norway's shipping NOx taxation provided potential carbon and NOx tax ranges. Break-even point values for emissions taxation in each scenario (Table 2) are estimated. This study conducted sensitivity analyses on: (a) fuel prices, and (b) CO_2 and NOx emissions taxes; the latter resulting in developing hydrogen and ammonia profitability maps. Table 5 lists the considered hydrogen and ammonia fuel prices, with the middle column (sensitivity study B) reflecting prices from conventional fossil-based production, as reported in Karvounis et al. [44]; the other columns list the expected extreme low and high prices.

3. Results and discussion

According to the analysis presented in the supplementary material (Appendix D), the diesel fuel substitution in the vessel AE is not adequate to achieve the decarbonisation targets set by IMO for 2030. The calculated annual CO_2 and NOx emissions for the scenarios listed in Table 2 are presented in Fig. 3; the dashed lines correspond to the respective values for the baseline scenario and 2030 IMO targets.

Scenarios $1H_2$ and $1NH_3$, $2H_2$ and $2NH_3$ and $3H_2$ and $3NH_3$ are associated with 90 %, 40 %, and 50 % CO_2 reduction, respectively. Scenarios 1, 2 and 3 support the achievement of 2030 targets whereas the scenarios 1, 3 can reach deeper decarbonisation targets. The NO_x emissions are reduced by 87 %, 39 % and 48 % compared to the baseline; the scenarios with ammonia exhibit slightly higher NO_x emissions, which is attributed to the increased mass of fuel required to achieve the same power output. It must be noted that the NOx emissions were calculated by using the respective emission factors, which (for ammonia and hydrogen) are lower from the NOx emission factor of MGO. The Tier III limits are satisfied only in the $1H_2$ and $1NH_3$ cases that correspond to maximum fuel substitution whereas in the other scenarios aftertreatment systems are essential to allow for further NOx abatement.

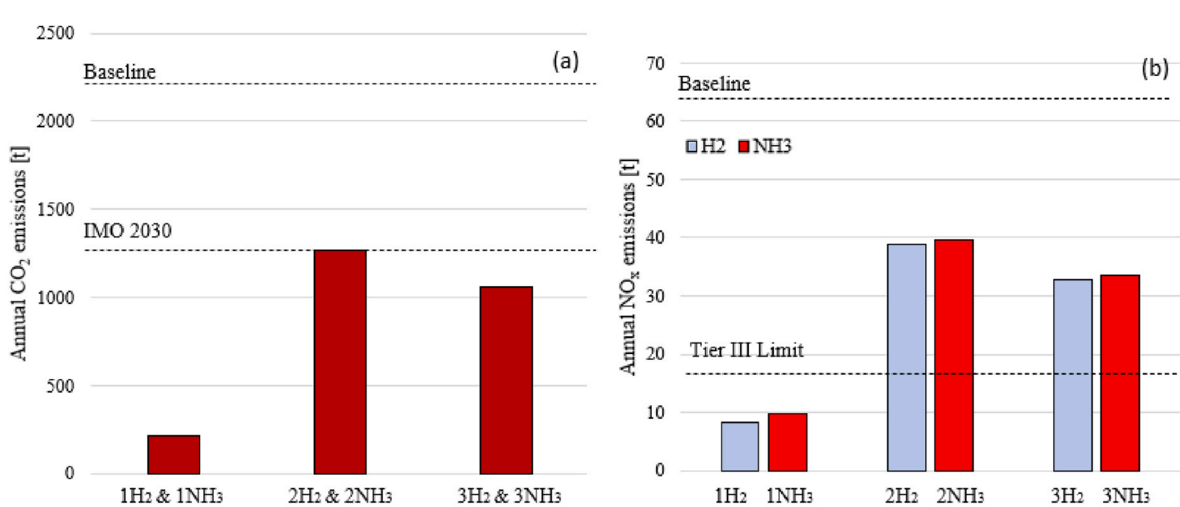

Fig. 3. Annual CO_2 (a) and NOx (b) emissions of the ship ME and AEs for the investigated scenarios with ME MGO substitution by hydrogen or ammonia.

