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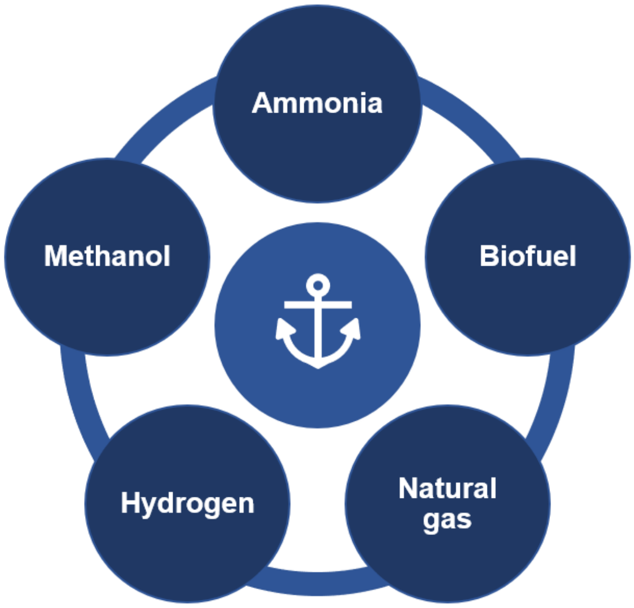

Evaluation of Ammonia as a Potential Marine Fuel

Modelling and assessment of alternative marine fuels for reducing GHG emissions from shipping

Master's thesis in Sustainable Energy Systems

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Department of Mechanics and Maritime Technology
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Gothenburg, Sweden 2019

Master's thesis 2019:NN

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Cover: Figure showing alternative fuels investigated in this thesis.

Printed by Chalmers University of Technology
Gothenburg, Sweden 2019

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Abstract

Alternative marine fuels are needed to mitigate emissions from the shipping sector in order to fulfil climate targets set by the International Maritime Organisation. This study assesses the potential of ammonia as a fuel for shipping compared to other alternative marine fuels by conducting energy systems modelling by the global energy transition (GET) model and a multi-criteria decision analysis (MCDA) with stakeholder preference taken into account. This contributes to an initial assessment of cost-effective fuel choices in the shipping sector and what marine fuel that is preferred when assessing economic, environmental, social and technical impacts with weights of criteria provided by stakeholders. Besides ammonia, the alternative marine fuels considered in this study are: liquefied natural gas (LNG), hydrogenated vegetable oil (HVO), methanol (MeOH) and hydrogen (H_2). The GET model perform simulations with constraints of the atmospheric CO_2 concentration that must be fulfilled by year 2100. Two scenarios of different constraints, 450 ppm and 550 ppm CO_2, are conducted with results stating that the most cost-effective shipping fuels at the end of the studied time period are H_2 and LNG in combination with fuel cells (FC) as propulsion technology. Ammonia is cost-effective as a shipping fuel under both constraints but only to a limited extent. In the MCDA other criteria than economic performance are introduced and the evaluation is performed by the Analytic Hierarchy Process. Eleven fuel options are included in the MCDA, combining different feedstocks, production methods and propulsion technologies; internal combustion engine (ICE) or fuel cell (FC). There are four ammonia options included representing if ammonia is produced from either electrolysis based or natural gas based hydrogen and combined with either ICEs or FCs. The MCDA results in a ranking where the most preferred fuel option is hydrogen produced by electrolysis and combined with FC. Ammonia combined with FCs also perform well and end up in 2nd and 4th place, while the ammonia options with ICEs are found in the bottom of the ranking in 9th and 11th place. The results of this thesis implies that several alternative marine fuels show potential, however further assessments are needed to draw firm conclusions about the potential of ammonia as an alternative marine fuel.

Keywords: Ammonia, Alternative Marine Fuels, Shipping sector, Global Energy Transition Model, Multi-Criteria Decision Analysis.

Acknowledgements

This master thesis was performed at IVL Swedish Environmental Research Institute (Gothenburg, Sweden) within the scope of the following projects:

i) The potential of ammonia as fuel for shipping – Pre-study funded by the Swedish Transport Administration via the trade program Hållbar Sjöfart (Sustainable Shipping) coordinated by Lighthouse, and

ii) Shift – Sustainable Horizons in Future Transport funded by Nordic Energy Research.

We would like to thank our supervisors Julia Hansson and Selma Brynolf for their guidance and support throughout this thesis, their positive attitude and competence has inspired and challenged us. We would also like to thank Mariliis Lehtveer who has helped us perform the simulations with the GET model. Further we would like to thank our examiner Erik Fridell for his valuable input and experience.

