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The Potential Role of Ammonia as Marine Fuel—Based on Energy Systems Modeling and Multi-Criteria Decision Analysis

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Abstract: To reduce the climate impact of shipping, the introduction of alternative fuels is required. There is a range of different marine fuel options but ammonia, a potential zero carbon fuel, has recently received a lot of attention. The purpose of this paper is to assess the prospects for ammonia as a future fuel for the shipping sector in relation to other marine fuels. The assessment is based on a synthesis of knowledge in combination with: (i) energy systems modeling including the cost-effectiveness of ammonia as marine fuel in relation to other fuels for reaching global climate targets; and (ii) a multi-criteria decision analysis (MCDA) approach ranking marine fuel options while considering estimated fuel performance and the importance of criteria based on maritime stakeholder preferences. In the long-term and to reach global GHG reduction, the energy systems modeled indicate that the use of hydrogen represents a more cost-effective marine fuel option than ammonia. However, in the MCDA covering more aspects, we find that ammonia may be almost as interesting for shipping related stakeholders as hydrogen and various biomass-based fuels. Ammonia may to some extent be an interesting future marine fuel option, but many issues remain to be solved before large-scale introduction.

Keywords: shipping; alternative fuels; ammonia; decarbonization; biofuels; greenhouse gas emission targets; scenarios; multi-criteria decision making

1. Introduction

In 2018, the International Maritime Organization (IMO) agreed to reduce greenhouse gas (GHG) emissions from international shipping by at least 50% by 2050, phase them out by 2100 at the latest, and to reduce the carbon dioxide (CO_2) emissions per transport work by 40% in 2030 and 70% in 2050, relative to 2008 [1]. To reach these objectives, the conventional use of fossil fuels needs to be drastically reduced and combined with the introduction of operational and technical measures that reduce fuel consumption in combination with the introduction of energy carriers with low or near zero GHG emissions [2–7].

There is a range of different marine fuel options with varying characteristics in terms of, for example, availability, cost, energy density, technical maturity, and environmental impact [2,8,9]. In recent years, ammonia has been proposed as a potential marine fuel that would give no emissions of CO_2 from the ship since it is a carbon-free molecule [8,10–14].

Ammonia (NH_3) produced from hydrogen and nitrogen may thus contribute to low climate impact if produced from renewable energy sources (or combined with carbon capture and storage, CCS). However, ammonia is currently mainly produced from fossil fuel-based hydrogen while production processes for renewable ammonia are still under development [15,16].

Ammonia, as energy carrier, can, with the development of existing technologies, be used in fuel cells or in internal combustion engines (ICE). There are some scientific papers assessing ammonia as transport fuel. For example, Kang and Holbrook [17] assessed the GHG reduction potential of introducing ammonia fueled light-duty vehicles in the US transportation sector to 2040. For shipping, some studies have applied multi-criteria decision analysis (MCDA) to assess and rank selected marine fuel options, for example liquefied natural gas (LNG), fossil methanol, and hydrogen [9,18–20]. However, while Hansson et al. [9] included several renewable options, none of these studies include ammonia.

By developing decarbonization pathways for international shipping that combine different technologies including ammonia as fuel, Halim et al. [21] assess the possible CO_2 reduction potential by 2035. The study assumes in some cases that hydrogen and ammonia may represent about 70% or more of the total marine fuel demand in 2035 [21]. Ben Brahim et al. [22] presented pathways to climate-neutral shipping by 2050 for the Danish maritime cargo sector and found that hydrogen, methanol, and ammonia are the most preferable from a socioeconomic cost perspective. However, to assess the potential role of ammonia as marine fuel in the future, there is a need for more studies clarifying the knowledge gaps and its prerequisites in relation to other options, for example when considering also other energy demand sectors and several other criteria such as safety, distribution, and development of engines/fuel cells.

The aim of this paper is to assess the prospects for ammonia as a future fuel for the shipping sector in relation to other marine fuel options. The paper includes a synthesis of knowledge on ammonia as an alternative marine fuel, which is used partly as basis for: (i) an assessment of the cost-effectiveness of ammonia as marine fuel for reaching global climate targets using energy systems modeling; and (ii) a multi-criteria decision analysis (MCDA) resulting in a ranking of different marine fuels.

From an overall point of view, this paper discusses prospects for ammonia as marine fuel with a broader perspective and in more detail than many other studies. In the long-term and to reach global GHG reduction, the energy systems modeled in this paper indicate that the use of hydrogen represents a more cost-effective option for the shipping sector than ammonia. However, in the MCDA covering more aspects, we find that ammonia may be almost as interesting for shipping related stakeholders as hydrogen and various biomass-based fuels. Due to primarily the potential low climate impact, ammonia has potential as future marine fuel, but many issues remain to be solved before it can be introduced in large-scale and more detailed additional assessments and comparisons are needed.

2. Materials and Methods

Initially, a literature review on ammonia covering for example production pathways, costs, and environmental impact was performed. Based on this the prospects for ammonia as marine fuel in relation to other fuel options were then assessed by: (i) energy systems modeling of the cost-effectiveness of ammonia as marine fuel compared to other alternative marine fuel options for reaching global climate targets; and (ii) applying a multi-criteria decision analysis (MCDA) approach that is based on the estimated fuel performance and on input from a panel of maritime stakeholders with varying preferences.

2.1. Ammonia as Fuel—A Brief Synthesis of Knowledge

Approximately 80% of the total global ammonia consumption is used in the production of fertilizers, such as urea, ammonium nitrate, ammonium phosphate, or direct use of ammonia while the rest is used in various industrial applications, e.g., explosives, healthcare, cosmetic, animal nutrition, nutrition, plastics, resins, and electronics, as well as in NO_X control systems in the automotive industry [16,23]. The global production amounted to approximately 180 million tons in 2016 [16,23].

Ammonia is currently produced mainly by the electricity demanding Haber–Bosch (HB) process and the nitrogen used is produced from air via the reforming step or by a separate air separation process [16,24].

Besides fossil fuels, hydrogen can also be produced from reforming biogas and renewable methane or from electrolysis of water using renewable energy sources, e.g., wind, solar, and water power. Electrochemical synthesis, where ammonia is synthesized in a single electrochemical reactor using water or steam, nitrogen, and electricity, represents another possible ammonia production pathway with for example potentially reduced energy use [25]. However, further development is needed to obtain ammonia production rates high enough for commercialization for this process [16,25,26]. A technology representing an integration of the electrolyzer and the HB units, without the need for an air separation unit is also being developed by Haldor Topsoe potentially resulting in reduced cost and energy use [27].

Globally, there are several initiatives for production of renewable ammonia. For example, the ammonia producer Yara plans to build a demonstration plant for ammonia from solar energy in Australia and Haldor Topsoe aims to demonstrate its next-generation green ammonia synthesis plant (using a solid oxide electrolysis cell) by 2025 [27,28].