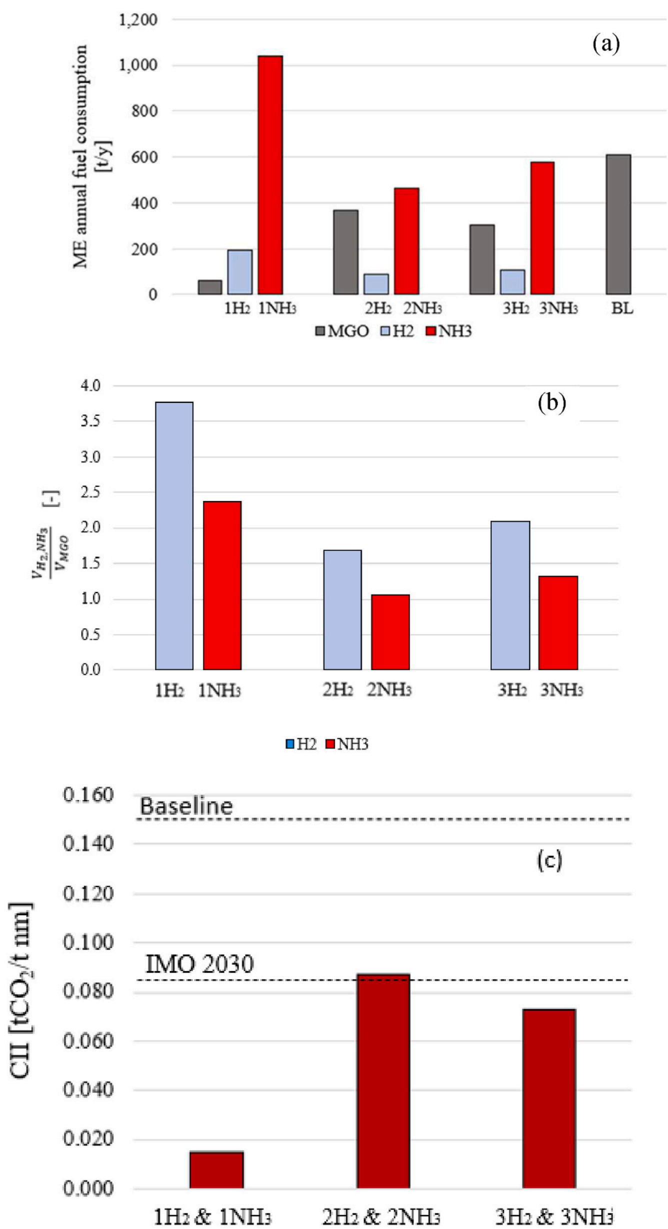

Fig. 4. For the three investigated scenarios with hydrogen or ammonia: (a) Main engine annual fuel consumption; (b) ratio of alternative fuel storage volume and baseline MGO volume; and (c) Carbon intensity indicator (CII).

Fig. 4(a) illustrates the annual consumption of considered fuels in each scenario. The exhibited variations are attributed to differences in these fuels lower heating values. Required ammonia amount is higher compared to hydrogen and MGO. Scenarios using hydrogen ($1H_2$, $2H_2$, and $3H_2$) required considerably lower fuel amount compared to MGO and ammonia. Fig. 4(b) displays the volume ratio between alternative fuel consumption in each scenario and the baseline scenario MGO. Depending on the scenario, ammonia (due to its higher density compared to hydrogen) needs 1–2.5 times the baseline MGO volume. Liquid hydrogen storage requires 3.5, 1.5, and 2 times the baseline MGO volume for scenarios $1H_2$, $2H_2$, and $3H_2$, respectively. This study considers the required fuel volume, whereas the overall fuel storage system volume is not estimated; the latter was estimated for ammonia and liquid hydrogen according to Ref. [61].

