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Research paper

Alternative marine fuels: Prospects based on multi-criteria decision analysis involving Swedish stakeholders

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ABSTRACT

There is a need for alternative marine fuels in order to reduce the environmental and climate impacts of shipping, in the short and long term. This study assesses the prospects for seven alternative fuels for the shipping sector in 2030, including biofuels, by applying a multi-criteria decision analysis approach that is based on the estimated fuel performance and on input from a panel of maritime stakeholders and by considering, explicitly, the influence of stakeholder preferences. Seven alternative marine fuels—liquefied natural gas (LNG), liquefied biogas (LBG), methanol from natural gas, renewable methanol, hydrogen for fuel cells produced from (i) natural gas or (ii) electrolysis based on renewable electricity, and hydrotreated vegetable oil (HVO)—and heavy fuel oil (HFO) as benchmark are included and ranked by ten performance criteria and their relative importance. The criteria cover economic, environmental, technical, and social aspects. Stakeholder group preferences (i.e., the relative importance groups assign to the criteria) influence the ranking of these options. For ship-owners, fuel producers, and engine manufacturers, economic criteria, in particular the fuel price, are the most important. These groups rank LNG and HFO the highest, followed by fossil methanol, and then various biofuels (LBG, renewable methanol, and HVO). Meanwhile, representatives from Swedish government authorities prioritize environmental criteria, specifically GHG emissions, and social criteria, specifically the potential to meet regulations, ranking renewable hydrogen the highest, followed by renewable methanol, and then HVO. Policy initiatives are needed to promote the introduction of renewable marine fuels.

1. Introduction

Seaborne transport, representing over 80% of global trade by volume, is dominated by the use of fossil fuels, mainly heavy fuel oil (HFO) and marine gas oil [1,2]. Due to the related emissions of greenhouse gases (GHG), nitrogen oxides (NO_x), and sulphur oxides (SO_x) [3–5], there is a need to reduce the environmental and climate impact of shipping in the short and long term [6–8].

The recent International Maritime Organization (IMO) strategy aims to reduce total annual GHG emissions from international shipping by at least 50% by 2050 compared to 2008 [9]. To achieve this, they have also set targets to reduce CO_2-emissions as measured by the payload-distance freight metric by 40% by 2030 and by 70% by 2050 compared to 2008 [9]. The EU targets reducing annual CO_2 emissions from shipping by at least 40% by 2050 compared to 2005 [10].

To achieve these CO_2 emission reductions, the implementation of energy efficiency measures needs to be supplemented by the introduction of alternative marine fuels with lower CO_2 emissions than conventional fuels [11–14]. This may also lead to reductions in NO_x, SO_x (which are regulated in certain emission control areas), and particulate matter (PM) [15].

There is a range of possible alternative marine fuels, including, e.g., liquefied natural gas (LNG), liquefied biogas (LBG), methanol, hydrogen, hydrotreated vegetable oil (HVO), ethanol, wind power, and electricity. Technical performance and other characteristics, including environmental impact, availability, cost, and infrastructure, vary for these fuels, influencing their potential for marine propulsion. The shipping industry and policy makers thus have to select future marine fuels by evaluating multiple factors for a range of alternatives [12,14,16,17].

Abbreviations: LNG, Liquefied natural gas; LBG, Liquefied biogas; HVO, Hydrotreated vegetable oil; MeOH, Methanol; H2, Hydrogen; ICE, Internal combustion engine; FC, Fuel cell; PCM, Pairwise comparison matrices

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Studies comparing the economic and environmental performance of selected marine fuels and propulsion technologies exist in the literature (e.g., Refs. [18–23]). However, to better understand the potential for different fuel options when specifically including biofuels, structured assessments that cover a broad range of factors are needed.

Recent studies have assessed different alternative marine fuel options, mainly based on fossil fuels, considering various factors and with varying consideration given to stakeholders and experts. Deniz and Zincir [24] compare four alternative marine fuels, fossil methanol, fossil ethanol, LNG, and hydrogen, with respect to eleven environmental and economic criteria. By applying multi-criteria decision analysis (MCDA), they find that LNG is the most suitable alternative fuel, followed by hydrogen (which may substitute for LNG), while fossil methanol and ethanol are found less suitable for the shipping sector. Ren and Liang [25] rank LNG, fossil methanol, and hydrogen for marine use by applying MCDA with eleven criteria. They find hydrogen or LNG to be the most sustainable marine fuel. While testing a proposed MCDA approach on LNG, nuclear power, and wind power using ten criteria, Ren and Lützen [26] find nuclear power to be the most sustainable alternative energy source for shipping, followed by LNG [26].

Results from studies of this kind depend on the included fuels, the assumptions made regarding fuel production pathways and current fuel performance, as well as the opinions of the included group of experts. Thus, additional studies that include a broader range of fuel options, specifically biofuels, and that more clearly assess the impact of the preferences of different stakeholders on the ranking of marine fuels may provide additional insights.

The purpose of this study is to assess the prospects for seven selected alternative fuels—including biofuels—for deep-sea shipping in 2030 by applying a multi-criteria decision analysis approach and specifically considering the influence of various stakeholder preferences. Liquefied natural gas (LNG), liquefied biogas (LBG), methanol from natural gas (fossil MeOH), renewable methanol from biomass (renewable MeOH), hydrogen (for fuel cells) produced from (i) natural gas (fossil H2) or (ii) electrolysis using renewable electricity (elec-H2), and hydrotreated vegetable oil (HVO) are included. In addition, heavy fuel oil (HFO) is included as a benchmark. The study includes an assessment of various factors influencing the choice of marine fuel (covering economic, technical, environmental, and social aspects). The multi-criteria analysis resulting in a ranking of the fuel options for different cases is performed based on input from a panel of Swedish maritime stakeholders using the Analytic Hierarchy Process (AHP).

Our hypothesis is that the priorities and values of different shipping related actors will result in different rankings of alternative marine fuel options. Of the fossil fuel-based alternatives LNG can be expected to be ranked high by shipping industry actors due to price- and supply-related advantages. For the renewable options, it is less obvious what to expect since all options have their pros and cons. Hydrogen is interesting from a broad environmental point of view, while methanol and HVO have advantages in terms of economics and infrastructure.

2. Materials and methods

Multi-criteria decision analysis (MCDA), also called multi-criteria decision making (MCDM) or multi-criteria analysis (MCA), is a tool for managing complex decision problems. MCDA is used to find the optimal and most consensual solution by considering stakeholders' interests and preferences alongside qualitative and quantitative information [27,28]. The method generally actively includes stakeholders and allows decision makers to manage multiple potentially conflicting criteria [27,29].

There are several MCDA methods used in environmental and transport sector assessments, including, Analytical Hierarchy Process (AHP); Analytic Network Process (ANP); Elimination and Choice Expressing the Reality (ELECTRE); Multi-Attribute Utility Theory (MAUT); Multi-Attribute Value Theory (MAVT); Preference Ranking Organization Method for Enrichment of Evaluations (PROMETHEE), and the Dominance-based Rough Set Approach (DRSA) [30–32]. The AHP method [33] represents an MCDA-model commonly used in transport projects [31]. We employ AHP in this study because it allows us to mix quantitative and qualitative input data and consider the views of different stakeholders specifically engaged for this purpose [28,33,34].

2.1. Analytic hierarchy process

The AHP method, or further-developed versions thereof, has been used to assess alternative marine fuels as well as alternative transport fuels for road transport [17,24–26,31,35,36]. The AHP approach relies on pairwise comparisons of the alternatives to be ranked using a set of criteria, alongside pairwise comparisons of those criteria in order to weight them [33]. The included options are thus ranked based on (i) the relative performance of one option compared to the other included options for a set of criteria and (ii) the relative importance of the criteria in fulfilling the goal of the decision [33].

In our case, the goal is to find the alternative marine fuel that is ranked highest when considering both the performance on different aspects and the importance of those selected aspects for different stakeholders. The impact of potential differences in stakeholder preferences is considered by including a few different cases representing different maritime stakeholder groups.