Josefin Lövdahl & Maria Magnusson, Gothenburg, June 2019

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Abbreviations

Marine fuels

Bio-MeOH	Methanol produced from biomass
Elec-H_2	Hydrogen produced by electrolysis
Elec-NH_3	Ammonia produced with hydrogen produced by electrolysis
H_2	Hydrogen
HFO	Heavy Fuel Oil
HVO	Hydrogenated Vegetable Oil
LBG	Liquefied Biogas
LNG	Liquefied Natural Gas
MeOH	Methanol (CH_3OH)
MGO	Marine Gas Oil
NG-H_2	Hydrogen produced from natural gas
NG	Natural Gas (CH_4)
NG-MeOH	Methanol produced from natural gas
NG-NH_3	Ammonia produced with hydrogen produced by natural gas
NH_3	Ammonia

Methodological

AHP	Analytic Hierarchy Process
GET	Global Energy Transition model
MC	Monte Carlo
MCDA	Multi-Criteria Decision Analysis

Organisations

IMO	International Maritime Organisation
UN	United Nations
UNCTAD	United Nations Conference on Trade and Development

Technical

ASU	Air separation unit
FC	Fuel Cell
HB	Haber-Bosch Process
HHV	Higher Heating Value / Gross Calorific Value
ICE	Internal Combustion Engine
LHV	Lower Heating Value / Net Calorific Value
SCR	Selective Catalytic Reduction

SMR	Steam Methane Reforming
SOFC	Solid Oxide Fuel Cell

Various

BAU	Business As Usual
CAPEX	Capital Expenditures
ECA	Emission Control Area
EEDI	Energy Efficiency Design Index
GHG	Greenhouse Gases (CO_2, CH_4, N_2O)
GWP	Global Warming Potential
N_2O	Nitrous oxide
OPEX	Operating expenses
PM	Particulate Matter

1
Introduction

In this chapter the background and purpose of this thesis is presented. The main research questions are defined as well as the project scope and demarcations. Included is also a section explaining the outline of this thesis.

1.1 Background

In year 2012 the total emissions from the shipping sector accounted for approximately 2.2% of the global CO_2 emissions, and 2.1% on a CO_2-equivalent basis when emissions of CH_4 and N_2O also were taken into consideration [1]. Between the years 2005 and 2017 the average annual increase of seaborne trade was 3.5%, and future projections by UNCTAD estimate an average annual increase by 3.8% for the years 2018 to 2023 [2]. Due to the forecast of the growth in seaborne trade, the emissions of CO_2 from the shipping sector has been projected to increase somewhere between 50% and 250% until year 2050 when the International Maritime Organisation (IMO) has been simulating different business as usual (BAU) scenarios. In the modelled BAU scenarios it is estimated that current energy efficiency- and emission policies are kept in use and that no other policies are introduced. The range of the increase vary depending on the energy-, efficiency- and economic development assumed for the different scenarios during the modelled time period [1].

The projected increase of greenhouse gas (GHG) emissions from the shipping sector must be countered by the shipping industry taking actions to reduce the emissions since an increase of GHGs pose a threat of raising the global temperature compared to pre-industrial time. There has been many negotiations in the United Nations (UN) during the last two-three decades regarding climate change, and the latest agreement was decided upon in Paris 2015 where almost all members of the UN accepted to work towards limiting the increase of the global temperature by 1.5°C. Based on the Paris Agreement, the IMO declared a strategy in 2018 with the aim of reducing GHG emissions from the shipping sector with 50% by year 2050 compared to emissions in 2008. There is also a need to restrict other types of emissions from shipping, such as sulphur and particles [2].

In recent years, the shipping industry has started to focus more on reducing emissions and the IMO has been an important actor for influencing this by introducing new policies and regulations. Some examples are the Energy Efficiency Design Index (EEDI) for new ships, while for existing ships the Ship Energy Efficiency Management Plan (SEEMP) has been introduced together with Emission Control Areas (ECA) [3]. In January 2020 a global sulphur cap will come into force by limiting the sulphur content in fuel oil to 0.5% and thus limit the emissions of SO_x [2][4]. To further succeed in reducing the emissions of GHGs and other air pollutants, there is a need for technology and energy efficiency measures combined with alternative fuels [3].

An emerging potential alternative marine fuel for transportation in the shipping sector is ammonia (NH_3). Ammonia is a carbon-free molecule and therefore possess the possibility of being CO_2 neutral from a tailpipe emission perspective [4]. As a fuel ammonia can be used either in fuel cells or in combustion engines [5] with some changes to existing technologies. Another advantage of ammonia is that compared to hydrogen which is another potential carbon-free fuel, ammonia has a higher volumetric density of hydrogen in its liquid form and thus can store more energy per volume [6]. Further there is no need for cryogenic storage when using ammonia which saves both energy and capital costs [4]. Moreover, ammonia is a well known chemical substance produced and traded globally with significant infrastructure, handling experience and safety regulations in place [4]. As ammonia possess advantageous characteristics for alternative fuels in the shipping sector, it is interesting to investigate and compare ammonia to other possible alternative marine fuels for shipping which have been more researched.