Based on the vessel general arrangement and operator feedback, it was inferred that the hydrogen or ammonia volume required for a return voyage can be accommodated for scenarios 2 and 3 ($2H_2$, $2NH_3$, $3H_2$, $3NH_3$) without significant loss of available cargo space. Kalikatzarakis et al. [30] and Louvros et al. [68] argued that the use of containerised fuel storage tanks (for liquefied natural gas and ammonia) installed on the ship main decks leads to no significant cargo loss; hence, this method is considered herein. However, for scenarios 1 ($1H_2$, $1NH_3$) with 90 % diesel substitution, the ship redesign is required. Alternatively, more frequent bunkering of ammonia or hydrogen could be planned for reducing these fuels storage requirements. However, the fuel storage system and bunkering operations are out of this study scope.

Fig. 4(c) presents the carbon intensity indicator (CII) for the investigated scenarios. To ensure compliance with IMO 2030 targets, the reduction of carbon emissions should be 40 %, corresponding to CII of 0.0873 $\frac{t\,CO_2}{t\,nm}$ (compared to the baseline CII of 0.1455 $\frac{t\,CO_2}{t\,nm}$). The 2030 target can be achieved either by using alternative zero-carbon fuels (e.g., scenarios $1H_2$, $1NH_3$, $2H_2$, $2NH_3$ and $3H_2$ and $3NH_3$).

Fig. 5(a) shows the net present value (NPV) for scenarios along with the CAPEX and OPEX contributions; the baseline scenario NPV is also superimposed (dashed line). NPV increases by 29 %, 23 %, and 24 % for $1H_2$, $2H_2$, and $3H_2$, and by 46 %, 33 %, and 36 % for $1NH_3$, $2NH_3$, and $3NH_3$, respectively. This denotes that the hydrogen and ammonia use is financially unsustainable. Ammonia scenarios exhibit higher OPEX and CAPEX than hydrogen. Although the hydrogen storage CAPEX is higher (compared to the respective ammonia scenario), ammonia scenarios OPEX are substantially increased (compared to the respective hydrogen scenario) due to higher fuel amount, leading to increased NPVs. Storage system cost uncertainty is acknowledged, and further studies are recommended. Scenarios $1H_2$ and $1NH_3$ have the worst financial output, while $2H_2$, $2NH_3$, $3H_2$, and $3NH_3$ exhibit better financial performance. Further incentivisation measures are essential for render these scenarios financial sustainable.

Fig. 5(b) and (c) depict marginal CO_2 and NOx emissions abatement costs (MEAC). Ammonia requires higher capital than hydrogen for equivalent emissions reduction, particularly for NOx emissions. MEAC for CO_2 emissions is approximately 0.004 M€/t CO2, 0.0085 M€/t CO_2, and 0.065 M€/t CO_2 for the three hydrogen scenarios, and 0.057 M€/t CO2, 0.0105 M€/t CO_2, and 0.085 M€/t CO_2 for the three ammonia scenarios. The latter values are in alignment with the figures reported in Ref. [50] for a bulk carrier operation with ammonia. As scenarios $3H_2$ and $3NH_3$ align with the IMO long-term decarbonisation targets, they are selected for the follow up environmental analysis and sensitivity studies.

Table 6 presents the PBP for the investigated scenarios, which was estimated considering the cash inflow from the subsequent CO_2 emissions taxation, as discussed in the next subsection. Payback period of 14.3, 14.9 and 14.8 years were estimated for scenarios $1H_2$, $2H_2$ and $3H_2$ respectively, and 5.2, 7.8 and 7 years for scenarios $1NH_3$, $2NH_3$ and $3NH_3$ respectively.

3.1. Environmental analysis

Table 7 presents the derived environmental KPIs for the baseline scenario as well as scenarios $3H_2$ and $3NH_3$. The global warming potential (GWP) is reduced by 51 % for ammonia and 50.6 % for hydrogen. The acidification, aerosol formation and eutrophication potentials exhibit reductions of around 50 % for the hydrogen/ammonia scenario, significantly reducing the ship operation impact on coastal ecosystems.