First, the alternative marine fuels and the criteria as well as sub-criteria to be included in the study are selected (Section 2.2). Second, the characteristics and performance of the selected alternative marine fuels in terms of the included criteria are mapped based on a literature review (Section 2.3). The marine fuel alternatives are then compared and scored, through pairwise comparisons, based on how they perform with regard to the different criteria (Section 2.3). Then, the included criteria and sub-criteria are given weights, through pairwise comparisons, based on the preferences of a panel of maritime stakeholders (Section 2.4).

In both cases, the comparisons are structured into pairwise comparison matrices (PCM) following the AHP guidelines and techniques [33,34]. To verify that the pairwise comparisons are consistent, a consistency check is included [34]. For each PCM, the normalized priority vector is calculated as the geometric mean for each row in the matrix, representing priority, divided by the sum of the priorities. Finally, the included fuels are ranked based on the scoring of alternatives and weighting of criteria, i.e., by combining the pairwise comparison matrices (linear combination of normalized priority vectors). Sensitivity assessments are also performed. For a more detailed description of the method used, see Appendix A.

2.2. Selection of alternative marine fuels and criteria

The seven alternative marine fuels assessed in this study are LNG, LBG, fossil MeOH, renewable MeOH, fossil H2, elec-H2, and HVO (Table 1). HFO with scrubbers is included as a benchmark. A scrubber is needed to clean the exhaust gas to obtain a comparable fuel with sulphur mass fraction of 0.5% that comply with IMO regulations from 2020 [37]. LBG is assumed to be produced from organic waste, renewable MeOH from short-rotation energy forest (willow), and HVO from tall oil (relevant for the Swedish case). The hydrogen is assumed to be used in fuel cells (FC), whereas the other fuels are assumed to be used in internal combustion engines (ICE).

The use of HFO with scrubbers and LNG as marine fuels are increasing, and fossil methanol is being tested as a marine fuel [38–40]. LBG could replace LNG, and renewable methanol may replace fossil methanol, but none of these are used for shipping in any considerable amounts yet [41]. There are several maritime fuel cell initiatives including hydrogen [42], and there are initiatives for biodiesel, such as HVO, which can be used for blending in fossil fuels or as a neat fuel for shipping [39]. Hydrogen in fuel cell is a possible solution for ocean

Table 1

Marine fuels included in the analysis. (ICE: internal combustion engine; FC: fuel cell).

Marine fuel	Energy carrier/propulsion technology	Physical state	Assumed process
HFO	HFO/ICE	Liquid	HFO is produced from refining of crude oil
LNG	Methane/ICE	Cryogenic liquid	LNG is produced through liquefaction of natural gas [44]
LBG	Methane/ICE	Cryogenic liquid	LBG is produced through anaerobic digestion of biomass (organic waste) and liquefaction to LBG [45]
Fossil MeOH	Methanol/ICE	Liquid	Methanol is produced through natural gas reforming into synthesis gas that is synthesized and processed [46]
Renewable MeOH	Methanol/ICE	Liquid	Renewable methanol is produced through gasification of biomass (willow) into synthesis gas that is synthesized and processed [46]
Fossil H2	Hydrogen/FC	Compressed gas	Fossil hydrogen is produced through desulfurization and reforming of natural gas [47]
Elec-H2	Hydrogen/FC	Compressed gas	Renewable hydrogen is produced through electrolysis based on renewable electricity such as wind or solar power [47]
HVO	HVO/ICE	Liquid	HVO is produced from tall oil [48]

going vessels, which is in focus in this study, however, the technology faces several challenges including space requirements, cost and infrastructure [21]. There are also initiatives for other marine fuel options, e.g., to apply battery-electric propulsion in shipping and to use wind for propulsion. Since these are mainly used to cover part of the fuel demand (e.g., wind), or mainly used for short-sea shipping (e.g., batteries), they are not included in this study, which focuses on deep-sea shipping by 2030.

Economic, technical, environmental, and social aspects are the main criteria in the assessment. In total, 10 sub-criteria, defined in Table 2, are also included. These sub-criteria were selected through a survey of maritime stakeholders based in Sweden (sent to 22 persons of whom 12 responded). The survey presented stakeholders with a total of 23 proposed factors (Table B.1 in Appendix B), asking respondents to choose from these (and/or name their own) the factors that, in their view, were the most important when selecting marine fuels [43]. The factors named by more than 40% of respondents were selected and included as the sub-criteria in the assessment [43]. The included criteria represent a limited number of all sustainability aspects linked to alternative marine fuels and the study does not claim to represent a complete sustainability assessment. Fig. 1 shows the so-called hierarchy tree illustrating the decision problem of this study.

2.3. Pairwise comparisons of alternative marine fuel performances

The data used to represent the different decision criteria are presented in Table 3, with the underlying assumptions described below. For sub-criteria that cannot be represented by a single quantitative-information parameter (Available infrastructure, Reliable supply of fuel, Safety, and Upcoming legislation), a four-level scale (1–4) representing *Poor, Moderate, Fairly good, and Good* is used for grading of underlying aspects, and the average is used to represent the sub-criteria (Appendix C). However, the criteria that are represented by detailed quantitative information are also converted to the range 1–4, assuming that 1 represents the lowest value, 4 the highest and the other criteria are expressed as their relative value (allowing decimals). The alternative marine fuels are then scored based on the relative estimated performance of one option compared to the other included options for each sub-criterion, presented in pairwise comparison matrices.

Table 2

Criteria and sub-criteria considered in the selection of alternative marine fuels.

Main criterion	Sub-criterion	Definition and delimitation
Economic	Investment cost for propulsion	Represented by the capital cost of propulsion and associated on-board infrastructure per installed engine capacity (i.e., normalized to the power output) and includes cost of engines, fuel tanks, pipelines, gas alarm systems, and fuel processors, etc., on-board.
	Operational cost	Refers to cost of crew, crew training, insurance, and maintenance cost (excluding fuel cost).
	Fuel price	Represented by the estimated relative price/cost differences among the investigated fuels based on bunker price (when available), production cost estimates, and estimates of raw-material prices and fuel production efficiencies.
Technical	Available infrastructure	Refers to compatibility with existing infrastructure (including ports, fuel infrastructure, and engines), current amount of storage, distribution, and bunkering facilities as well as maturity of ship propulsion technology.
	Reliable supply of fuel	Refers to raw material availability, current production capacity and use as marine fuel, as well as energy security indicated by global distribution of supply potential and political stability or risk for supply disruptions in countries with large supply potential [49–52]. For natural gas, raw material availability depends on the reserves, and for biofuels it depends on the annual biomass production level, which is influenced by land availability and forestry and/or waste streams.
Environmental	Acidification	Represented by acidification potential based on NOx and SO_2 emissions from combustion of fuels[a].
	Health impact	Represented by particulate matter formation potential (in terms of $PM_{2.5}$-equivalents) from combustion considering PM_{10}, SO_2 and NO_X. ., PM is extremely small particles or liquids like dust, smog, and soot and is the main contributor to health impacts from shipping [3]. .
	Climate change[b]	Represented by the global warming potential for CO_2, CH_4, and N_2O emissions in a 100-year time horizon (GWP_{100}) [53] from a lifecycle, well-to-propeller[c], perspective.
Social	Safety	Includes the risk of fire, explosion, and health hazards related to handling the fuel, which depend on fuel properties such as auto-ignition point, flammability range, flashpoint, and toxicity.
	Upcoming legislation	Represented by the possibility for meeting known regulations connected to SO_x, NO_x, and GHG reductions linked to SECA and NECA[d], and existing GHG reductions targets as well as possible future emission regulations (e.g., connected to particle and ammonia emissions)

[a] Acidification potential is based on NOx and SO_2 emissions from combustion using characterisation factors for acidification potential based accumulated exceedance methods for NOx and SO_2.

[b] Since the environmental assessment has an attributional LCA perspective that considers emissions from the activities within the product life cycle only, indirect land use changes should not be considered.

[c] Including e.g., methane emissions (leakage) from biogas plants and upgrading facilities and direct land use effects in terms of GHG impact.

[d] SECA and NECA means Emission Control areas for shipping linked to regulations of sulphur and NOx.