1.2 Aim

The overall aim of this thesis work is to evaluate the potential of ammonia as an alternative marine fuel to reduce GHG emissions from the shipping sector using two methods; linear optimisation by the Global Energy Transition Model (GET) and Multi-Criteria Decision Analysis (MCDA). Further, the purpose is to assess the competitiveness of ammonia and if there are any conditions under which ammonia is cost-effective or preferred compared to other alternative fuels for the shipping sector.

The more specific goals of this thesis is to (i) map and evaluate different technological and operational options to reduce GHG emissions from shipping, (ii) collect data on ammonia as an alternative marine fuel (including economic, technical, environmental, and social impacts), and (iii) make a comparison with other alternative marine fuels using data and methods from existing studies by applying energy systems modelling and multi-criteria decision analysis. From this aim the following research questions are formulated:

- What are the economic, technical, environmental and social impacts of the investigated alternative marine fuels, and particularly of ammonia?

- Under which conditions is ammonia cost-effective compared to other alternative marine fuels?

- How does ammonia perform as an alternative marine fuel when multiple criteria, prioritised by stakeholders within the shipping sector, are taken into consideration?

1.3 Demarcations

A mapping and overall assessment of different alternative marine fuels is performed, but the main focus of this thesis is ammonia. Besides ammonia, the alternative marine fuels considered in this study are: liquefied natural gas (LNG), biofuels (LBG, HVO), methanol (MeOH) and hydrogen (H_2). The propulsion technologies for shipping included in this thesis are internal combustion engines (ICEs) and fuel cells (FCs).

Since international shipping is expected to increase over the century it is of significant interest to assess possible alternative marine fuels for far distances. Thus, the focus of this thesis is on short sea shipping (by Coastal ships), deep sea shipping (by Ocean ships) as well as shipping by container (by Container ships). Further, it is assumed that for very short distances there might be other alternative fuels or mitigation measures available to reduce GHG emissions than those suitable for far distance shipping and is thus not included in this study. This is why electricity is not included as an alternative fuel in this study.

Specific limitations concerning the methods applied in this study are presented in Chapter 5 where the methods are presented separately.

1.4 Report outline

This thesis is organised in eight chapters, where Chapter 1 covers the introduction and Chapter 2 presents the shipping sector and its challenges. In Chapter 3 the alternative marine fuels included in this study are presented and Chapter 4 presents a synthesis of knowledge on ammonia and its potential as a marine fuel. Chapter 5 gives a description of the methodologies used to evaluate the alternative marine fuels included in this study. In Chapter 6 the results are presented and interpretations of these are further discussed in Chapter 7 along with an outlook for the future. Lastly, conclusions drawn from this thesis work are presented in Chapter 8.

2

Current status of international shipping

In this chapter an introduction to the shipping sector and its challenges is presented. Included is also a presentation of technological and operational mitigation measures possible to reduce emissions from shipping.

2.1 Fuel and emissions

Transport by shipping is used to carry 90% by volume of the total globally traded goods [7], and projections show that seaborne trade is to grow by an average annual increase of 3.8% between the years 2018-2023 [2]. The projections of increased seaborne trade are based on the anticipated increase in global population and economic development. Seaborne transport emits less CO_2 per mass and per distance than other forms of transport but considering the projected increase, the IMO foresees an increase of global GHGs emissions from the shipping sector by 50% to 250% in 2050. [1][4]

In 2015, 300 Mton of marine fuel (corresponding to 12 EJ) was consumed of which 98% was Heavy Fuel Oil (HFO) or Marine Diesel Oil (MDO) and the remaining 2% was Liquefied Natural Gas (LNG) [8]. Besides emitting large amounts of GHGs and contributing to climate change, the marine fuels emit large amounts of hazardous substances including sulphur oxides (SO_x), nitrogen oxides (NO_x) and particulate matter (PM) which have implications on both the environment, ecosystem and human health [3].

2.2 Governance and regulations

As mentioned in the introduction, the International Maritime Organisation (IMO) is the United Nations (UN) agency responsible for global shipping. The IMO is a global authority developing regulations to mitigate climate change and the environmental impacts of international shipping [9]. The shipping sector has historically been an unregulated sector due to the international character of shipping [8], but recent actions have started to change this. In 2015 the Paris Agreement was adopted with the aim to limit the global temperature increase by 1.5°C compared to pre-industrial levels, however international shipping was not mentioned in the agreement.

Although international shipping was not explicitly mentioned in the Paris Agreement, in 2018 the IMO set up a target of decarbonisation of global shipping by at least 50% by 2050 compared to levels of 2008 [4]. Major companies in the shipping industry are also starting to commit to mitigate emissions from the shipping sector. An example of this is the major container shipping company Maersk, which have set a goal to acquire carbon neutral ships by 2030 and emit net-zero CO_2 by 2050 [8].