3.2. Emissions taxation

Policies on emissions taxation have been adopted in several countries and industries [62]. Fig. 6 provides the required carbon and NOx taxes for each scenario to achieve financial sustainability (baseline NPV – break-even point). The dashed lines on Fig. 6(a) and (b) correspond to the current carbon tax for other sectors in the Emissions Trading Scheme (ETS) [63], and Norway's 2019 NOx tax in shipping [64], respectively.

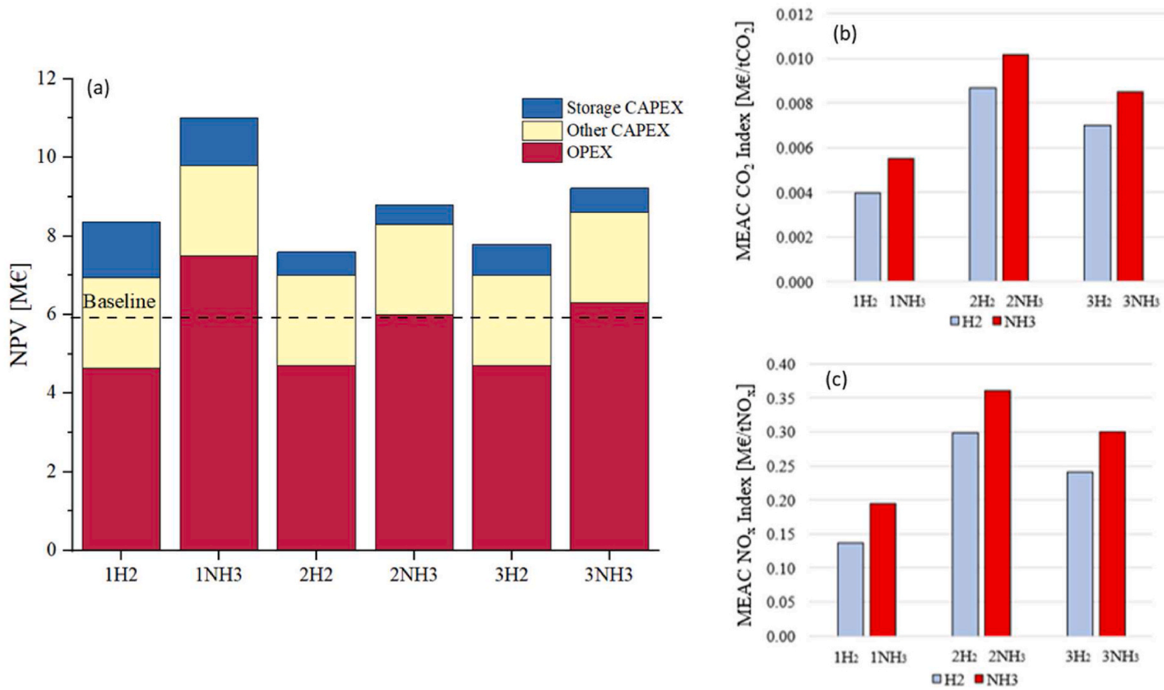

Fig. 5. (a) NPV, (b) marginal emission abatement cost (MEAC) for CO_2 emissions, and (c) MEAC for NOx emissions for the investigated scenarios.

Table 6
Payback period for the investigated scenarios.

Scenarios	Payback Period (y)
$1H_2$	14.3
$1NH_3$	5.2
$2H_2$	14.9
$2NH_3$	7.8
$3H_2$	14.8
$3NH_3$	7.0

Table 7
Lifetime environmental KPIs for scenarios $3H_2$ and $3NH_3$.