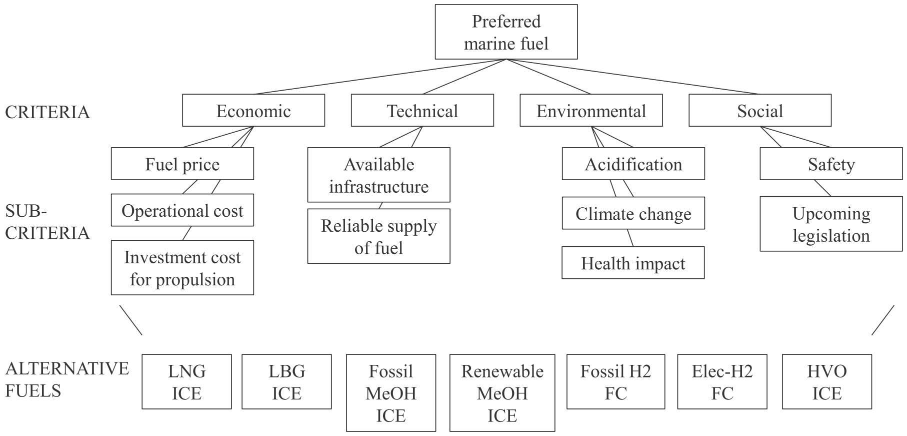

Fig. 1. Hierarchy tree for the decision problem when selecting the alternative marine fuel with the highest overall performance for the included criteria and sub-criteria.

2.4. Weighting of criteria and sub-criteria with a panel of maritime stakeholders

The pairwise comparisons of different criteria and sub-criteria resulting in the criteria weightings were performed by a group of shipping-related stakeholders at a workshop. The panel of Swedish stakeholders included ship-owners, fuel producers, engine manufacturers, representatives from Swedish government authorities, and researchers in the area of marine fuels (see Table D.1 in Appendix D).

In the first round, all stakeholders individually produced pairwise comparison matrices for the criteria and for each group of sub-criteria based on their preferences using the fundamental scale of absolute numbers for intensities defined by Saaty [33], Table 4. By aggregating the individual priorities using the weighted geometric mean [75–77] and assuming that each individual weighting is equally important, a base case was created, representing the “combined view” of the entire stakeholder panel.

In the second round, stakeholders were sorted into groups related to their main expertise and representing the views of (i) ship-owners, (ii) Swedish government authorities, (iii) fuel producers, and (iv) engine manufacturers. The participants were asked to jointly (within their respective groups) perform the pairwise comparisons of criteria and sub-criteria as representatives of the specific stakeholder group. Due to the relatively low number of engine manufacturer representatives, the same actors were included in the fuel producer and engine manufacturer groups but they produced two different sets of pairwise comparison matrices, one for each stakeholder group. The individual and stakeholder group pairwise comparison matrices are presented by Månsson et al., [43].

All five sets of weighting factors were then combined with the fuel scoring. Thus, the alternative marine fuels were ranked based on (i) the combined preference of the involved stakeholders based on individual weightings, and preferences representing (ii) government authorities, (iii) ship-owners, (iv) fuel producers, and (v) engine manufacturers.

2.5. Sensitivity analysis

Sensitivity analyses are performed to test the robustness of the fuel rankings and to consider uncertainties linked to the relative performances of the different fuel options. The most uncertain marine fuel performance estimates for the included sub-criteria are varied in different cases (Table 5). These cases were identified from literature ranges and in discussion with experts. The resulting fuel scores were combined with the weighting factors for all included stakeholder groups (combined, ship-owners, authorities, fuel producers, and engine manufacturers). The changes in ranking compared to the original rankings for each stakeholder group were noted.

The influence of different criteria/sub-criteria weights is assessed with the different stakeholder groups and is thus not included specifically in the sensitivity analysis.

3. Results

3.1. Relative alternative marine fuel performance

Fig. 2 illustrates the relative performances of the studied alternative marine fuels in terms of each of the included sub-criteria and their estimated overall performance (expressed as the normalized priorities). High values represent a more preferable performance in terms of lower cost, lower emissions, available infrastructure, etc.

LNG has the lowest fuel price. HFO has the best performance in terms of available infrastructure and reliable supply of fuel and has together with HVO the lowest operational cost. HVO has the lowest investment cost and represents the best performance in terms of safety. Hydrogen (both fossil and renewable) has the lowest acidification and health impact. Renewable MeOH and elec-H2 have the lowest climate change impact, while elec-H2 has the best performance in terms of upcoming legislation.

3.2. Stakeholder weighting of criteria

For each of the main criteria, the relative importance is presented in Fig. 3 for the combined group and for the four stakeholder groups (expressed as normalized priorities). For the combined group, the economic criteria are the most important, followed by social and environmental criteria. Ship-owners, fuel producers, and engine manufacturers value economic criteria the highest, followed by social and technical aspects for the former and technical and social for the two latter. Government authorities (Scenario 2), on the other hand, value environmental and social aspects the most, followed by economic criteria.

The relative importance of each sub-criterion (expressed as normalized priorities) is presented in Table 6. Fuel price is the most important economic criterion, and reliable supply is the most important technical criterion, for all cases. Climate change is considered the most important environmental criterion, with the exception that engine manufacturers consider health impact more important. Upcoming legislation is the most important social criterion, with the exception that ship-owners consider safety more important. The distribution of weights (normalized priorities) from the individual pairwise comparisons of criteria and sub-criteria for all the stakeholders is presented in Table E.1 in Appendix D.

Table 3

Marine fuel performance for heavy fuel oil (HFO), liquefied natural gas (LNG), liquefied biogas (LBG), methanol produced from natural gas (fossil MeOH) and renewable methanol (renewable MeOH), hydrogen produced from natural gas (fossil H2), hydrogen produced from electrolysis with renewable electricity (elec-H2), and hydrotreated vegetable oil (HVO).

	HFO ICE	LNG ICE	LBG ICE	Fossil MeOH ICE	Renewable MeOH ICE	Fossil H2 FC	Elec-H2 FC	HVO ICE
Capital cost for the propulsion system in 2015 dollars ($/kW)	4800-7300 [22,54,55]	5100-7710 [22,55]	5100-7710 [22,55]	4700-7180 [22,55]	4700-7180 [22,55]	6500-12040 [21,22,55]	6500-12040 [21,22,55]	4500-7040[a] [22,55]
Operational cost in 2015 dollars ($/MWh)	5[b]	9 [56]	9 [56]	6 [56]	6 [56]	11[b]	11[b]	5[b]
Indicative fuel price in 2030 in 2015 dollars (($/GJ)[c]	10 [57]	7 [58,59]	16 [60–63]	12 [64,65]	24 [60]	16 [66]	36 [66,67]	27 [60]
Available infrastructure[d]	4	2.4	1.9	2.2	2.2	1.1	1.1	3.0
Reliable supply of fuel[e]	3.3	2.6	2.2	2.4	2.2	1.6	2.8	1.6
Acidification potential as mole H^+equiv (mole H^+ equiv/ MJ fuel)[f]	3E-04 [13] [g]	8E-05 [18,19,68]	Assumed same as LNG	2E-04 [18,19] [g]	2E-04 [18,19] [g]	0	0	2E-04 [13] [g]
Health impact as $PM_{2.5}$ equivalents (<mu>g/MJ)[h]	0.021 [13] [g]	0.001 [18,19,68]	Assumed same as LNG	0.003 [18,19] [g]	0.003 [18,19] [g]	0	0	0.004 [13]
Climate change as GWP_{100} for CO_2-equiv mass over entire lifecycle (g/MJ)[i]	90 [13]	80 [18,19,69,70]	50 [18,19]	90 [18,19]	20 [18]	130 [19]	20 [19]	30 [71]
Safety[j]	2.1	2.5	2.5	2.0	2.0	1.0	1.0	3.5
Upcoming legislation[k]	2.1	2.9	3.1	2.9	3.2	3.7	4.0	2.9

[a] The capital cost for HVO is assumed equal to the capital cost for marine gas oil ships due to the physical similarities.

[b] Hydrogen is assumed to have slightly higher operational cost than LNG. HFO and HVO are assumed to have slightly lower operational cost than methanol.

[c] It is difficult to predict fuel prices in 2030. Our estimate is therefore based on available data on fuel production cost, historical prices, and rough estimates based on raw material prices and conversion efficiencies. These figures do not represent today's fuel prices but is our best estimate of the relative price levels in 2030 between the compared fuels without carbon taxes.

[d] Based on 5 maritime expert judgments of compatibility of the alternative marine fuel with the existing infrastructure, adaptability to existing ships including engine, engine technology maturity, and current amount of storage and bunkering capability, see Appendix C.