2.1.1. Ammonia Fuel Performance

Ammonia has been demonstrated as a fuel in compression ignition (CI) engines, spark ignition (SI) engines, and fuel cells [29–34]. A recent review of the literature on engine tests with ammonia shows that there are a limited number of tests published on ammonia in combustion engines and that significant amounts of ignition fuel (e.g., hydrogen, diesel, or alcohols) are needed for both CI and SI engines [35]. The review concludes that there are remaining issues with ignition, specific fuel consumption, materials, and emissions [35]. Besides ammonia slip, there are potential emissions of NO_X, CO, hydrocarbons (depending on pilot fuel), and N_2O, even if it seems likely that these emissions can be handled with after treatment further assessments are needed.

In fuel cells, either ammonia can be used directly or ammonia is split into hydrogen and N_2 and the hydrogen then used in the fuel cell. Two fuel cell options that may be used in marine applications are proton-exchange membrane fuel cells (PEM) using purified hydrogen and solid oxide fuel cells (SOFC) using ammonia [36]. PEM fuel cells are commercial and tested in marine applications [37]. Fuel cells using ammonia directly, besides SOFC also, e.g., alkaline and alkaline membrane, are under development [31]. No reports from tests onboard vessels have been found, but SOFC using methanol and methane have been tested [37].

Ammonia linked to fuel cells might compared to combustion engines potentially offer higher thermal efficiencies, less noise, and lower emissions of air pollutants. However, the emissions associated with ammonia fuels cells need to be confirmed. There is for example a risk for NOx emission [31]. The ammonia fuel cell pathway might also be relatively costly.

No ammonia driven propulsion technologies for marine operation have been commercialized yet. However, there are initiatives; for example, MAN Energy solutions claim that their dual-fuel engine developed for LPG may use liquid ammonia in a dual fuel setup [38]. MAN Energy solutions together with Shanghai Merchant Ship Design & Research Institute (SDARI) and American Bureau of Shipping (ABS) also has a development project for an ammonia-fueled feeder container vessel intended to use this technology. There is also an EU funded project, ShipFC, that aims to convert an offshore vessel to run on an ammonia fuel cell.

Ammonia is a toxic substance. Ammonia released into the atmosphere in high concentrations provides health risks and is lethal over certain concentrations and time periods. It may also contribute to formation of secondary particles. Ammonia is toxic for organisms living in water with potential long-term effects mainly in the case of direct exposure [11,28,36]. Ammonia in water will be converted into ammonium ions [36]. Ammonia released in the air will due to its lower density dilute and evaporate upwards; however, several factors influence how fast and to what extent ammonia diffuses

in the air [28]. Ammonia may, for example, also, as many other fuels, form explosive mixtures with air and hydrogen from cracked ammonia is a very flammable gas [36].

Leakage and potential exposure to humans and the environment (including aquatic life) represent key safety issues linked to ammonia used as marine fuel and specific safety regulations will be needed.

Ammonia is corrosive and this need to be considered in the design of marine fuel systems [38]. The safety regulations and associated safety measures will influence the fuel handling system for bunkering and during operation, likely increasing the cost but potentially also the use of the space on-board [24,35,36].

2.1.2. Potential Cost and Supply

From 2016 to mid-2019, the global ammonia price corresponded to a range of about 10–20 USD/GJ (using a lower heating value of 18.8 MJ/ton for ammonia) [39]. The production cost for renewable ammonia was estimated to range within about 7–23 USD/GJ ammonia by Tun et al. (2014) and in a forthcoming study by Hochman [40] the cost of renewable ammonia production in 2040 amounts to approximately 20 and 25–35 USD/GJ for electrochemical ammonia production and electrolysis of water followed by the HB synthesis in large and small scale, respectively.

The additional propulsion system cost for an ammonia-fueled vessel with an internal combustion engine has been estimated to approximately 2–60% compared to a conventional HFO-fueled vessel and in the case of fuel cells 8–300% due to large uncertainties about requirements [14].

Ammonia is more energy dense than compressed hydrogen and liquid hydrogen. It is normally stored in insulated pressurized tanks, which require larger space requirement onboard ships than LNG and methanol [8]. However, there is no need for cryogenic storage, which is required for liquefied hydrogen [10].

There does not seem to be any main issues with fuel infrastructure or bunkering related to ammonia as marine fuel. However, a well-functioning fuel infrastructure and bunkering systems need to be implemented.

In terms of reliable supply of fuel in order for ammonia to be used as marine fuel, the global production needs to be increased, in particular from renewable sources. This will require large amounts of electricity, but the production is not constrained by any other raw materials. For comparison, the current total global ammonia production could replace about 30% of the global shipping fuel consumption if assuming equal efficiencies when used in ship propulsion systems (calculated using [16,23,41]).

2.2. Energy Systems Modeling

The cost-effectiveness of ammonia compared to other alternative marine fuel options for reaching global climate targets is performed using energy systems modeling with the Global Energy Transition (GET) Model version 10.0 [42]. The GET model has in this study been developed by adding ammonia as marine fuel.

2.2.1. Model Structure and Main Assumptions

GET is a cost minimizing "bottom-up" systems model of the global energy system constructed as a linear programming problem with 10-year time steps and divided into 10 regions. The GET model is used to study various carbon mitigation strategies and the objective is to minimize the discounted total energy system cost for the studied period (in our case, 2010–2100) while meeting an externally defined energy demand and a carbon constraint [42]. The carbon constraint is in the form of a carbon budget corresponding to a maximum atmospheric CO_2 concentration by the year 2100. The model has a supply side focus but has five end use sectors covering electricity, transport, residential–commercial heat, industrial process heat, and feedstock.

In the GET-model, the included primary energy sources (primarily coal, oil, natural gas, nuclear, wind, hydro, solar energy, and biomass) are by different technologies converted into secondary energy

carriers (e.g., heat, electricity, and different transport fuels), used to supply the energy demand in the different sectors. Thus, the demand in each sector can be met by various technologies that are assumed to be available in all ten regions.

All the technologies are described by the energy carriers they can convert and estimates of their individual characteristics, e.g., costs (expressed in real terms), efficiencies, carbon emissions, and load factors. Scarcity of relevant resources, e.g., oil and biomass, are considered by maximal supply levels and are allocated endogenously to fulfill the demand in the sectors where the model finds it most cost-effective to use them. Carbon capture and storage (CCS) for stationary combustion of fossil fuels and biomass is included and linked to a maximum carbon storage capacity [42]. This applies also for fossil fuel-based ammonia production for which this option is available at a cost.

Scenarios for the demand in the different sectors, except transport, are based on the B2 scenarios from the IIASA GGI Scenario Database (for details, see Lehtveer et al. [42]). Transport includes demand for freight and personal transportation. For transport demand scenarios used for road, train, and aviation, see Grahn et al. [43]. Shipping is described in the next section. To better describe the real world, there are constraints included in the model on, e.g., how rapidly technologies can be introduced and expanded in the system (generally representing a turnover of 50 years for the entire system) and maximal extraction limits for the included energy sources.