Besides from the target of 50% reduction of GHGs by 2050, there are regulations in place to mitigate emissions and environmental impacts from shipping. The Maritime Agreement Regarding Oil Pollution (MARPOL) Annex VI is a regulation covering emissions of air polluting substances such as SO_x, NO_x and PM. The current limit of sulphur content in marine fuel is 3.5% and by 2020 the sulphur cap is lowered to 0.5% to limit the emissions of SO_x. A more stringent limit for sulphur content is employed in so called sulphur emission control areas (SECAs), where the cap is set to 0.1%. [9]

Emission control areas (ECAs) are areas particularly sensitive to pollution and to protect areas sensitive to NO_x emissions special nitrogen emission control areas (NECAs) has been introduced by MARPOL. Emissions of NO_x are regulated on two levels by Tier II and Tier III [8]. The Tier II NO_x emission standard is set to 7.7 - 14.4 g/kWh and apply to ships with engines installed on or after 1st of January 2011. The Tier III emission standard is set to 2.0 - 3.4 g/kWh and apply to ships with engines installed on or after 1st of January 2016 operating in NECAs in North America and 1st of January 2021 in the North- and Baltic Sea. [7]

Included in MARPOL is also the Energy Efficiency Design Index (EEDI) aiming to improve energy efficiency and to mitigate emissions of CO_2 from all new ships to be constructed. The current EEDI targets to be met are set to 20% efficiency improvement (reduction of grams CO_2 per tonne mile) by 2020, and 30% by 2025 for bulk- and gas carriers, tankers and container ships [10]. [8]. For existing ships, the corresponding Ship Energy Efficiency Management Plan (SEEMP) has been introduced [7].

2.3 Mitigation measures

To succeed in reducing the emissions of GHGs and air pollutants from shipping, there is a need for technology and energy efficiency measures combined with alternative fuels [3]. In this section, an overview of different technological and operational measures to mitigate GHGs emissions from shipping is presented.

It is possible to mitigate GHG emissions from shipping by improving the energy efficiency, and there are several possible technological measures that can be applied and combined to do this. Some of the main technological measures concern the ship design, reduction of friction and the energy recovery systems. [4] Another way to improve the energy efficiency of a ship is to consider how it can be operated in a more efficient way. Operational measures include controlling the operational speed, power generation while at berth, routing and scheduling. [4] [11]

In table 2.1 an overview of technological and operational measures with their respective individual fuel saving or CO_2 mitigation potential is shown as reported by The International Transport Forum (OECD) in 2018 [4]. As can be seen in table 2.1 some measures (both technological and operational) have large potential while others have less mitigation potential.

Table 2.1: Overview of technological and operational measures.

Technological measures	*Fuel saving potential [%]*
Light materials	0-10
Slender design	10-15
Propulsion improvement	1-25
Bulbous bow	2-7
Air lubrication and hull surface	2-9
Heat recovery	0-4
Operational measures	*CO_2 mitigation potential [%]*
Speed	0-60
Ship size	0-30
Ship-port interface	0-1
Onshore power	0-3

Values gathered from The International Transport Forum 2018 [4].

3

Alternative fuels

In this chapter information about the alternative marine fuels included in this thesis is presented. The focus is on economic, technical, environmental and social impacts of the fuels.

3.1 Liquefied Natural Gas

Since established that liquefied natural gas (LNG) exhibit environmental advantages compared to HFO including reduction of CO_2 and other pollutants, there has been a growing interest for LNG as an alternative marine fuel [12]. LNG is produced by allowing natural gas to be cooled to -162°C reaching a liquid state [4]. Generating natural gas in its liquid form allows to shrink the volume of the gas about 600 times making it easier to store and transport [4].

LNG has the potential of reducing the emissions of CO_2 by up to 20% and emissions of SO_2 and PM by 90% compared to HFO [12]. Emissions of NO_x can be reduced by about 80% compared to HFO [7]. The GHG mitigation potential of LNG is affected by the release of unburnt methane (CH_4) during storage and operation, also referred to as the methane slip [4]. Because methane is a strong GHG with a GWP of 28 over a period of 100 years and 84 over a period of 20 years, merely a small methane slip can significantly reduce the CO_2 mitigation potential of LNG [4].

According to the IHS Maritime Database in 2015, there are 196 LNG-powered vessels in service and another 133 vessels ordered to be built in the period of 2016-2021 [13]. There are several different propulsion techniques available for LNG-powered vessels including gas and steam turbines and ICEs. A promising and proven propulsion technique for LNG vessels is 2-stroke dual fuel low pressure engines making it possible to comply with the IMO Tier III emission regulation without the need of installing any additional post-combustion exhaust gas treatment [14].