[e] Data are based on information on raw material availability, current production level, current use as marine fuel, and energy security in terms of (i) global distribution of supply potential, and (ii) political stability in countries with large supply potential, see Appendix C.

[f] Acidification potential is based on NOx and SO_2 emissions from combustion using characterisation factors for acidification potential based accumulated exceedance methods for NOx and SO_2 resulting in 0.74 and 1.31 mol of charge (mole) per kg substance emitted respectively [72,73].

[g] NO_x emissions of 280 mg/MJ fuel has been used for HFO, MeOH and HVO. It is assumed that engine modifications and exhaust gas after treatments are made to comply with IMOs Tier III regulation for NO_x emissions [37].

[h] Human health impact is based on emissions of PM_{10}, SO_2 and NO_X from combustion and represented by mass $PM_{2.5}$-equivalents. Characterisation factors for PM_{10}, SO_2 and NO_X are 0.2278, 0.0611and 0.0072 respectively [73].

[i] Global warming potential relative to a pulse emission of an equal mass of CO_2 for fossil CH_4, renewable CH_4 and N_2O are 30, 28, 265 for a time horizon of 100 years and 85, 84 and 264 for a time horizon of 20 years respectively [74]. Some references did only report aggregated data.

[j] Data are based on hazard statement codes found in material safety data sheets explicitly considering risk of explosion or fire, toxicity, health hazards, and cryogenic liquid, see Appendix C.

[k] Data are based on compliance with known and potential coming regulations, see Appendix C.

Table 4
Fundamental scale of absolute numbers used in pairwise comparisons of alternatives and criteria according to Saaty [33].

Intensity of importance	Definition	Explanation
1	Equal importance	Two elements contribute equally to the objective
3	Moderate importance	Experience or judgment slightly favors one element over another
5	Strong importance	Experience or judgment strongly favors one element over another
7	Very strong importance	One element is favored very strongly over another
9	Extreme importance	The evidence favoring one element over another is of the highest possible order of affirmation

When the difference in the comparison is somewhat less pronounced than described above, the intermediate values 2, 4, 6, and 8 can also be used2.5 Sensitivity analysis.

3.3. *Ranking of alternative marine fuels*

The fuel rankings differ among the stakeholder groups (Fig. 4). For the combined case, LNG and HFO is ranked the highest, followed by HVO and elec-H2, then renewable MeOH, followed by fossil MeOH. For ship-owners and fuel and engine producers, LNG and HFO is also ranked as top two, followed by fossil methanol. On the other hand, for authorities, renewable hydrogen is ranked the highest, followed by renewable methanol and HVO.

When focusing on renewable marine fuels, HVO is ranked the highest for the combined case followed by elec-H2 and then renewable MeOH. However, elec-H2 is ranked highest for the authorities case, followed by renewable MeOH and then HVO. For the other cases, HVO and LBG (ship-owners), renewable MeOH and HVO (fuel producers) or LBG or renewable MeOH (engine manufacturers) are ranked the highest, followed by renewable MeOH (ship-owners), LBG (fuel producers) or HVO (engine manufacturers) while elec-H2 turns out to be the least interesting option in all these cases.

The importance of each criterion for the final outcome differs to some extent for the different alternative marine fuel options. For most criteria the difference in importance for different fuels were minor. However, the fuel price is found to be more important for the fossil fuel-based alternatives in particular LNG, HFO and fossil methanol compared to the renewable based options for all stakeholder cases. For the combined case the criteria climate change also differs in importance with the highest levels for renewable hydrogen, renewable methanol and HVO. For the authority case where the importance of the fuel cost is relatively low, climate change is most important for renewable methanol and the criteria up-coming legislations is most important for the fossil hydrogen option.

Besides the difference in importance for the fuel price, for the ship-owner case, engine manufacturer and fuel producer cases the reliable supply of fuel is more important for the renewable hydrogen option compared to other options and for the two latter cases upcoming legislation is also clearly more important for both hydrogen options.

3.4. *Sensitivity analysis*

The relative ranking of the fuel options varies considerably in the different cases in the sensitivity analysis and is thus sensitive to

Table 5
Cases tested in the sensitivity analysis. The cases represent various changes in marine fuel performance linked to relevant sub-criteria.

Case	Description of change tested (new marine fuel performance values in parenthesis)
1	Increasing the capital cost for the propulsion system for LNG and LBG by 25% (LNG: 8010 $/kW, LBG: 8010 $/kW)
2	Decreasing the capital cost for the propulsion system for LNG and LBG, by setting it equal to MeOH (LNG: 5940 $/kW, LBG: 5940$/kW)
3	Increasing the capital cost for the propulsion system for fossil H2 and elec-H2 (H2 FC: 12,040 $/kW)
4	Replacing the indicator for operational cost for all fuel alternatives with the metric of cost of lost cargo space per vessel and trip using data and methodology based on Horvath et al. [21], (LNG ICE: 41,160 $, LBG ICE: 41,160 $, MeOH ICE: 90,770 $, H2 FC, HVO 0 $, HFO ICE with scrubber 20,580 $). The losses in cargo space with a scrubber is assumed to be equal to half of the volume lost with LNG.
5	Setting operational cost for H2 FC equal to LNG (both ranked as moderate (3))
6	Assuming the same operational cost for all fuel alternatives (Good (1))
7	Decreasing the indicative fuel price of elec-H2 by setting it equal to HVO (elec-H2: 27 $/GJ)
8	Increasing the indicative fuel price on fossil fuels compared to renewable fuels by including a CO_2 tax of 50 $/t of CO_2-equiv based on life-cycle GHG emissions in Table 3
9	Changing the indicative fuel price by including a CO_2 tax of 100 $/t of CO_2-equiv based on the life-cycle GHG emissions in Table 3
10	Changing the indicative fuel price by including a CO_2 tax of 150 $/t of CO_2-equiv based on life-cycle GHG emissions in Table 3
11	Changing the metric for indicative fuel price to only consider raw-material cost and production efficiency (HFO: 9 $/GJ, LNG:7 $/GJ, LBG: 13 $/GJ, fossil MeOH: 8 $/GJ, renewable MeOH: 10 $/GJ, fossil H2: 7 $/GJ, elec-H2: 7 $/GJ, HVO: 10 $/GJ).
12	Decreasing the indicative fuel price for elec-H2, by setting it equal to fossil H2 (elec-H2:16 $/GJ)
13	Increasing the indicative fuel price for LNG by setting it equal to fossil MeOH (LNG:12 $/G)
14	Replacing the metric for evaluating climate change impact for GWP_{100} with GWP_{20}.
15	Reducing the acidification impact of MeOH and HVO by setting NO_x emissions for MeOH and HVO equal to LNG and LBG e.g., SCR or exhaust gas recirculation used to reach the same level (MeOH, HVO: 8E-05 mol H^+ equiv/MJ fuel, HFO: 1E-04 mol H^+ equiv/MJ fuel)
16	Reducing the acidification and health impacts for all marine fuels alternatives to zero by assuming that exhaust abatement is used to eliminate SO_2, NO_X and PM_{10} emissions
17	Increasing the acidification impact of HFO and HVO by assuming PM, SO_2 and NO_x emissions, similar to today's emissions without exhaust abatement equipment (HFO: 2E-03 mol H^+ equiv, 0.075 g $PM_{2.5}$, HVO: 1E-03 mol H^+ equiv, 0.012 g $PM_{2.5}$)
18	Increasing the relative difference in infrastructure availability between options by setting infrastructure availability to Good (4) for LBG, LNG, fossil MeOH, renewable MeOH, and HVO; and Poor (1) for fossil H2 and elec-H2
19	Assuming higher supply reliability for elec-H2 by changing supply reliability of elec-H2 to Good (4)
20	Changing upcoming legislation to Poor (1) on all fuels that cannot comply with the IMO 2050 (50% GHG reduction of exhaust gas emissions) target without complementary solutions (HVO and HFO changed to poor (1))
21	Changing upcoming legislation to Poor (1) on all fuels that cannot comply with the IMO 2100 (100% GHG reduction of life-cycle emissions) target without complementing solutions (LNG, LBG, fossil MeOH, fossil H2 and HFO changed to poor (1), LBG due to methane slip)
22	Assuming lower safety for fossil H2 and elec-H2 by setting safety to Poor (1)
23	Assuming the same climate change impact ranking for LBG, renewable MeOH, HVO, and elec-H2 (GWP_{100} equal to 20 g/MJ fuel)
24	Assuming the same climate change impact ranking for LNG and fossil MeOH (GWP_{100} equal to 90 g/MJ fuel)
25	Assuming higher performance in terms of safety for HFO and HVO by setting safety to Good (4)