The net present value calculations include a global discount rate of 5% per year. Since perfect foresight is assumed, the GET model identifies the least-cost solution for the entire period included in the assessment. The solutions for each region are aggregated to represent global results.

As with all models, the GET model represents a simplified description of the real energy system, for example by basing choices only on cost-effectiveness and perfect foresight, considering a limited number of technologies, and assuming a price inelastic demand. The model cannot be used to predict the future but is used to produce scenarios and assess the potential role of different options in relation to the development for other options in a carbon constrained world, potentially providing useful insights for industry, researchers, and policy makers.

2.2.2. Marine Fuel Options and Climate Targets

The marine fuel options included in the model are marine gas oil (MGO) and heavy fuel oil (HFO), liquefied natural gas (LNG), methanol (MeOH), hydrogen, and ammonia. For several of the fuels, different production pathways are possible. Methanol is used as a proxy for: (i) several different biofuels but represented by the characteristics of biomass-based methanol; (ii) fossil fuel-based methanol; and (iii) different kinds of electrofuels that are represented by the characteristics of the electro-methanol pathway. Electrofuels are fuels produced from CO_2 and water using electricity. Hydrogen can be produced from natural gas, biomass, or through electrolysis using electricity.

Ammonia is assumed to be produced by the HB process with nitrogen and hydrogen as feedstock, and thus requires the production of hydrogen through any of the possible pathways included. A conversion efficiency of the HB process of 74% is assumed and the process is assumed to be used 80% of the year. The current investment cost for ammonia production is estimated as 2100 USD/kW and is assumed to decrease to 1900 USD/kW in 2050 [42].

Onboard the ship, the fuels can be used in internal combustion engines (ICE) or fuel cells (FC). Thus, hybrid and electric engines are not considered in this study.

In the GET model, the shipping sector is divided in three ship categories: (i) short sea ships; (ii) deep sea ships; and (iii) container ships. The ship cost consists of the construction cost that depends on the cost of engines, fuel tanks, and other extra costs such as pipeline and gas alarm system. The propulsion efficiency of the ship depends on the ship type. The ship characteristics and the cost for the ammonia propulsion technologies included are presented in Table 1. A 30-year lifetime is assumed for all ship types.

For technology performance and costs of marine fuels besides ammonia, see Lehtveer et al. [42] and Taljegard et al. [6]. The total fuel cost is calculated based on the primary energy cost, engine

and other investment cost, conversion efficiency, capacity factor, operation and maintenance cost, distribution cost, and scarcity rent.

Table 1. Characteristics and costs for the propulsion technologies for ammonia for the three ship categories in 2050, based on estimates by Lövdahl and Magnusson [44] and Taljegard et al. [6].

Characteristics	Unit	Short Sea Ship	Deep Sea Ship	Container Ship
Engine power	kW_{output}	2400	11,000	23,000
Voyage range full speed	h	162	720	360
Tank capacity	GJ	3500	71,300	74,600
ICE engine cost [1]	USD/kW_{output}	800	600	600
ICE propulsion efficiency [1]	%, LHV	45	40	40
FC stack cost [2]	USD/kW_{output}	925	925	925
FC propulsion efficiency	% LHV	45	60	45
Storage cost [3]	USD/GJ	55	35	35
SCR cost for ICE	USD/kW_{output}	133	133	133

[1] Assumed equal to H_2 ICE. [2] Estimated as the mean value of the range 350–1500 USD/kW where the former represents low cost estimates for FC and 1500 USD/kW is the higher estimate of SOFC cost by van Biert et al. [45]. [3] Assumed to be half the storage cost for LNG estimated at 35 USD/GJ [6].

Our assessments are made with two different climate scenarios, 450 and 550 ppm. This means that we apply cumulative carbon emission constraints that correspond to atmospheric CO_2 concentrations in 2100 of 450 and 550 ppm roughly corresponding to 70% and 50% likelihood of keeping the global average warming below 2 °C. The model considers CO_2 emissions and methane leakage from the use of gas in engines (at 2%) is included as CO_2 equivalents.

2.2.3. Sensitivity Assessment: Monte Carlo Analysis

Cost developments (linked to fuel and propulsion technology and infrastructure) and other characteristics for new marine fuels are uncertain. In our assessment, key parameters include: (i) the investment costs for ammonia synthesis (including nitrogen generation) in 2050; (ii) the efficiency of ammonia synthesis; and (iii) the additional cost for different vessels compared to conventional marine gas oil fueled ships, which depend on engine cost, fuel cell cost, and additional storage cost. To confirm our findings related to ammonia as marine fuel, a Monte Carlo (MC) analyses, in which the values of these key parameters are varied within specific intervals, are performed. The intervals used for each parameter in the MC analysis are presented in Table 2. The parameter values are varied simultaneously and uniformly within these intervals for 100 model runs. The climate target is set to 450 ppm of CO_2 for the MC analysis.

Table 2. Intervals used for the Monte Carlo sensitivity analysis. The parameter values are varied simultaneously and uniformly within these intervals for 100 model runs. For assumptions and underlying references, see Lövdahl and Magnusson [44].

Parameters Changed	Unit	Minimum Value	Base Case Value	Maximum Value
Efficiency of ammonia production	%, LHV	68%	74%	80%
Ammonia production investment cost	USD/kW	1700	1900	2100
Additional cost compared to conventional MGO ship for different ship types:	kUSD/ship			
MGO FC Container ship		200	1500	2800
MeOH FC Container ship		200	1500	2800
Bio FC Container ship		300	1600	2900
LNG FC Container ship		400	1700	3000
H_2 FC Container ship		1300	2200	3100
NH_3 FC Container ship		200	1500	2800
NH_3 ICE Container ship		800	1100	1400

Table 2. *Cont.*

Parameters Changed	Unit	Minimum Value	Base Case Value	Maximum Value
MGO FC Deep sea ship		1000	7000	13,000
MeOH FC Deep sea ship		1000	7000	13,000
Bio FC Deep sea ship		2000	8000	14,000
LNG FC Deep sea ship		3500	10,000	16,500
H$_2$ FC Deep sea ship		12,000	16,000	20,000
NH$_3$ FC Deep sea ship		1000	8000	15,000
NH$_3$ ICE Deep sea ship		5000	6000	7000
MGO FC Short sea ship		200	1600	3000
MeOH FC Short sea ship		200	1600	3000
Bio FC Short sea ship		300	1500	2800
LNG FC Short sea ship		400	1700	3000
H$_2$ FC Short sea ship		400	1800	3200
NH$_3$ FC Short sea ship		200	1600	3000
NH$_3$ ICE Short sea ship		1200	1500	1800

2.3. Multi-criteria Decision Analysis

The range of MCDA methods is used to find the optimal and most consensual solution while considering both qualitative and quantitative information and stakeholders' preferences to different extent. The multi-criteria decision analysis approach based on the Analytic Hierarchy Process (AHP) and set up applied by Hansson et al. [9] is adapted and used in this study. This approach combines estimated fuel performance and input on criteria importance from a panel of maritime stakeholders.