Indicator	Units	Baseline	$3NH_3$	$3H_2$
GWP	$kg_{CO_{2eq}}$	$6.44\ 10^7$	$3.31\ 10^7$	$3.26\ 10^7$
AP	$kg_{SO_{2eq}}$	$1.39\ 10^6$	$7.32\ 10^5$	$7.15\ 10^5$
AFP	$kg_{PM2.5_{eq}}$	$1.71\ 10^6$	$9.07\ 10^5$	$8.85\ 10^5$
EP	$kg_{PO_{4eq}}$	$2.48\ 10^5$	$1.31\ 10^5$	$1.28\ 10^5$

Current carbon tax prices at 67 €/t are not adequate for incentivising alternative fuels adoption. The calculated marginal tax values are 965 €/t, 136 €/t, and 169 €/t for the hydrogen scenarios and 2647 €/t, 261 €/t, and 356 €/t for the ammonia scenarios. However, Norway's NOx tax, applied to hydrogen and ammonia fuel scenarios, does not lead to the break-even points. The calculated marginal values are: 24,731 €/t, 4439 €/t, 5.460 €/t for hydrogen, and 57.483 €/t, 8.345 €/t, 11.199 €/t for ammonia.

The higher carbon tax for ammonia scenarios are attributed to ammonia increased fuel consumption, which, despite lower prices, results in considerably higher fuel costs and OPEX. Similar trends are exhibited for the NOx taxation with considerably higher tax though (due to lower NOx emissions), which render it non-plausible as standalone policy. However, its simultaneous implementation with other policies (carbon tax or fuel subsidies) can positively impact alternative fuels adoption. NOx taxation is scarcely discussed in literature, whereas carbon taxation is considered effective in several studies. Menon and Chan [65] proposed a carbon tax of 100 $/t to incentivise the use of proton exchange membrane fuel cells with hydrogen for tugboats. This aligns with the range 140–180 €/t for the 'sustainable development scenario',

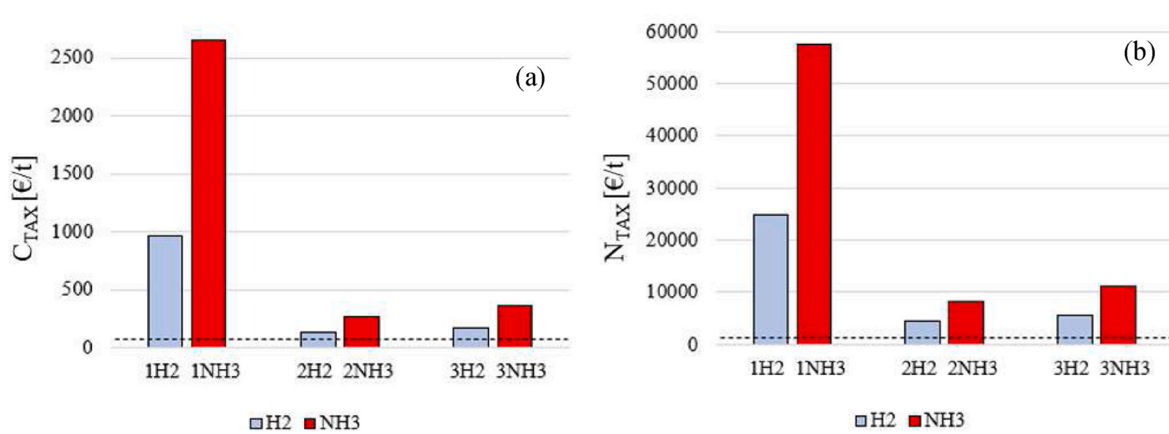

Fig. 6. CO_2 and NOx tax to render the investigated scenarios financially sustainable (dashed line denotes the current level of emissions tax in other industries).