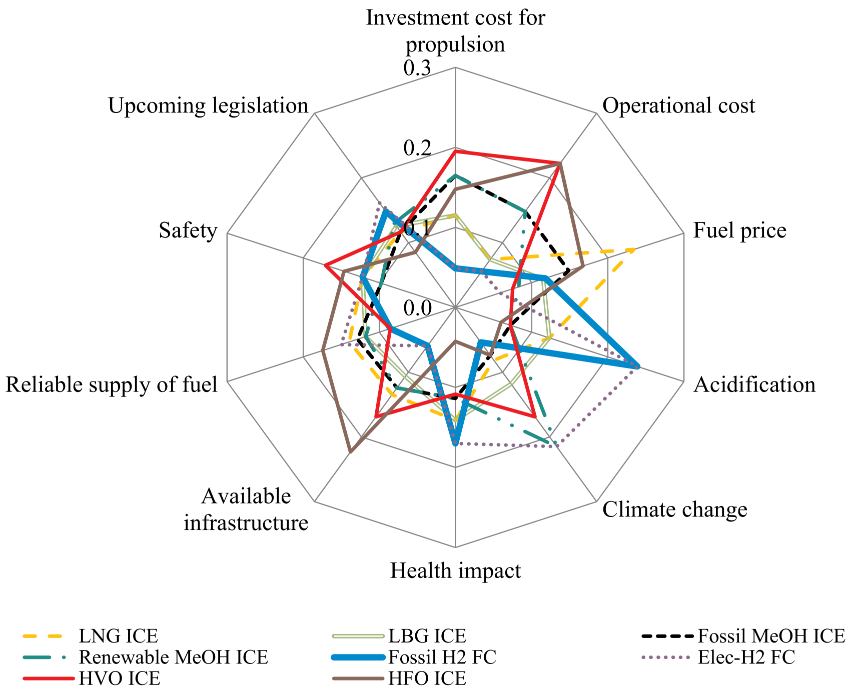

Fig. 2. Relative marine fuel performance for each sub-criterion based on the pairwise comparison of marine fuels. Higher values represent better performance.

parameter values (Table 7). The ranking was changed in at least one of the stakeholder groups for all sensitivity cases but one (case 5).

The fuel price is one of the most uncertain parameters and were shown to have a large impact on the ranking (especially in case 10 and 11). However, elec-H2 FC is still top-ranked in all sensitivity cases by the government authority group, while LNG is top-ranked in almost all sensitivity cases by the ship-owner, fuel producer and engine manufacture groups. However, if LNG and fossil MeOH are equal in price, fossil MeOH is ranked the highest for these groups while fossil H2 is always ranked low. The relative ranking of the renewable fuel options varies considerably in the different cases and is thus also sensitive to parameter values.

A carbon (CO_2) tax will increase the fuel price on fossil fuels compared to renewable fuels. However, to change the fuel ranking significantly a carbon tax above 300 \$/t of CO_2-equiv is needed. The carbon tax was based on the life cycle GWP_{100} for the investigated alternatives, however from a regulatory perspective it is easier to connect the carbon tax only to the direct emissions from ship propulsion. This would also change the level of the tax needed to shift the fuel rankings.

4. Discussion

Alternative marine fuels are needed in order to reduce the environmental and climate impact of shipping, in the short and long term. Alternative marine fuels have garnered increasing interest in recent years, and a range of different options with different characteristics are under consideration. Marine fuel performances vary by fuel and by area of consideration. For instance, this study confirms that some fuels have better economic performance or environmental performance, and some perform better in terms of infrastructure or availability. This means that a comprehensive comparison is a complex task, requiring an approach along the lines of multi-criteria decision analysis.

Despite LNG only being top-ranked in terms of fuel price, it is ranked the highest overall by the entire combined group and by the ship-owner, fuel producer, and engine manufacturer groups. This is because fuel price and economy in general are ranked very high by most shipping-related stakeholders. This result also reflects current developments in the shipping sector, where LNG is being introduced together with ships using HFO and scrubbers. Ship-owners, fuel

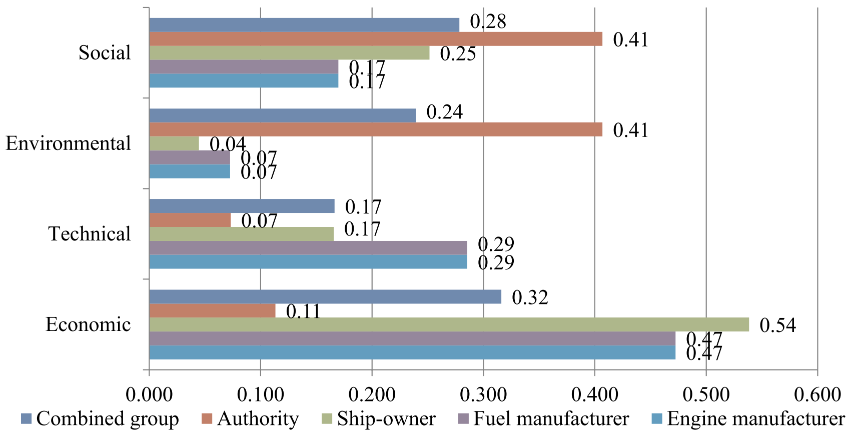

Fig. 3. Relative importance of the main criteria expressed as normalized priorities based on the pairwise comparisons of the criteria performed by the stakeholders individually and representing different stakeholder groups. A higher value represents higher importance.

Table 6
Relative importance of the sub-criteria expressed as normalized priorities based on the pairwise comparisons of the criteria performed by the stakeholders individually and as representatives of their various stakeholder groups (rounded figures).

Sub-criteria	Priority (Priority order in parenthesis)				
	Combined all stakeholders	Authorities	Ship-owners	Fuel producers	Engine manufacturers
Investment cost	0.26 (2)	0.25 (2)	0.20 (2)	0.23 (2)	0.23 (2)
Operational cost	0.16 (3)	0.25 (2)	0.07 (3)	0.12 (3)	0.12 (3)
Fuel price	0.58 (1)	0.50 (1)	0.73 (1)	0.65 (1)	0.65 (1)
Acidification	0.21 (3)	0.19 (2)	0.10 (3)	0.11 (3)	0.26 (2)
Climate change	0.50 (1)	0.73 (1)	0.67 (1)	0.58 (1)	0.11 (3)
Health impact	0.30 (2)	0.08 (3)	0.23 (2)	0.31 (2)	0.64 (1)
Available infrastructure	0.29 (2)	0.17 (2)	0.20 (2)	0.20 (2)	0.20 (2)
Reliable supply of fuel	0.71 (1)	0.83 (1)	0.80 (1)	0.80 (1)	0.80 (1)
Safety	0.48 (2)	0.25 (2)	0.80 (1)	0.17 (2)	0.17 (2)
Upcoming legislation	0.52 (1)	0.75 (1)	0.20 (2)	0.83 (1)	0.83 (1)