The availability of LNG depend on the abundance of natural gas which is estimated to suffice for 200-600 years at current production [15]. According to this estimate, it can be expected that the use of natural gas will not decline due to increased price related to scarcity [15]. However, as the use of natural gas conflicts with long-term climate targets, it can be suggested that declining use of natural gas could come from the consumer side implementing more stringent CO_2 emission caps or CO_2 taxes [15]. Other economic impacts of using LNG as a marine fuel considers investment costs in required infrastructure. According to Wang & Notteboom (2014), a critical barrier to the development of LNG is the lack of bunkering and distribution infrastructure [16].

3.2 Methanol

Methanol (MeOH) is a widely known substance within the chemical industry used to manufacture consumer and industrial products but is also being exploited as an alternative marine fuel [17]. In this study both methanol made from fossil fuels and non-fossil feedstock are investigated. The most economical and prevalent way to produce fossil methanol is by natural gas reforming and it is therefore the assumed pathway for fossil methanol and onward called NG-MeOH in this thesis. The most economical and prevalent way of producing non-fossil methanol is by biomass gasification and it is therefore the assumed pathway for non-fossil methanol and onward called Bio-MeOH in this thesis. [7]

Adopting NG-MeOH as a marine fuel has the potential of extensively reducing the emissions of SO_x, NO_x and PM compared to using conventional marine fuels. Thus, NG-MeOH have the potential to meet both SECA emission standards and Tier III but it depends on which propulsion system that is used. Some engine types do need additional catalyst to comply with Tier III. Adopting Bio-MeOH as a marine fuel has the same reduction potential as NG-MeOH concerning emission of SO_x, NO_x and PM, however, Bio-MeOH also has the potential of being a carbon neutral fuel in a life cycle perspective.[7] The first ship converted to be powered by methanol was the passenger ferry *Stena Germanica* which started operating in 2015 between Gothenburg and Kiel [18], and in 2016 seven new methanol powered ships was put in operation [19].

Of the global production of methanol estimated at 2.6 EJ/year, 0.02 EJ/year of Bio-MeOH is produced. In total, if assuming a marine fuel demand of 20 EJ/year, methanol can supply 13% of the total fuel demand at current production rates. Bio-MeOH can be produced by different types of biomass including municipal waste and forest residues and when assessing the future potential of Bio-MeOH it is important to consider land use constraints such as growing population and competition for food. [7]

Since methanol is a widely traded commodity, some distribution infrastructure already exist as well as considerable handling experience. There is also some bunkering infrastructure available [20]. The infrastructure for methanol can though still be assessed as limited considering using it for marine fuel purposes [7].

3.3 Biofuels

3.3.1 Liquefied Biogas

LBG is a methane-based alternative marine fuel produced from biomass and cooled to -161 °C reaching a liquid state at atmospheric pressure using cryogenic technology [21]. In this study the LBG is assumed to be produced by biomass residues using anaerobic digestion and liquefaction. Once produced, LBG can be used similarly to LNG in ICEs and exhibit a similar emission profile of NO_x, SO_2 and PM in a tank-to-propeller perspective for transportation of 1 ton cargo 1 km with a ro-ro vessel [3]. In the same assessment it is also concluded that due to differences in fuel composition, LBG has a higher contribution of methane to the GWP than LNG while LNG emit more hydrocarbons than LBG [3]. Overall LBG exhibit a lower life cycle GWP than LNG since the emitted CO_2 origins from biomass compared to the fossil origin of LNG. LBG can therefore be used in shipping as a renewable alternative to LNG, however the reduction of life cycle emissions depend on which biomass feedstock that is used as well as the production method applied to produce the LBG [3].

From an economic point of view, LBG is assumed to require the same investment cost for propulsion and operational cost as LNG, but have a higher fuel price [22]. The annual production of biogas is 1.1 - 1.4 EJ (2013) [23] which is a considerably small amount compared to the annual production of natural gas which is about 121.5 EJ (2013) [24]. Because of this, the infrastructure for LBG is assumed to be less available compared to LNG, however, the fuels can use the same infrastructure for distribution and bunkering.

3.3.2 Hydrogenated Vegetable Oil

Hydrogenated vegetable oil (HVO) is a liquid synthetic biofuel considered for marine applications. In this study HVO is assumed to be synthesised from tall oil from pulp and paper production as primary energy source.

HVO has a low sulphur content and hence low SO_x exhaust emissions [25]. Reported NO_x emissions by using HVO differ tremendously and range from numbers implying that HVO emit more NO_x than conventional fossil marine fuels to HVO reducing emissions of NO_x compared to conventional fossil marine fuels. In this study, it is assumed that there is a need for exhaust gas cleaning to comply with NO_x Tier III. Emissions of PM related to the use of HVO are reported slightly lower compared to conventional fossil marine fuels. [26]

Because HVO have similar chemical and technical properties as conventional marine fuels, it can be used as a drop-in fuel meaning that in can be used in existing infrastructure and as a substitute for diesel in diesel engines [27]. It is possible to use 100% of HVO as a substitute for diesel [27], however this needs to be approved by engine manufacturers. One of the major marine engine manufacturers, Volvo Penta, has approved the use of 100% HVO in their engines [28].