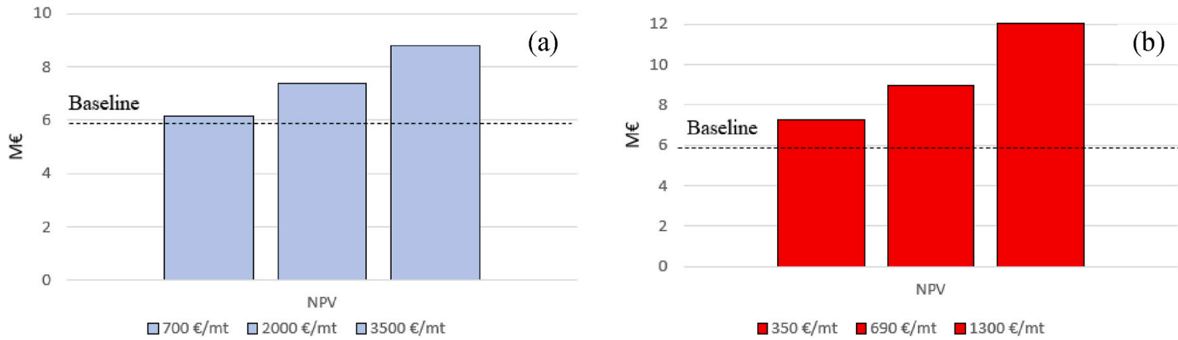

Fig. 7. Sensitivity study results – NPV variation with (a) hydrogen price, and (b) ammonia price.

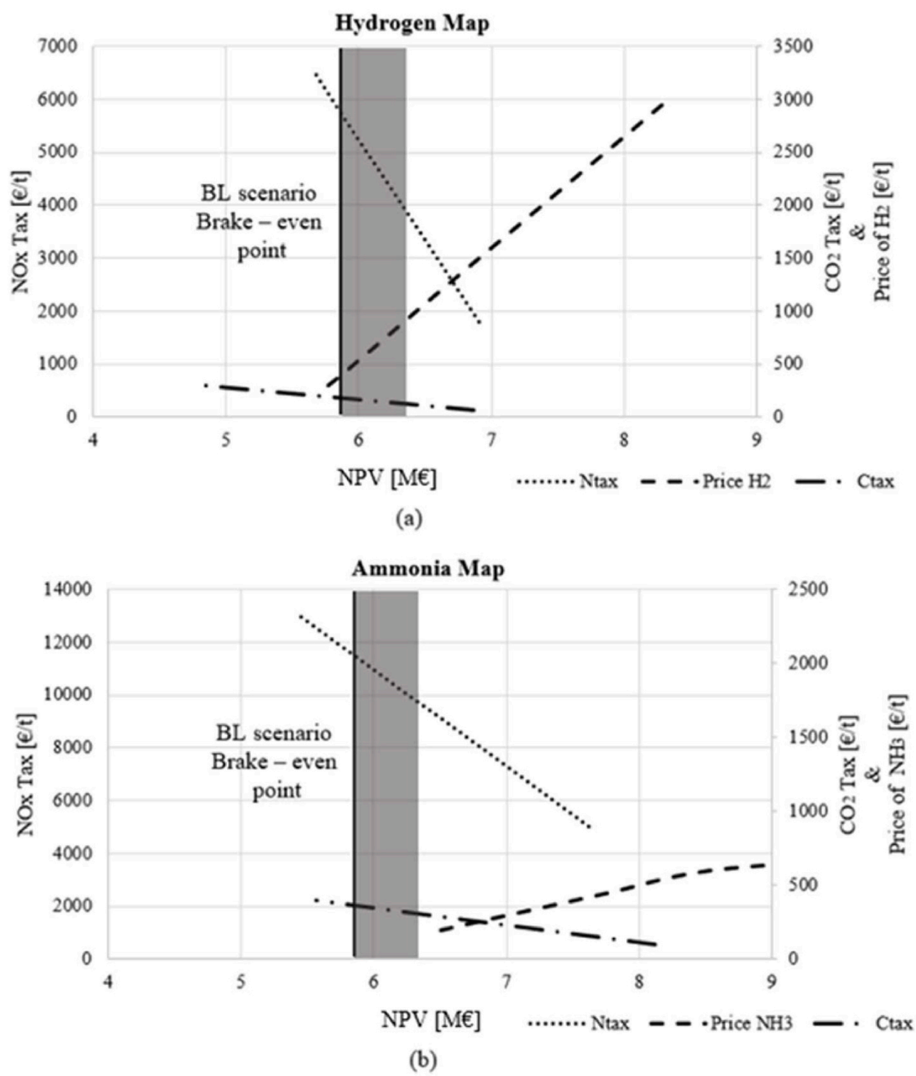

Fig. 8. Hydrogen (a) and ammonia (b) lifetime brake-even point maps.

according to 2020 World Energy Outlook [66].