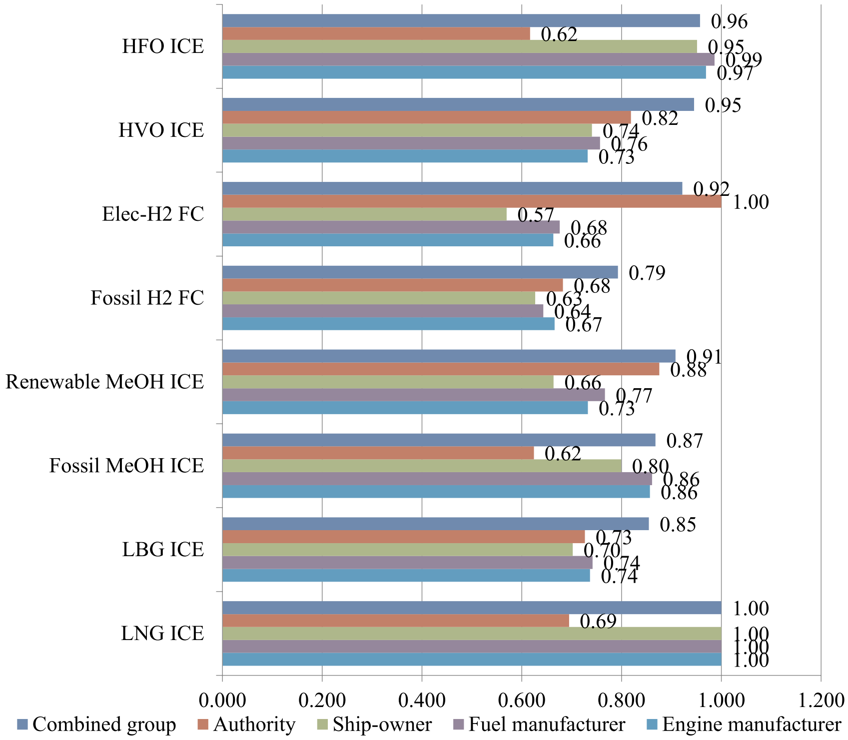

Fig. 4. Final idealized ranking of the studied alternative marine fuels for the different stakeholder groups. The fuel ranked the highest is assigned the value "1"; the values for the other fuel are expressed relative to the top choice.

Table 7
Outcome of the sensitivity analysis: Fuel ranking (from 1 to 8 where 1 indicate highest ranking) in the different stakeholder groups when evaluating changes in performance of the fuels for selected sub-criteria in 25 sensitivity cases (see Table 5) with range given in parenthesis. The number of cases where ranking changed is also included.

Fuels	Combined group	Gov. authorities	Ship-owner	Fuel producer	Engine manufacturer
HFO ICE	2.3 (1–5)	7.6 (6–8)	1.8 (1–2)	1.3 (1–2)	1.8 (1–2)
LNG ICE	1.7 (1–5)	55.2 (4–6)	1.2 (1–3)	1.3 (1–3)	1.3 (1–3)
LBG ICE	6.7 (4–8)	4.01(3–8)	5.2 (5–8)	5.8 (4–8)	4.8 (4–8)
Fossil MeOH ICE	6.1 (5–7)	7.1 (6–8)	3.1 (1–6)	3.1 (2–5)	3.0 (2–4)
Renewable MeOH ICE	4.6 (3–6)	2.1 (2–4)	6.0 (5–7)	4.3 (3–6)	5.2 (4–7)
Fossil H2 FC	7.9 (6–8)	5.8 (4–8)	7.0 (4–8)	8.0 (7–8)	7.2 (5–8)
Elec-H2 FC	3.7 (1–7)	1	7.6 (3–8)	6.6 (3–7)	7.2 (3–8)
HVO ICE	3.0 (2–7)	3.1 (2–6)	4.0 (3–5)	5.2 (4–7)	5.6 (4–8)
Cases where ranking changed	18	14	9	17	19

producers, and engine manufacturers rank HFO second after LNG and then fossil methanol, which is interesting to note from a Swedish perspective, where Stena Line has implemented fossil methanol on one of their ships (operating on a route Sweden-Germany).

Renewable hydrogen is deemed to have high performance in terms of upcoming legislation, reliable supply of fuel, and all environmental impacts. This explains why it is ranked highest by the authorities group. However, in all other cases except the combined case, it is, together with fossil H2, ranked the lowest because it is expected to have the highest fuel, investment, and operational costs. That LNG and hydrogen are ranked highest for some cases is in line with the findings in Deniz and Zincir [24] Ren and Liang [25]. However, these studies do not include the same additional fuel options.

The highest-ranked biofuel varies considerably among the groups. For the authorities group and the fuel producers group, renewable MeOH seems more interesting, while for other stakeholder groups the other options are somewhat more interesting. Thus, it is not possible to draw any firm conclusions about the potential for different biofuels for the shipping sector based on this assessment. In the shorter term, low-blending of LBG (in LNG) and HVO in fossil diesel seem to be easier options than renewable methanol since it requires less changes. Complementary assessments with an energy-system perspective are needed in order to gain an increased understanding about the role of biofuels and under which circumstances different renewable marine fuels are cost-effective and interesting for different parts of the shipping sector.

The relative importance of each criteria for the final outcome differ to some extent for the different alternative marine fuel options. For most criteria the difference in importance for different fuels were minor. However, the fuel price is found to be more important for the fossil fuel-based options compared to the renewable based options for all stakeholder cases.

The selection of criteria influences the fuel ranking. A different set of criteria could result in a different outcome. The greater the number of criteria included, the smaller the risk that another set would yield an equally or more comprehensive assessment with a very different ranking. However, the criteria set chosen in this study already includes many key aspects, and a greater number of criteria might not be more useful for the decision-making process or clarify the role of the different biofuels [78]. Nevertheless, it would be interesting to study the effect of including additional criteria, such as more specifically the effect on cargo capacity, fuel choice potentially influencing the environmental profile (linked to green marketing), or the more specific potential for low-blending. Also, the importance of technology lock-in for the introduction of alternative fuel options could specifically be addressed, in particular in assessments in the more long-term. This, since the engine type on the ship decides which fuel type that is possible to use. However, the development and introduction of more flexible dual fuel engine on ships increasing the fuel compatibility may limit the risk for lock-in to some extent [79]. But for example, a transition to LNG may facilitate for the introduction of LBG. That said, some criteria are more difficult to represent in quantitative terms than others (e.g., green marketing).

The sensitivity analysis tests assumptions and uncertainties linked to some of the parameter values to a certain extent. However, different fuel production pathways for a given fuel may yield different criteria performance, and in some cases, there may be a lack of data, which adds to the difficulty in predicting or estimating future fuel characteristics. For example, in the case of biofuels, the climate impact differs depending on the assumed raw materials. This may influence the internal ranking of biofuels.

The fuel price in 2030 is very uncertain yet heavily influences the results. The fuel price of fossil fuels can be increased by a carbon tax, and shipping stakeholders have indicated a willingness to pay 50 $/t of CO_2 emissions in survey by Lloyds Register [80]. However, a significant change in the fuel ranking in this study requires a carbon tax above 300 $/t of CO_2-equiv.

In the overall combination and in several of the groupings, stakeholders in this study consider overall economic criteria, in particular the fuel price, more important than technical, environmental, and social factors in choosing marine fuels. However, the government authorities group values environmental criteria, in particular GHG impact, the highest. A reliable supply of fuel, the possibility to meet current and upcoming regulations, and safety are also considered important aspects. One limitation with this study is the limited number of stakeholders included. However, they cover many different relevant stakeholder groups. Other stakeholders or stakeholder groups may value the criteria differently, potentially influencing the fuel ranking. For comparison, in assessing marine fuels, Ren and Liang [25] include three more general stakeholder groups covering ship-owners, administrators, and scholars. Osorio-Tejada, Llera-Sastresa [31], assessing transport fuels for the road sector, include four different stakeholder groups (company owners, society, small and medium enterprises, and environmentalists). For this study, it would be interesting to also include a stakeholder group representing transport buyers, e.g., companies like IKEA or SCA (a large Swedish forest-products company).

The preferences of different stakeholders and stakeholder groups are captured by the different weights they assign to the different criteria, which influence the fuel rankings and hence selections of options. In any methodology aiming at generating a single ranking there is a challenge in considering trade-offs for example to avoid information being outweighed by other information and thus potentially concealed in the overall outcome [81]. To reduce this impact in this assessment we have tried to define the criteria to reduce the risk for trade-offs and to avoid overlap to the extent possible and have also described the criteria carefully for the stakeholders.

The performance and importance of criteria might also change, for example due to new policies, potentially improving the conditions for biofuels. The IMO strategy for reducing the GHG emissions from international shipping by 2050 represents a challenge for the shipping sector. Policy analyses are needed to understand which policy measures and specific policy designs could be implemented effectively.

Additional sensitivity analyses could vary the weights for the most important criterion/criteria and sub-criteria for each stakeholder group. It would also be interesting to test the robustness of our findings by applying another MCDA approach to the same data. For example, there are other methods being developed to handle incomplete and uncertain information. That said, in the case of marine fuels, Ren and Lützen [26] find that the results from one such method are comparable with that determined by the traditional AHP.