The current installed global production capacity of HVO is about 0.2 EJ/year [29], which is not sufficient to cover the annual demand of marine fuel. A possible pathway to increase the production capacity of HVO is to integrate the production of HVO in oil refineries after some adjustments to the existing processes. As mentioned, because HVO is a drop-in fuel, the extent of available infrastructure is a driver for HVO, however, the small production volumes represents a barrier. The estimated future production capacity of HVO is predicted to reach 0.3 EJ/year [29], yet, this is also not sufficient since it is enough to meet only 1.5% assuming a fuel demand of 20EJ/year [7].

3.4 Hydrogen

Hydrogen (H_2) is a potential marine fuel that can be used in FCs to produce electricity which can be used for various purposes in a ship, but also in ICEs [4]. There are several types of FC systems that can use hydrogen and the system layout can deviate significantly which affect the performance criteria and suitability for maritime applications [30]. When using hydrogen powered FCs, there are no GHG-emissions produced during operation, however, the production pathway and choice of feedstock can widely affect the life cycle climate impact [8]. The most common feedstock for hydrogen production is natural gas and the steam methane reforming (SMR) process. An emerging alternative pathway for hydrogen production is electrolysis which can be used together with renewable electricity [31].

A challenge with hydrogen is how to store it because of the low storage density and lack of infrastructure for distribution. It can be stored either as a compressed gas at pressures up to 700 bars or as a liquid in cryogenic tanks at -253°C [8][30]. There is currently no International Code for the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk (IGC Code) in place for transporting liquid hydrogen in large quantities, though it is possible if there is an agreement between pertinent nations for shipping. As of today there are a few ships using hydrogen as energy carrier and FC technology. [8] Some advantages with hydrogen fuel cells is their high energy efficiency, up to 60 % [32] and in combination with electric motors with efficiencies of about 95 %, the propulsion system becomes significantly more efficient and silent than with internal combustion engines. [8]

4

Ammonia

In this chapter a knowledge synthesis on ammonia is presented. As for the other alternative fuels presented in Chapter 3, the focus is on economic, technical, environmental and social impacts.

4.1 Production

Ammonia (NH_3) is one of the most extensively produced chemicals worldwide and is mainly produced by the Haber-Bosch process (HB) using hydrogen and nitrogen gas, but other pathways including electrochemical processes are also possible [33][34]. The annual global production of ammonia is around 170-180 Mt/year and is expected to increase until 2050 to around 200 Mt/year [35][36]. There is ongoing research in the field of electrochemical ammonia production and the ultimate goal of the electrochemical reactors is to be able to use water in situ as the hydrogen source which would present a big advantage over the HB process. However, electrochemical processes have still not reached industrial scale or matured as production technologies [33], and are thus not included as possible production pathways in this study. In this study it is assumed that ammonia is produced by the HB process and that hydrogen is supplied either by SMR or electrolysis of water.

4.1.1 Market

Currently most of the hydrogen needed for ammonia production is supplied using fossil fuels such as coal and natural gas while only a small share is produced from other sources like electrolysis [5][37]. In the beginning of the 20th century, a large share of hydrogen for ammonia production was supplied by electrolyzers powered by excess electricity from hydropower. This sustainable way of producing hydrogen for ammonia production remained until the price of ammonia produced from natural gas dropped below the price of ammonia produced from electricity. The price on ammonia is thus highly coupled with the price of natural gas. [38]

The main use of ammonia today is in the agricultural sector for fertiliser production which corresponds to about 80% of the globally produced volume of ammonia. Other applications for ammonia include being used as refrigerant or as a base chemical for the production of pharmaceuticals, explosives and other industrial processes. [33] As can be concluded by the large share of ammonia used in the agricultural sector, ammonia is essential for food production and it has been estimated that almost one third to half of the global population would starve without it [34]. However competition with food production is not further handled in this thesis.