3.3. Fuel prices sensitivity

Fig. 7 presents the NPV for scenarios $3H_2$ and $3NH_3$ considering extreme (low and high) values compared to current prices. Scenario $3H_2$ economic performance improves with decreasing hydrogen prices, approaching the baseline NPV (break-even point) at prices slightly below 700 €/t. However, a 50 % reduction in ammonia prices is not adequate to reach the break-even point. Fuel prices significantly impact scenarios financial sustainability. Substantial incentives are needed to boost these fuels production (and supply) and hence lower prices. Emissions taxation could act as a driver towards achieving the zero-carbon fuels financial sustainability.

3.4. Financial sustainability analysis

Fuel prices, carbon tax, and NOx tax constitute the more sensitive

Table 8
Elasticity of KPIs for hydrogen and ammonia scenarios $3H_2$ and $3NH_3$.

Parameter	Ammonia elasticity [%]	Hydrogen elasticity [%]
Carbon tax	− 39	− 21
NOx tax	− 46	− 21.5
Fuel price	29	9

input parameters; hence they are selected for the mapping-sensitivity study. Fig. 8(a) and (b) present the brake-even point maps for scenarios $3H_2$ and $3NH_3$, respectively. The dash-dotted line (right vertical axis) denotes the carbon tax; the dashed line denotes the fuel price (right vertical axis); the dotted line (left vertical axis) refers to the NOx tax. These maps highlight different alternative pathways for achieving the hydrogen and ammonia scenarios financial sustainability, considering policy measures (emissions taxation) and the fuel prices. For both fuels, the NOx taxation exhibits a greater impact on the NPV.

A potential pathway could include the simultaneous reduction of the hydrogen or ammonia price (which can be achieved by scaling up or subsidising their production, and introducing new technologies), along with the emissions taxation. It is expected that the shipping sector may accept a slight increase for future ships power systems NPV as indicated by the grey area in Fig. 8, which determines the targeted ranges for the acceptable hydrogen/ammonia prices as well as the carbon and NOx emissions taxes.

Table 8 confirms the preceding findings, as the NOx emissions tax exhibits the highest elasticity (1 % NOx tax increase results in reducing the NPV by 46 % and 21.5 % for ammonia and hydrogen, respectively), rendering it the most sensitive parameter. The fuel price exhibits the lowest elasticity; hence, it impacts scenarios $3H_2$ and $3NH_3$ financial sustainability at a smaller extend (considerably though).

4. Implications to shipping sustainability

Considering the immense pressure in the shipping sector to achieve decarbonisation by 2050, this study reveals the economic and environmental impacts and interactions associated to the fuel substitution. The lack of existing infrastructure in the supply chain of alternative fuels along with storage space constraints lead to shipping industry's hesitance on using zero-carbon fuels. However, forthcoming policies promoting environmental sustainability and decarbonisation are expected to incentivise the needed shift towards low or zero-carbon fuels. Hence, this study supports the decision-making process contributing to obtain better understanding and in-depth insights for the key parameters and trade-offs that impact the technical, economic, and environmental performance for decarbonising the operations of short sea shipping vessels. The proposed methodology can be adapted to other vessel types and can be extended to include other fuel types including biofuels and electrofuels.