There are several initiatives in progress for the use, as well as production, of alternative marine fuels [79]. Except for LNG and electric propulsion in short-sea shipping, most of the initiatives and activities are at the pilot or test scale. Thus, implementation of economically feasible alternative marine fuels is still quite a long way off, in particular for deep-sea shipping. Electrofuels (produced from CO_2 and water with the aid of electricity) may also be an interesting future option for deep-sea shipping [82]. The potential for this option requires further assessment. Irrespective of the specific fuel option, and since many stakeholders rank fossil fuel-based options high while governmental authorities rank the renewable options higher the introduction of renewable marine fuels would need to be supported by policy initiatives. The policies should influence for example fuel price relationships.

Currently, biofuels are primarily of interest for minor applications in short-sea shipping and for public transport. This is in part due to their limited availability. However, some biofuels (LBG, HVO, and renewable methanol) could also be blended in fossil marine fuels. The development of biofuel production pathways from, e.g., forest residues and sea-based resources may increase the total availability of biofuels, improving the potential for marine applications. The competition for biofuels from other sectors (road transport and aviation), as well as biomass demand in other sectors, will influence the potential for biofuels in the shipping sector.

5. Conclusions

This study assesses and ranks selected marine fuel options based on their relative performances on ten criteria covering economic, environmental, technical and social aspects, and on the relative importance of these criteria based on Swedish stakeholder preferences.

The variation in preferences among stakeholders results in different rankings of the included alternative marine fuel options. Based on the views of ship-owners, fuel producers, and engine manufacturers, LNG is ranked the highest, with HFO second, and then the fossil methanol followed by biofuels (in various orders). These rankings stem from economy, in particular fuel price, being the top criterion for these actors. On the other hand, the views of governmental authorities result in renewable hydrogen being ranked highest, with renewable methanol second, and then HVO. The reason for this is that GHG emissions and the potential to meet regulations are top criteria for these stakeholders. Thus, in order to promote other options than LNG and HFO with scrubbers policies influencing the cost-competitiveness of renewable marine fuel options are needed.

This assessment does not provide any firm conclusion on the potential for different marine biofuels. Although biofuels are not ranked highest by any of the stakeholder groups, they may still be of interest for marine applications. Biofuels can, e.g., represent an attractive solution if the transition to fuels with low GHG emissions is urgent, since some biofuels are already commercially available, and most biofuels can be used in existing engines (or with minor modifications, which is not the case for hydrogen) and provide a larger CO_2 reduction potential than LNG. Currently, there are no large-scale solutions for hydrogen production, distribution, storage, and use in fuel cells, so this option is less available in the short term. The development and demand for biofuels (as well as bioenergy in general) in other sectors will influence the potential for marine biofuels. Like the road transport sector, the shipping sector might not be dominated by one alternative fuel in the future. However, all the renewable marine fuel options will require policy initiatives and instruments that support their introduction, both in the short and long term. To be effective, such support should influence renewable options' performances on the relevant criteria. Possible support mechanisms include CO_2 taxes on marine fuels, quota systems promoting a specific level of renewable marine fuels, and subsidies for investments in renewable marine fuels (for retrofits and new construction). A better understanding of stakeholder preferences may improve the design and implementation of policies.

Declarations of interest

None.

Paper type

Research paper describing original study.

Acknowledgments

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Appendix A. Pairwise comparisons following the Analytic hierarchy process (AHP)

Mathematically the pairwise comparison matrices (PCM) applied in the study is expressed by Eq. (A.1) where aij > 0 express the degree of preference of aspect xi to xj with e.g., Saaty's fundamental scale of absolute numbers as basis [33].

$$\mathrm{PCM} = (a_{ij})_{n\times n}\mathrm{PCM} = \begin{pmatrix} a_{11} & a_{12} & \cdots & a_{1n} \\ a_{21} & a_{22} & \cdots & a_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ a_{n1} & a_{n2} & \cdots & a_{nn} \end{pmatrix} \tag{A.1}$$

A consistency check of the comparisons included in the PCM is done by solving the characteristic equation Eq. (A.2). The maximum eigenvalue, λ_{max}, is used for calculating a consistency index (CI), Eq. (A.3), and thereafter a consistency ratio (CR), Eq. (A.4) where n is the size of the PCM and RIn a random index that depends on the size of the PCM (see Table A.1). A CR below 0.1 (which represents 10% inconsistency in the pairwise comparison) is considered as consistent comparison while comparisons returning in larger inconsistency need to be revised [83].

$$\det(\mathrm{PCM} - \lambda\cdot I) = 0 \tag{A.2}$$

$$\mathrm{CI(PCM)} = \frac{\lambda_{max} - n}{n - 1} \tag{A.3}$$

$$\mathrm{CR(PCM)} = \frac{\mathrm{CI(PCM)}}{\mathrm{RI}_n} \tag{A.4}$$

Table A.1
Random index values for calculating the consistency ratio [34].

n	3	4	5	6	7	8	9	10
RIn	0.5247	0.8816	1.1086	1.2476	1.3417	1.4057	1.4499	1.4854

The normalized priority vector NPV = $\{NPV_i, \ldots, NPV_n\}$ is for each PCM calculated as the geometric mean for each row in the matrix divided by the sum of the priorities (Eq. (A.5)).

$$NPV_i = \left(\prod_{j=1}^{n} a_{ij}\right)^{\frac{1}{n}} \Big/ \sum_{i=1}^{n}\left(\prod_{j=1}^{n} a_{ij}\right)^{\frac{1}{n}} \tag{A.5}$$

Based on the individual stakeholder pairwise comparison matrices, group priority vectors (GPV) are constructed by aggregation of individual priorities [76] assuming equal importance and using the weighted geometric mean as it is the preferred aggregation method in group decisions [75,77].

The global priorities, i.e., the final ranking of the alternative marine fuels, are then derived by linear combination of the group priority vectors (GPV) and the normalized priority vector (NPV) from the pairwise comparison of alternatives by sub-criterion [34,83].

Appendix B. Criteria in survey to maritime stakeholders

Table B.1
Results from survey to maritime stakeholders

Criteria	Share of votes (%)
Investment cost for propulsion	75
Operational cost	42
Fuel price	92
Infrastructure cost	17
Production cost	25
Mature propulsion technology	17
Technical adaptations at ship	33
Available infrastructure	50
Reliable supply of fuel	100
Bunkering time	8
Bunkering frequency	17
Climate change	100
Acidification	67
Eutrophication	33
Health impact	50
Impacts from fuel spills	0
Other impacts (biodiversity loss)	8
Safety	75
Job creation	0
Public opinion	0
Competition with food	17
Upcoming legislation	42
Risk of fire and explosion	25

Appendix C. Underlying expert evaluation of certain sub-criteria

The underlying expert valuation for the sub-criteria available infrastructure, reliable supply of fuel, safety and upcoming legislation is presented in Table C1-C4.

Table C.1
Expert evaluation of sub-criteria “Available infrastructure”. Average evaluation of 5 expert judgments on the scale: Poor 1, Moderate 2, Fairly good 3, Good 4. Range given in parenthesis.

	HFO ICE	LNG ICE	LBG ICE	Fossil MeOH ICE	Renewable MeOH ICE	Fossil H2 FC	Elec-H2 FC	HVO ICE
Compatibility of the alternative marine fuel to existing infrastructure	4	1.4 (1–2)	1.4 (1–2)	2.4 (1–3)	2.4 (1–3)	1 (1–3)	1	3.6 (3–4)
Adaptability to existing ships	4	2	2	2.75 (2–3)	2.75 (2–3)	1	1	3.75 (3–4)
Engine technology maturity	4	3.25 (2–4)	3.25 (2–4)	2.75 (2–3)	2.75 (2–3)	1.25 (1–2)	1.25 (1–2)	3.75 (3–4)
Current amount of storage and bunkering capability	4	3	1	1	1	1	1	1

Table C.2
Expert evaluation of sub-criteria “Reliable supply of fuel”. The scale used is: Poor 1, Moderate 2, Fairly good 3, Good 4.