4.1.2 Haber-Bosch

About 90% of the ammonia production worldwide uses the HB process to react hydrogen and nitrogen over an iron oxide catalyst at elevated pressure and temperature [5]. The HB process is energy intensive due to operation at high temperatures (400 - 500°C) and pressures (150 - 300 bar), and together with the production of hydrogen and nitrogen [33][34], ammonia production corresponds to 1-3 % of the annual global energy demand [39]. The synthesis reaction between the elemental hydrogen and nitrogen is shown in reaction 4.1 below [34].

$$3H_2 + N_2 \rightarrow 2NH_3 \tag{4.1}$$

The reaction between hydrogen and nitrogen is exothermic meaning that no extra heat needs to be added to the synthesis and the only energy input needed for the HB process is that for compression of the feedstock gases to an appropriate operation pressure of the reactor. Thus it is possible to run the HB process exclusively on electricity. [40]

4.1.3 Feedstock production

The nitrogen is supplied from an air separation unit (ASU) which is usually operated at cryogenic conditions to separate nitrogen from air [5]. The main energy input to the ASU is electricity to compress the air and therefore the associated emissions depend on the electricity mix used. Hydrogen on the other hand, can be produced in several ways including SMR or electrolysis, where the former is the most common [30][31].

The hydrogen production required for the HB process dominates the overall energy demand needed to produce ammonia and is also accountable for a large share of the environmental impact of ammonia production. A vast majority of the hydrogen used in ammonia production comes from fossil resources like natural gas and coal, but it is also possible to use electrolysis and connect it to renewable electricity production. [31]

4.2 Potential as a marine fuel

Ammonia can be used in both internal combustion engines (ICEs) and fuel cells (FCs) [6] which represent the two main propulsion technologies considered possible for the shipping sector in this study. It is possible to either use ammonia as a fuel itself or as a hydrogen carrier by decomposing ammonia into nitrogen and hydrogen by implementing a reformer in the propulsion system, and then use the hydrogen as fuel [37][41]. Some important properties of ammonia affecting its suitability as fuel are compiled and shown in table A.1 in Appendix 1. Ammonia has emerged as a potential fuel option as an alternative to hydrogen since it possess feasible storing and transportation characteristics [31]. The energy density of liquid ammonia (LHV of 12.7 MJ/dm^3) is higher than that of liquid hydrogen (LHV of 8.5 MJ/dm^3)[33], although lower than the other alternative fuels included in this thesis as shown in table A.2 in Appendix 1. Large amounts of fuel needs to be stored on-board and the type of chosen storage solution affects the vessel investment cost as well as the space available for cargo. Ammonia can be stored as a liquid at ambient temperature at pressures up to 16-18 bar or at lower pressures if refrigerated, it liquefies below -33 °C at atmospheric pressure [42]. Therefore cryogenic storage is not needed for ammonia which is necessary for liquid hydrogen and LNG [35].

4.2.1 Propulsion technologies

The propulsion technologies considered to be suitable for operation of ammonia as fuel in the shipping sector are ICEs and FC which are described in more detail below.

4.2.1.1 Internal combustion engines

The idea and application of using ammonia in combustion engines is not new, in fact it was used during the 1940s in Belgium to propel busses where it was blended with conventional fuel. Since then ammonia has been tested both as primary fuel and together with pilot fuels in both Otto cycles (spark ignition engines) and Diesel cycles (compression ignition engines) with positive outcomes. [43][44][45]

Due to a low laminar flame speed when combusting ammonia it can be necessary to adapt the ICEs if using ammonia as fuel. Another possibility is to decompose part of the ammonia to hydrogen and nitrogen to improve the combustion characteristics or blend it with another fuel as a combustion promoter for operation in a regular ICE without adaptations [6]. Other unfavourable characteristics of ammonia to have in mind when assessing its potential as fuel for combustion in ICEs are the narrow flammability limits, high ignition temperature, low flame temperature and toxicity [6][43][45]. On the other hand the narrow flammability limits and the high ignition temperature gives an advantage to ammonia over hydrogen by lowering the risk of fire and explosion while stored or transported [6].

Another advantage of ammonia in ICEs is that no carbon based products are formed during the combustion process, however NO_x emissions are accumulated. The main contributor to the formation of NO_x is believed to come from the fuel bound nitrogen and reducing this formation is important. [6] One way to handle NO_x from ICEs is to use a Selective Catalytic Reduction (SCR) system where the NO_x is reduced to nitrogen (N_2) which is a technology currently used to handle the emissions from conventional ICEs [46].

4.2.1.2 Fuel cells

Ammonia for fuel cell applications has also been previously studied with records dating back to 1966 for the development of direct ammonia fuel cells. Ammonia fuelled FC vehicles have been investigated and demonstrated in a number of projects and ammonia has been tested both as direct fuel and as hydrogen carrier after thermal cracking to H_2 [41]. In a fuel cell, the fuel is directly converted to electricity with a high efficiency. There are several types of fuel cells available for shipping applications and they can be categorised based on the electrolyte used and system layout [47]:

- Alkaline fuel cells (AFC)
- Phosphoric acid fuel cells (PAFC)
- Solid oxide fuel cells (SOFC)
- Molten carbonate fuel cells (MCFC)
- Proton exchange membrane fuel cells (PEMFC)