AHP is chosen due to its strengths in combining quantitative and qualitative input data while specifically considering the views of different stakeholders and since it has been used in other studies of alternative marine fuels [9,18–20]. The chosen approaches rank marine fuel options based on their relative performance for included criteria and the relative importance of the criteria considering stakeholder preferences providing weights, in both cases by applying pairwise comparisons and resulting in pairwise comparison matrices [46,47]. For a more detailed description of the method used, see below and further in Appendix A and Hansson et al. [9].

The main difference to the assessment by Hansson et al. [9] is that two production pathways for ammonia are included as fuel option both for ICEs and fuel cells in ships (i.e., four more options).

2.3.1. Marine Fuel Options and Criteria

In total, 11 alternative marine fuel options—liquefied natural gas (LNG), liquefied biogas (LBG, from organic waste), methanol from natural gas (NG-MeOH), renewable methanol (renewable MeOH, from willow), hydrogen for fuel cells produced from natural gas (NG-H$_2$) or electrolysis based on renewable electricity (elec-H$_2$), hydrotreated vegetable oil (HVO, from tall oil), and ammonia for both fuels cells and ICEs produced from natural gas (NG-NH$_3$) or electrolysis based on renewable electricity (elec-NH$_3$)—are included. The other fuels are assumed used in ICEs.

The 11 fuel options are ranked by ten different performance criteria that influence the choice of marine fuel and their relative importance based on stakeholder preferences. The performance criteria include economic, environmental, technical, and social aspects. The following criteria are included, and described in Table 3: (i) investment cost for propulsion; (ii) operational cost; (iii) fuel price; (iv) available infrastructure; (v) reliable supply of fuel; (vi) acidification; (vii) health impact; (viii) climate change; (ix) safety; and (x) upcoming legislation. The time perspective of the MCDA is 2030 and the focus is on deep sea shipping. The specific criteria were selected through a survey for Swedish maritime stakeholders [9,48].

Table 3. Description of the criteria included in the multi-criteria decision analysis (MCDA).

	Criterion	Description
Economic	Investment cost for propulsion	Defined as capital cost of propulsion and associated on-board infrastructure per installed engine capacity in terms of power output and includes cost of engines, fuel tanks, pipelines, etc., on-board.
	Operational cost	Includes crew related cost and maintenance insurance cost.
	Fuel cost	Defined as the estimated relative cost differences of the fuels based on estimates of production costs, raw-material prices, and production efficiencies but the efficiency of the propulsion is also considered.
Technical	Available infrastructure	Defined as compatibility with current infrastructure including storage, distribution, and bunkering facilities as well as maturity level of the propulsion technology.
	Reliable supply of fuel	Includes availability of raw material, existing production and use, and energy security.
Environmental	Acidification	Acidification potential due to NOx and SO_2 emissions from fuel combustion.
	Health impact	Defined as particulate matter (PM) formation potential from combustion (in terms of $PM_{2.5}$-equiv.).
	Climate change	Global warming potential (GWP100) for emissions of CO_2, methane (CH_4), and nitrous oxide (N_2O) in lifecycle perspective.
Social	Safety	Includes risk of fire, explosion, and health hazards related to fuel handling, considering fuel properties such as toxicity.
	Upcoming legislation	Defined as the likelihood for meeting known and future emission regulations.

2.3.2. Comparison of Marine Fuel Performance

The characteristics of the included marine fuels are mapped through a literature review. The information used to represent the various criteria for the ammonia pathways are presented in Table 4. Data for LNG are included for comparison. For assumptions related to the non-ammonia fuel options, the reader is referred to Hansson et al. [9] and, for underlying assumptions linked to ships, see Table 1.

For four criteria (available infrastructure, reliable supply of fuel, safety, and upcoming legislation) that are difficult to represent by a single quantitative parameter, a four-level scale (1–4, representing poor, moderate, fairly good, and good) is used for grading underlying aspects (see Table 5) and the average of this grading represent the criteria. The grading for the aspect available infrastructure is based on a judgement from a panel of experts, provided specifically for this study including shipowners, an ammonia producer, a fuel producer and supplier, and marine fuel experts. In the MCDA assessment as well, the other criteria are converted to the range 1–4, where 1 represents the lowest value and 4 the highest, while the remaining parameter values are expressed as their relative value since the relative relation between the options represents a central feature of the assessment. The marine fuel options are then compared and scored, based on their relative estimated performance.

Table 4. Marine fuel performance for the included ammonia fuel options produced from natural gas (NG-NH$_3$) or electrolysis based on renewable electricity (elec-NH$_3$) and for use in fuels cells (FC) and internal combustion engines (ICE) and liquefied natural gas (LNG).

	NG-NH$_3$ FC	Elec-NH$_3$ FC	NG-NH$_3$ ICE	Elec-NH$_3$ ICE	LNG
Capital cost for the propulsion system (USD$_{2015}$/kW)	5300–11,400 [1]	5300–11,400 [1]	5200–7710 [1]	5200–7710 [1]	5100–7710 [6,42]
Operational cost (USD$_{2015}$/MWh)	11 [2]	11 [2]	9 [2]	9 [2]	9 [49]
Indicative fuel cost in 2030 (USD$_{2015}$/GJ) [3]	27 [6,39,50–53]	35 [54]	27 [6,50,51]	35 [54]	7 [6,50,51]
Available infrastructure [4]	1.5	1.5	1.5	1.5	2.4
Reliable supply of fuel [4]	2.2	2.8	2.2	2.8	2.6
Acidification potential (mole H+ equiv./MJ fuel) [5]	0 [6]	0 [6]	2×10^{-4} [7]	2×10^{-4} [7]	8×10^{-5} [55–57]
Health impact as PM$_{2.5}$ equivalents (mg/MJ) [8]	0	0	3.4 [9]	3.4 [9]	1.4 [55–57]
Climate change entire lifecycle, GWP100 (g CO$_2$-equiv /MJ) [10]	140	30	140	30	80 [56–59]
Safety [4]	2.3 [11]	2.3 [11]	2.3 [11]	2.3 [11]	2.5 [11]
Upcoming legislation [4]	3.6 [12]	3.9 [12]	3.0 [12]	3.3 [12]	2.9 [12]