	HFO ICE	LNG ICE	LBG ICE	Fossil MeOH ICE	Renewable MeOH ICE	Fossil H2 FC	Elec-H2 FC	HVO ICE
Raw material availability	3 (Conventional crude oil, 4900–7610 EJ [84])	3 (Natural gas, 7400 EJ [85])	3 (Biomass residues, 35.9 EJ/year [86])	3 (Natural gas, 7400 EJ [85])	3 (Short rotation forest, forest residues, 60 EJ/year [87])	3 (Natural gas, 7400 EJ [85])	4	1 (Tall oil, 0.13 EJ [88])
Current fuel production	4	4 (12.5 EJ/year [89])	1 (1.25 EJ/year [86]	4 (2.6 EJ/year [29])	1 (0.004 EJ/year [90])	1 (6.8 EJ/year [66,91])	1 (0.03 EJ/year [66,91])	1 (0.0044–0.0066 EJ/year [88]])
Current use as fuel in shipping sector	4	3 [92]	1	2 [93]	1	1	1	1

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Table C.2 (*continued*)

	HFO ICE	LNG ICE	LBG ICE	Fossil MeOH ICE	Renewable MeOH ICE	Fossil H2 FC	Elec-H2 FC	HVO ICE
Energy security 1: Global distribution of supply potential	4 [84]	1 [85]	2 [94]	1 [85]	2 [94]	1 [85]	4 [94]	1 [94]
Energy security 2: Political stability in countries with large supply potential	2 [85]	2 [85]	4 [94]	2 [85]	4 [94]	2 [85]	4 [94]	4 [94]

Table C.3
Expert evaluation of sub-criteria "Safety". The scale used is: Poor 1, Moderate 2, Fairly good 3, Good 4.

	HFO ICE	LNG ICE/LBG ICE	Fossil MeOH ICE/Renewable MeOH ICE	Fossil H2 FC/ Elec-H2 FC	HVO ICE
Safety in terms of Risk of explosion or fire	4 (Not classified as explosive of flammable under CLP criteria)	1 (H220: Extremely flammable gas. Theoretical possibility of a rapid phase transition explosion occurring in the event of gross spillage of LNG on water, possibility of rollover in large storage tanks)	2 (H225 Highly flammable liquid and vapor. Burns with a nearly invisible flame but is less flammable than petrol. The risk of handling methanol in fuel tank in an electric car has been considered equal to that of conventional fuel)	1 (H220: Extremely flammable gas)	4 (Not classified as explosive of flammable under CLP criteria)
Safety in terms of Toxicity	2 (H332: Harmful if inhaled)	4 (Not classified as toxic under CLP criteria. Not toxic, but can act as an asphyxiant by replacing oxygen in enclosed spaces)	1 (H301 Toxic if swallowed, H311 Toxic in contact with skin, H331 Toxic if inhaled. Toxic to humans, the lethal dosage of methanol is between 30 and 10 ml per kilogram body weight)	4 (Not classified as toxic under CLP criteria)	4 (Not classified as toxic under CLP criteria)
Safety in terms of Health hazards	2 (H350: May cause cancer. H361d: Suspected of damaging unborn child. H373: May cause damage to organs through prolonged orrepeated exposure, H-EUH066: May cause skin dryness)	4 (Not classified as a health hazard under CLP criteria)	1 (H370 Causes damage to organs)	4 (Not classified as a health hazard under CLP criteria)	2 (H304: May be fatal if swallowed and enters airways, H315: Causes skin irritation, H373: May cause damage to organs through prolonged or repeated exposure)
Safety in terms of Cryogenic liquid	4 (Not classified as a cryogenic liquid under CLP criteria.)	1 (H281: Contains refrigerated gas; may cause cryogenic burns or injury)	4 (Not classified as a cryogenic liquid under CLP criteria)	1(H281: Contains refrigerated gas; may cause cryogenic burns or injury)	4 (Not classified as a cryogenic liquid under CLP criteria)

Table C.4
Expert evaluation of sub-criteria "Upcoming legislation". The scale used is: Poor 1, Moderate 2, Fairly good 3, Good 4.

	HFO ICE	LNG ICE	LBG ICE	Fossil MeOH ICE	Renewable MeOH ICE	Fossil H2 FC	Elec-H2 FC	HVO ICE
SO_2 2020 global	2 (Need exhaust gas cleaning)	4 (Yes)	4 (Yes)	4 (Yes)	4 (Yes)	4 (Yes)	4 (Yes)	4 (Yes)
NO_X Tier III	2 (Need exhaust gas cleaning)	4 (Yes)	4 (Yes)	3 (No, but probably with engine development)	3 (No, but probably with engine development)	4 (Yes)	4 (Yes)	2 (Probably need exhaust gas cleaning, e.g. SCR)
IMO GHG target 2050 (exhaust emissions)	2 (Possibly in combination with energy efficiency measures)	3 (Possibly in combination with energy efficiency measures)	4 (Yes)	2 (Possibly in combination with energy efficiency measures)	4 (Yes)	4 (Yes)	4 (Yes)	4 (Yes)
IMO GHG targets 2100 (fuel life cycle)	1 (No)	1 (No)	3 (Yes, if there are no methane slip)	1 (No)	4 (Yes)	1 (No)	4 (Yes)	4 (Yes)
Particle mass (PM_{10})	1	3	3	3	3	4	4	2 (Relatively high PM emissions, but can be combined abatement technologies, e.g. filters)
Particle numbers[1]	2 (may needs to be combined with abatement technology)	2 (may needs to be combined with abatement technology)	2 (may needs to be combined with abatement technology)	2 (may needs to be combined with abatement technology)	2 (may needs to be combined with abatement technology)	4	4	2 (may needs to be combined with abatement technology)

(*continued on next page*)

Table C.4 (*continued*)

	HFO ICE	LNG ICE	LBG ICE	Fossil MeOH ICE	Renewable MeOH ICE	Fossil H2 FC	Elec-H2 FC	HVO ICE
Methane emissions	4	1	1	3	3	4	4	3
Ammonia emissions	4	4	4	3 (if combined with SCR)	3 (if combined with SCR)	4	4	3 (if combined with SCR)

[1] This assessment is very uncertain as there are limited measurements of particle mass.

Appendix D. Stakeholders involved in the MCDA

Table D.1
External stakeholders participating in the MCDA.

Stakeholder	Company/Association	Stakeholder group
Reidar Grundström	Swedish Maritime Administration	Gov. authority
Magnus Lindgren	Swedish Transport Administration	Gov. authority
Rebecka Bergholtz	Swedish Energy Agency	Gov. authority
Olle Hådell	Consultant, formerly Swedish Transport Administration	Gov. authority
Magnus Wallenbert	Preem	Engine manufacturer/Fuel producer/
Toni Stojcevski	Wärtsilä	Engine manufacturer/Fuel producer/
Joanne Ellis	SSPA	Researcher/Engine manufacturer/Fuel producer
Martin Svanberg	SSPA	Researcher/Engine manufacturer/Fuel producer
Cecilia Andersson	Environmental Manager at Stena Line Group	Ship-owner
Martin von Sydow	Vice President and Head of Ship Design Wallenius Marine AB	Ship-owner
Fredrik Backman	Preem	Ship-owner
Fredrik Svensson	The Swedish Gas Association (Swedish industry association for actors linked to biogas, vehicle gas, natural gas, hydrogen, and liquified petroleum gas)	Ship-owner
Zoi Johansson Nikopoulou	Göteborg University	Researcher/Ship-owner

Appendix E. Outcome of individual pairwise comparisons of criteria

Table E.1
Distribution of priorities from the individual pairwise comparison of criteria and sub-criteria for all the involved stakeholders.

	Min. priority	Max. priority	Median priority
Economic	0.035	0.632	0.420
Technical	0.055	0.286	0.113
Environmental	0.047	0.514	0.229
Social	0.055	0.564	0.222
Investment cost	0.105	0.637	0.243
Operational cost	0.072	0.481	0.105
Fuel price	0.200	0.731	0.637
Acidification	0.069	0.455	0.163
Climate change	0.091	0.731	0.582
Health impact	0.105	0.594	0.279
Available infrastructure	0.125	0.750	0.250
Reliable supply of fuel	0.250	0.875	0.750
Safety	0.167	0.833	0.333
Upcoming Legislation	0.167	0.833	0.667

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