It was demonstrated that hydrogen and ammonia can be among the potential solutions to reduce the shipping operations carbon emissions and complying with forthcoming stringent carbon emissions limits, however, at the expense of considerable investments (capital expenses). Presently, carbon and nitrogen oxides emissions taxes are not employed widely in the shipping sector, however this may change in the short- to medium-term, thus incentivising the shipping decarbonisation. This study demonstrated that emissions taxation can be effective for the adoption of hydrogen and/or ammonia fuels. The employed methodology is expected to be a useful tool for the financial sustainability appraisal and de-risking of future technologies pertinent to the implementation of zero-carbon fuels in the shipping sector. Moreover, the impact assessment of the emissions taxation and fuels prices on the financial viability via sensitivity studies is expected to support policy makers to test and fine-tune potential measures prior to their implementation. This study provides data and tools for decision-making in the shipping sector stakeholders pertinent to the techno-economic and environmental impact of the hydrogen and ammonia fuels adoption in their fleets.

5. Conclusions

This study investigated the lifetime economic and environmental sustainability of the diesel fuel substitution by zero-caron fuels (hydrogen or ammonia) in marine engines providing pathways to reduce the shipping sector environmental footprint. The main findings of this study are summarised as follows.

- Auxiliary engines diesel fuel substitution is not adequate to reach CO_2 emissions reduction aligned with the IMO 2030 and 2050 targets.
- In economic terms and without accounting for the technological maturity, ammonia requires higher investment than hydrogen to achieve the same amount of emissions reduction due to its lower calorific value compared to the MGO and hydrogen.
- The adoption of zero-carbon fuels is financially unsustainable, due to the higher fuel price (for hydrogen) and low energy density (for ammonia) as well as associated considerably higher investment compared to the conventional fuels.
- The fuels price fluctuations greatly impact the financial sustainability of the considered scenarios. Low ammonia price is not sufficient to overcome barriers pertinent to the fuel operating cost due to the low ammonia energy content. For hydrogen, lifetime financial output may reach the break-even point for prices below 700 €/t.
- Emissions taxation is a key instrument to incentivise the adoption of hydrogen and ammonia as zero-carbon fuels. A carbon tax close to 169 €/t for hydrogen and 356 €/t for ammonia would render the scenarios of 50 % diesel substitution financially sustainable.
- Rendering the deep decarbonisation scenarios with 90 % diesel substitution financially sustainable requires carbon and NOx nitrogen oxides taxation of 965 €/t and 24731 €/t respectively for hydrogen, as well as 2647 €/t and 57483 €/t for ammonia.
- Financial sustainability maps facilitate the identification of pathways for zero-carbon fuels adoption, as the required ranges of emissions taxation and fuel prices are revealed for a targeted acceptable NPV.

This study limitations pertain to the made assumptions, fuel prices, storage systems costs, and emissions factors. Future research studies could focus on numerical and experimental investigations of marine engines operating with several hydrogen and ammonia fractions, the optimisation of these fuels storage and bunkering operations, as well as holistic ship design considering the fuels supply chain.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Abbreviations list

AE	Auxiliary Engine
IMO	International Maritime Organisation
KPI	Key Performance Indicator
LNG	Liquified Natural Gas
ME	Main Engine
MGO	Marine Gas Oil
SR	Substitution Ratio

Nomenclature list

AFP	Aerosol Formation Potential (kg $PM_{2.5,\ eq}$)
AP	Acidification Potential (kg $SO_{2,\ eq}$)
bsfc	Brake-Specific Fuel Consumption (g/kWh)
CAPEX	Capital Expenditure (M€)
CII	Carbon Intensity Indicator (tCO_2/t nm)
EP	Eutrophication Potential (kg $PO_{4,\ eq}$)
FS	Fuel storage system cost (M€)
GWP	Global Warming Potential ($tCO_{2,\ eq}$)
LHV	Lower Heating Value (kJ/kg)
MEAC	Marginal Emissions Abatement Cost (M€/t CO_2)
NPV	Net present value (M€)
OPEX	Operational expenditure (M€/y)

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ijhydene.2024.01.058.

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