[1] SCR technology is assumed applied for the ICE alternatives (at 133 USD/kW), assumed ICE engine price 600 USD/kW and SOFC price 925–1315 USD/kW [44]. Storage cost is assumed to be in the range from half of the LNG storage cost to the same as the LNG storage cost estimated at 35–70 USD/GJ [6]. [2] Assumed to have slightly higher operational cost than LNG, but lower than H$_2$ [6]. [3] 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. [4] A four-level scale (1–4, representing Poor, moderate, fairly good, and good) is used for grading underlying aspects for these parameters and the average value represent the criteria. For some aspects this is partly based on judgement from a panel of experts. Available infrastructure is for input on current loading infrastructure of ammonia in ports based on [24]. [5] Acidification potential is based on NOx and SO$_2$ emissions from combustion using characterization factors for NOx and SO$_2$ resulting in 0.74 and 1.31 mol of charge (mole) per kg substance emitted respectively [60,61]. [6] For ammonia used in fuel cells, there is a risk of nitrogen oxides (NO$_X$) and N$_2$O emission but, due to the lack of quantitative data, zero emission is used here. There is also a risk of ammonia emissions for all ammonia pathways potentially influencing acidification but due to lack of data that has not been considered in this study. [7] Assumed to have the same level of acidifying emissions as LNG. [8] 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. Characterization factors for PM$_{10}$, SO$_2$, and NO$_X$ are 0.2278, 0.0611, and 0.0072, respectively [61]. [9] Assumed to be associated with the same level of PM$_{2.5}$ equivalents emissions as MeOH ICE [9]. [10] Estimated based on emission data by Bicer and Dincer [62], Kramer et al. [63], and Wood [64]. [11] Based on safety data in various ammonia safety sheets and Zamfirescu and Dincer [65]. [12] Based on Ash [24], Bartels [66], and Reiter and Kong [67].

Table 5. Expert evaluation of the underlying aspects of the criteria "available infrastructure", "reliable supply of fuel", "safety" and "upcoming legislation". The scale 1–4 (poor, moderate, fairly well, and good) is applied and for the underlying aspects linked to "available infrastructure" the average evaluation is presented with range given in parenthesis.

	NG-NH$_3$ FC	Elec-NH$_3$ FC	NG-NH$_3$ ICE	Elec-NH$_3$ ICE
Available infrastructure				
Compatibility to existing infrastructure	1.86 (1–3)	1.86 (1–3)	1.86 (1–3)	1.86 (1–3)
Adaptability to existing ships	1.57 (1–2)	1.57 (1–2)	1.57 (1–2)	1.57 (1–2)
Engine technology maturity	1.71 (1–3)	1.71 (1–3)	1.71 (1–3)	1.71 (1–3)
Current amount of storage and bunkering capability	1	1	1	3
Reliable supply of fuel				
Raw material availability	3	4	3	4
Current production	4	1	4	1
Current use as marine fuel	1	1	1	1
Energy security 1: Global supply potential distribution	1	4	1	4
Energy security 2: Political stability	2	4	2	4

Table 5. *Cont.*

	NG-NH$_3$ FC	Elec-NH$_3$ FC	NG-NH$_3$ ICE	Elec-NH$_3$ ICE
Safety				
Risk of explosion or fire	3	3	3	3
Toxicity	1	1	1	1
Health hazards	1	1	1	1
In terms of cryogenic liquid	4	4	4	4
Upcoming legislation				
Sulphur dioxide (SO$_2$) global 2020	4	4	4	4
NO$_X$ Tier III	4	4	2	2
IMO 2050 GHG target (exhaust emissions)	4	4	4	4
IMO 2100 GHG targets (life cycle perspective)	1	4	1	4
Particle mass	4	4	3	3
Particle numbers	4	4	2	2
Methane emissions	4	4	4	4
Ammonia emissions	3	3	3	3
Scrubber ban	4	4	4	4

2.3.3. Weighting of Criteria

The weights of the different criteria applied in this study are based on Hansson et al. [9] and Månsson [48]. These weights were settled during a workshop with a group of shipping related stakeholders. The stakeholders included ship-owners, engine manufacturers, fuel producers, Swedish government authority representatives, and relevant researchers.

Weightings were produced individually and in groups representing the preferences of: (i) ship-owners; (ii) fuel producers; (iii) engine manufacturers; and (iv) Swedish government authorities. The base case, representing the "combined view" of the stakeholders is based on the weighted geometric mean of all stakeholders individually produced pairwise comparison matrices for the included criteria showing their individual preferences.

In terms of outcome for the relative importance of the overall criteria, the economic criteria are the most important, followed by social and environmental criteria for the combined group. Ship-owners, fuel producers, and engine manufacturers also value economic criteria the highest, but followed by social and technical aspects for ship-owners while technical and social for the other groups. On the other hand, government authorities value environmental and social aspects most, followed by economic criteria.

In terms of outcome for the relative importance of each criterion, fuel cost is, as expected, the most important economic criterion (followed by investment cost), and reliable supply the most important technical criterion, for all stakeholder groups. As environmental criterion climate change is considered the most important, except for engine manufacturers that give health impact higher weight. In terms of social criterion, upcoming legislation is the most important except for ship-owners that value safety most.

As the final step of the MCDA, the included fuel options are ranked based on the scoring of alternatives and the criteria weighting, i.e., by combining the pairwise comparison matrices (linear combination of normalized priority vectors) produced following the AHP approach. For more details on the method, see Appendix A. The influence of different criteria weights on the final fuel ranking (outcome of the MCDA) is assessed with the weightings of the different stakeholder groups. This represents the sensitivity analysis of the MCDA assessment.

3. Results

3.1. Cost-effective Future Marine Fuel Options

In the beginning of the studied time period, the use of MGO and LNG in ICEs dominates the fuel use in the shipping sector. In the 450-ppm scenario, the use of MGO starts to decrease from 2020 and

is almost phased out by 2100. The use of LNG in ICEs increases but peaks around 2040; thereafter, it decreases and instead LNG in FCs are introduced to some extent. Further, from 2050, the use of hydrogen in FCs increases substantially replacing the major share of all other fuels. The development until 2040 is similar in the 550-ppm scenario. However, in this scenario, LNG in FCs becomes the dominating fuel, replacing most of the MGO and LNG in ICEs while H_2 in FCs is found cost-effective first from around 2080. The cost-effective fuel options for shipping in 2050 and 2070 for the two climate scenarios in energy terms are presented in Figure 1. The share of different fuel options of the total fuel use for shipping in 2050 and 2070 for the two climate scenarios are also presented in Figure 1.
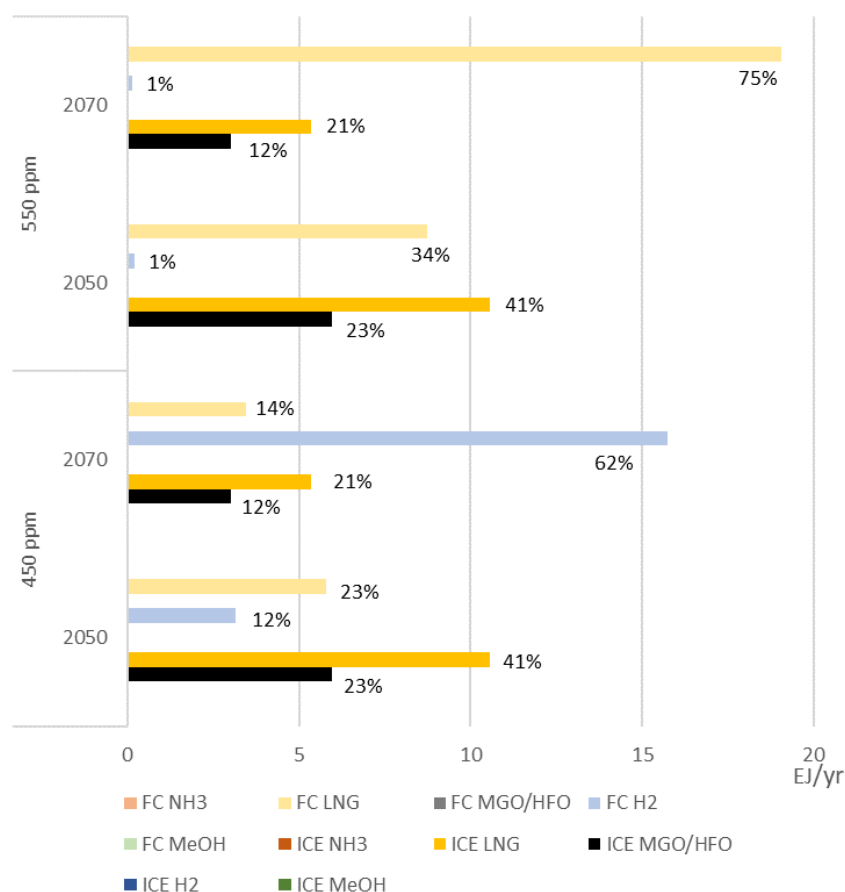
Figure 1. Fuel volumes (in EJ/year) for different fuel/powertrain combinations in cost-effective fuel choices for shipping in 2050 and 2070 for the two climate scenarios 450 and 550 ppm. The share of different fuel options of the total fuel use for shipping (in percentage) in the four cases are presented at the end of each bar. FC, fuel cells; ICE, internal combustion engine; MGO/HFO, conventional fossil oil; LNG, liquefied natural gas; NH_3, ammonia; H_2, hydrogen; MeOH, biofuels, fossil MeOH, and electro-methanol.

To summarize, the energy systems modeled indicate that in climate scenarios the use of oil-based marine fuels decreases as expected and in the short-term natural gas-based fuels in the form of LNG represent cost-effective fuel choices. However, in the long-term and in the case of more stringent climate targets, the use of hydrogen represents the most cost-effective option for the shipping sector, thus being more cost-effective than ammonia. The reason is that, although ammonia has significantly lower storage costs on container ships, this does, in our model setup, not outweigh the additional cost of converting hydrogen to ammonia in a system perspective. For example, in terms of electricity demand, in the case of renewable ammonia produced from electricity, it is estimated that an electricity input of 3–4 times the actual work propelling the ship is needed.

Biofuels and methanol pathways do not turn out to be cost-effective fuel options in the shipping sector either. The reason is that the biomass is used for other energy sectors, which with the given model set up is found more cost-effective.

The Monte-Carlo analyses performed on efficiency and investment cost of ammonia production as well as ship costs also confirm that this finding does not seem to be sensitive to key parameter values since only very marginal amounts of ammonia are introduced in these runs. Thus, using hydrogen in the case of stringent climate targets turns out to be more cost effective in all cases.

3.2. Ranking of Marine Fuels Based on the MCDA Assessment

The relative performances of the included marine fuels for the different criteria is presented in Figure 2. A high value represents a better performance, e.g., lower cost, lower emissions, higher level of reliable supply of fuel, etc. None of the investigated options performs best for all criteria. Ammonia produced from renewable electricity and used in fuel cells has comparable performance to hydrogen produced from renewable electricity used in fuel cells. Ammonia used in ICEs has worse performance related to acidification and health impacts and ammonia produced from natural gas has worse performance connected to climate change.
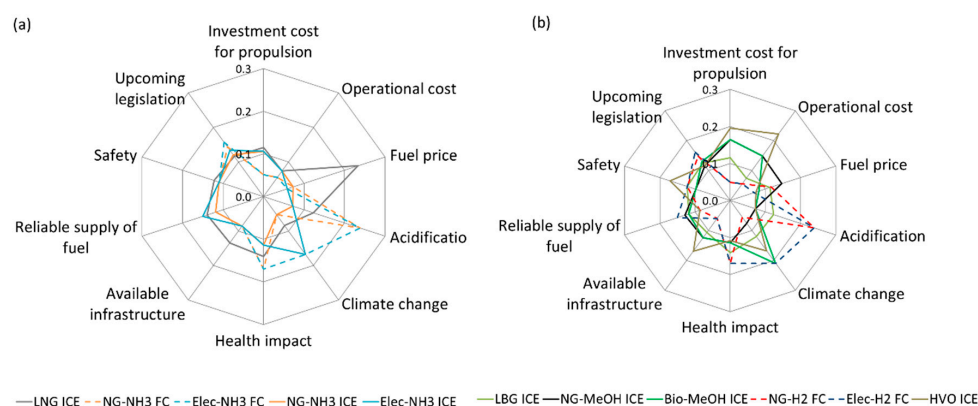

Figure 2. Relative marine fuel performance for each criterion: (**a**) the ammonia fuel options and LNG; and (**b**) the remaining fuel options. Higher values represent better performance.

The rankings of the studied marine fuels for the combined stakeholder group and for the different stakeholder subgroups are presented in Figure 3 and the ranking order for the ammonia options is in Table 6. The presented ranking is valid for the assumptions linked to criteria and performance made in this study.

For the combined stakeholder case, LNG is ranked highest with hydrotreated vegetable oil (HVO ICE) second, and then renewable hydrogen in fuel cells (Elec-H$_2$ FC). Renewable ammonia in fuel cells (Elec-NH$_3$ FC) and in internal combustion engines (Elec-NH$_3$ ICE) are ranked fifth and eighth, respectively, while natural gas-based ammonia ends up in the bottom of the ranking. For ship-owners, fuel producers, and engine manufacturers, LNG is ranked highest followed by natural gas-based methanol (NG-MeOH ICE). The ammonia options end up in the bottom or lower part of the ranking for all these stakeholder groups (seventh or lower) and there are only minor differences between the other included fuel options. The main reason behind the similar ranking for these stakeholder groups is their relatively high weight on economy and particularly fuel cost and similar weighting overall. The views of governmental authorities result in Elec-H$_2$ FC being ranked highest followed by Elec-NH$_3$ FC, but here biomass-based methanol (Bio-MeOH ICE) is in third place, HVO ICE in fourth place, and Elec-NH$_3$ ICE in fifth place. The reason for this is that these stakeholders consider GHG emissions and the potential to meet regulations as the top criteria. The natural gas-based ammonia options are in the bottom of the ranking for governmental authorities.
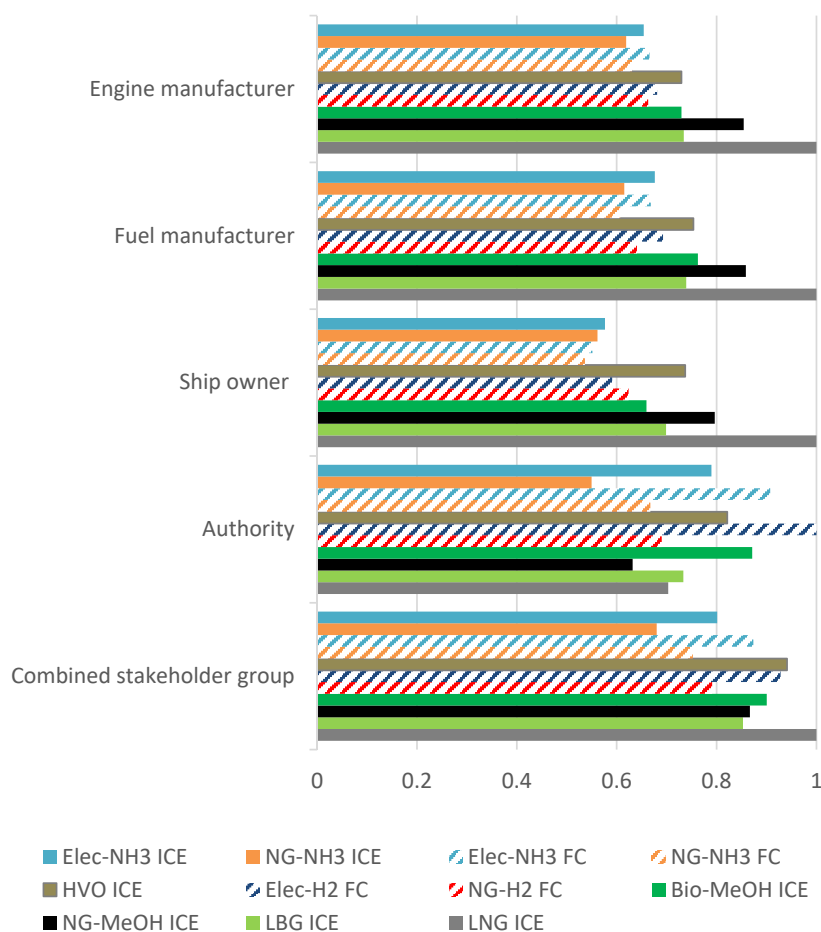
Figure 3. Ranking of the studied marine fuels for the combined stakeholder group and for the different stakeholder groups. The value "1" is assigned to the fuel ranked the highest and the values for the other fuel are expressed relative to the fuel ranked the highest.

Table 6. Ranking order of the ammonia fuel options (from 1 to 11, where 1 indicates highest ranking) in the different stakeholder groups.

Fuels	Combined Group	Gov. Authorities	Ship-Owner	Fuel Producer	Engine Manufacturer
NG-NH$_3$ FC	10	9	11	11	10
Elec-NH$_3$ FC	5	2	10	8	7
NG-NH$_3$ ICE	11	11	9	10	11
Elec-NH$_3$ ICE	8	5	8	7	9

4. Discussion

To support a demand for ammonia as fuel in shipping, the production of renewable ammonia needs to increase substantially. As ammonia is currently mainly used for fertilizer production, this might lead to competition with potentially higher ammonia prices and higher food prices at least in the short-term. However, compared to biofuels, large-scale production of renewable based electricity needed for renewable ammonia production does not have the same physical restrictions.

Currently, the price related to energy content of ammonia is substantially higher than for MGO and LNG. However, when comparing future cost estimates of alternative marine fuels, the price for ammonia is expected to be in almost the same range as hydrogen.

Regarding performance of ammonia as a fuel, there are remaining issues with ignition, specific fuel consumption, materials, and emissions linked to ammonia as marine fuel. Emissions from the use

of ammonia as fuel can possibly be dealt with and the engines can be improved. However, before ammonia can be used on ships further demonstrations of emissions and efficiencies are called for. There are also remaining issues linked to safety that is a major concern when considering ammonia as a fuel. Firm rules for design of ammonia systems and for the handling of such systems are needed in order to avoid negative impacts. It remains to conclude if safety issues will represent a key obstacle for ammonia as marine fuel.

Although ammonia is not considered to be the most cost-effective option in the GET model in this study, ammonia may still be of interest for marine applications, as indicated by the MCDA. For example, the current version of the GET model does not consider the possibility to produce ammonia directly from hydrogen without compression or liquefaction. Including this might influence the result for ammonia. In addition, it is possible that the shipping sector in the future will not be dominated by only one alternative fuel but a combination of fuels. The introduction of dual-fuel engines supports this, and this might improve the prerequisites for ammonia as marine fuel. There might also be situations where ammonia becomes a cost-effective option also in future energy scenarios developed with cost-minimization. For example, if hydrogen liquefaction, storage, distribution, and use in fuel cells turns out to be more expensive than expected while the ammonia production process improves, the use in ICEs ammonia might be more attractive.

In addition, unexpected development for other options in the shipping as well as other sectors might also influence the outcome since the development in other sectors influences the cost-effective fuel choices in the shipping sector. Future cost estimates are always uncertain and assuming a higher cost for individual parts of the chain might also change the cost-effectiveness of ammonia vs. hydrogen. The sensitivity analysis performed tests uncertainties linked to some of the parameter values. However, more sensitivity assessments might yield more insights. For example, costs linked to liquefaction of hydrogen (which is needed for use in ships) and cost for converters should be studied more. It should also be remembered that the GET model is not used to predict the future but to understand how future fuel choices are influenced by different assumptions.

The modeling and scenario development by ben Brahim et al. [22] indicate that changes in costs for a specific fuel technology influences the outcome to a large extent; for example, in the case of a 20% reduction in costs for ammonia or methanol, they would take over the role of hydrogen as the main renewable fuel in their scenarios. However, in our energy systems modeling, the prospects for ammonia is not found sensitive to changes in costs to the same extent with the given set up and sensitivity assessments made. The reason might be the different system boundaries, the focus on Danish shipping in the study by ben Brahim et al. [22] vs. the total global energy system in this study or different assumptions regarding fuel cost relations and how linked they are.

The ranking of the included alternative marine fuel options varies depending on the preferences among stakeholder groups. The ranking in this study is only valid for the included criteria, i.e., extending with additional criteria may change the ranking. The key insight from the MCDA assessment is that ammonia is only ranked high for governmental authorities and to some extent for the total stakeholder group and then primarily renewable ammonia in fuel cells. It is also important to note that the ranking is very sensitive to assumption about the fuel prices in 2030; a change in the relative fuel prices has the potential to change the overall ranking in the MCDA.

From an overall perspective in the MCDA, using ammonia in fuel cells seems to perform better than ammonia in internal combustion engines. This is partly due to the higher efficiency of the fuel cells but also due to better performance in terms of health impact and acidification, and it is therefore somewhat more likely that the fuel cell pathway will meet upcoming legislation However, ship owners and fuel producers rank ammonia in ICEs somewhat higher than corresponding FC options. Thus, this relation should be further assessed as more certainty in cost, performance, etc. becomes available.

Further sensitivity assessment of the parameter values judged most uncertain would also be valuable (i.e., to change the scoring of selected criteria). For example, estimating the fuel price in 2030

is very difficult. It would be interesting to further test the influence on the fuel ranking in the MCDA of changes in the fuel prices.

The fuel ranking is also influenced by the selection of criteria. Adding more criteria may change the outcome to some extent. The impact in terms of fuel ranking will depend on the performance and weight of the new criteria in comparison to the already included criteria and is not possible to predict. However, the criteria included in this study cover several key aspects, and it is not clear that a larger number of criteria will clarify the role of ammonia. However, it would be interesting to specifically study the effect on cargo capacity, more issues related to the toxicity of ammonia, and the impact of current investments. Thus, the criteria included in the MCDA cover a limited number of all sustainability aspects related to marine fuels and the study should not be seen as a complete sustainability assessment.

Ammonia from natural gas with CCS is another option with potentially low climate impact and could be further assessed in future studies. Policy makers need to consider that some ammonia routes are more beneficial than others and make sure that policy and regulations promote these pathways.

To conclude, in the long-term and to reach global GHG reduction, the energy systems modeled in this paper indicate that the use of hydrogen represents a more cost-effective option for the shipping sector than ammonia. However, in the MCDA covering more aspects but with a shorter time perspective, we find that ammonia may be almost as interesting for shipping related stakeholders as hydrogen and various biomass-based fuels. Due to primarily the potential low climate impact, ammonia has potential as a future marine fuel, but many issues remain to be solved before it can be introduced in large-scale, and more detailed additional assessments and comparisons are needed. The following future research areas are suggested:

- In-depth assessments of ammonia as marine fuel from a system perspective comparing ammonia with other potential marine fuel options and considering technical and economic feasibility, safety, and environmental performance are needed.
- Feasibility studies could assess the possibility of introducing ammonia as a marine fuel covering assessments of fuel systems, bunkering, safety routines, etc.
- Demonstration projects could convert marine engines to use ammonia as fuel.
- Demonstration projects could test fuels cells in combination with ammonia to show a business case regarding costs and durability.
- Additional assessments with an energy-system perspective with more detailed representation of the shipping and aviation sector will increase understanding about under which circumstances different renewable marine fuels are cost-effective and interesting for different parts of the shipping sector.

A large-scale introduction of alternative marine fuels, ammonia as well as others, needs to be supported by policy measures. The choice and design of these policies will also influence the prerequisites for different marine fuels. Thus, policy analysis clarifying the impact of different policies and policy designs on different marine fuel options are also needed.

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List of Abbreviations

Abbreviation	Meaning
AHP	Analytic Hierarchy Process
CCS	Carbon capture and storage
CH_4	Methane
CI	Compression ignition
CO_2	Carbon dioxide
Elec-H_2	Hydrogen from electrolysis based on renewable electricity
Elec-NH_3	Ammonia from electrolysis based on renewable electricity
FC	Fuel cell
GET	Global Energy Transition Model
GHG	Greenhouse gas
GWP100	Global warming potential over 100-year time horizon
H_2	Hydrogen
HB	Haber–Bosch
HFO	Heavy fuel oil
HVO	Hydrotreated vegetable oil
ICE	Internal combustion engine
IMO	International Maritime Organization
LBG	Liquefied biogas
LNG	Liquefied natural gas
MCDA	Multi-criteria decision analysis
MeOH	Methanol
MGO	Marine gas oil
NG	Natural gas
NG-H_2	Hydrogen from natural gas
NG-MeOH	Methanol from natural gas
NG-NH_3	Ammonia from natural gas
NH_3	Ammonia
N_2O	Nitrous oxide
NO_X	Nitrogen oxides
PEM FC	Proton-exchange membrane fuel cell
PM	Particulate matter
SCR	Selective Catalytic Reduction
SI	Spark ignition
SO_2	Sulphur dioxide
SOFC	Solid oxide fuel cells
USD	US dollar

Appendix A. Pairwise Comparisons in the Analytic Hierarchy Process (AHP)

The pairwise comparison matrices for the included criteria applied in this study are expressed in mathematical terms by Equation (A1) where $a_{ij} > 0$ expresses the degree of preference of aspect x_i to x_j using the fundamental scale of absolute numbers for intensities defined by Saaty in AHP (Table A1).

$$PCM = \left(a_{ij}\right)_{n \times n} \qquad PCM = \begin{pmatrix} a_{11} & a_{12} & \cdots & a_{1n} \\ a_{21} & a_{22} & \cdots & a_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ a_{n1} & a_{n2} & \cdots & a_{nn} \end{pmatrix} \qquad (A1)$$

Table A1. Fundamental scale of absolute numbers used in pairwise comparisons of alternatives and criteria defined by Saaty in AHP [47].

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 the highest possible

A consistency check of the comparisons in the matrices is done by solving the characteristic equation (Equation (A2)). The maximum eigenvalue, λ_max, is used for calculating a consistency index (CI), Equation (A3), and thereafter a consistency ratio (CR), Equation (A4), where n is the size of the pairwise comparison matrix and RI_n a random index.

$$\det(PCM - \lambda \cdot I) = 0 \tag{A2}$$

$$CI(PCM) = \frac{\lambda_{max} - n}{n - 1} \tag{A3}$$

$$CR(PCM) = \frac{CI(PCM)}{RI_n} \tag{A4}$$

The normalized priority vector is for each matrix calculated as the geometric mean divided by the sum of the priorities. Based on the individual stakeholder pairwise comparison matrices, group priority vectors are constructed by aggregation of individual priorities assuming equal importance and using the weighted geometric mean. The normalized priority (i.e., relative importance) for each criterion is presented in Table A2. The final ranking of the alternative marine fuels is then derived by linear combination of the group priority vectors and the normalized priority vector from the pairwise comparison.

Table A2. Relative importance of the criteria expressed as normalized priorities (rounded figures) based on the pairwise comparisons of the criteria performed by the stakeholders individually and for the stakeholder groups.

Criteria	Combined Case	Authorities	Ship-Owners	Fuel Producers	Engine Manufacturers
Investment cost	0.26	0.25	0.20	0.23	0.23
Operational cost	0.16	0.25	0.07	0.12	0.12
Fuel cost	0.58	0.50	0.73	0.65	0.65
Available infrastructure	0.29	0.17	0.20	0.20	0.20
Reliable supply of fuel	0.71	0.83	0.80	0.80	0.80
Acidification	0.21	0.19	0.10	0.11	0.26
Health impact	0.30	0.08	0.23	0.31	0.64
Climate change	0.50	0.73	0.67	0.58	0.11
Safety	0.48	0.25	0.80	0.17	0.17
Upcoming legislation	0.52	0.75	0.20	0.83	0.83

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