In some of the FC types, ammonia must be split into H_2 and N_2 before entering the cell since ammonia can damage the FC. Especially the PAFC and the PEMFC types are sensitive and require very pure (above 99.99%) hydrogen. The main option for direct use of ammonia as fuel is the SOFC which operate at high temperatures and the decomposition into hydrogen can occur inside of the FC itself. The hydrogen is then the species taking part in the electrochemical reaction of the fuel cell. [37] To reach full conversion of ammonia to hydrogen in a SOFC, it must be operated at temperatures above 873 K [47]. When using high temperature FCs like SOFCs, it is common to heat up the equipment during the start up phase with a burner which, depending on the fuel used, can cause GHG emissions [30]. The high temperature of a system with SOFC makes it suitable to combine with a heat recovery system which can be used to generate steam for a bottoming power cycle, with potential of improving the efficiency from 60 to 85% [4][30].

FC technology for marine purposes has been tested in several studies for on-board operation of different sea vessels. The types of FCs that has been tested include PEMFCs, MCFCs, SOFCs and AFCs, and has included various fuels [30]. However ammonia has not yet been tested in marine applications. Despite this, the potential for using ammonia is considered substantial for lowering the tailpipe GHG emissions from shipping [32].

4.2.2 Safety and technological aspects

When evaluating the potential operation of ammonia as a marine fuel there are several practical aspects to take into consideration regarding safety and technical applicability. Ammonia is a very toxic chemical substance and the *Immediately Dangerous to Life and Health* (IDLH) limit is 300 ppm [47], yet possible to detect by its characteristic smell at concentrations as low as 1.5 ppm [48]. The toxicity entails the need for installation of gas detection systems on-board vessels carrying ammonia for either propulsion or transportation purposes. The density of ammonia is lower than air making it lighter and sensors must be placed above possible leakage sources or at human breathing height [48]. This is especially important in enclosed spaces such as engine rooms. Since ammonia is an extensively traded and shipped compound, there is a lot of handling experience available for transportation and loading as well as safety regulations [31]. Despite this, new safety regulations are needed when ammonia is to be used as a fuel instead of solely transported. Moreover ammonia is corrosive to some materials like alloys containing copper and zink, but compatible with many common materials like carbon and stainless steels which should be considered when constructing the equipment which comes in contact with ammonia [48]. The main fuel cell technology for direct use of ammonia is the SOFC which operates at high temperatures (up to 1000 °C), which can pose a safety risk during operation [4][49].

The HT-PEMFC and SOFC are more suitable for large ships as a consequence of their long start up periods and slow load changes [30], while LT-PEMFC (the most mature FC technology) is more well suited for smaller vessels operating on short distances [4]. Even if SOFC is a very promising technology that has been researched and advanced, it is considered a moderately mature technology that needs further development to reach competitive prices and widespread use [30]. As mentioned before ammonia can also be used in regular ICEs with some modifications and the dual fuel engine concept appears to be a suitable technology to introduce ammonia as a fuel in shipping since it possess the possibility to use a supporting fuel. New engine concepts for 100 % ammonia operation and other options are reportedly being developed and it is yet to be determined if spark ignition or compression ignition is the more suitable choice for marine ammonia engines. [48]

As mentioned NO_x is formed during ammonia combustion and SCR-technology will most probably be needed to comply with the NO_x Tier III regulations. This situation is not exclusive for ammonia, conventional and many of the carbon-based fuel options produce NO_x emissions that must be handled with SCR or other mitigation technologies. In the catalytic reactor a reducing agent is introduced to reduce the NO_x to N_2. The most common reducing agent is urea which is decomposed into ammonia when heated by the exhaust gases inside the reactor. This means that ammonia can be used directly instead, if already used on-board. [48]

No projects or studies of real ammonia powered ships have yet been published (2018) [4], although it is expected to be done in the near future (2020) [35][48], which could more clearly show the practical applicability of ammonia to the technical and safety systems.

4.2.3 Drivers and barriers

There are several drivers and barriers related to ammonia and its potential use as an alternative marine fuel, and the main advantages and disadvantages of using ammonia for shipping are summarised in table 4.1.

Table 4.1: Summary of drivers and barriers of ammonia as alternative marine fuel.

Advantages	*Disadvantages*
Carbon-free molecule –> No tailpipe GHG emissions	Production determines life cycle GHG emissions
Can be stored as liquid at reasonable T/P	Lack of regulations to be used as fuel
Existing infrastructure	Not yet tested in real marine engines
Can be used in ICE and FC	Need SCR to handle NO_x if used in ICE
No SO_x-emissions	Corrosive to some materials
Handling experience	Current production reliant on natural gas
Abundant commodity	Might require a supplementary fuel in ICE
Relatively high energy density compared to H_2	Toxic

5 Method

To evaluate the potential of ammonia as an alternative fuel for reducing GHG emissions from the shipping sector two methods are used; linear optimisation by the Global Energy Transition Model and Multi-Criteria Decision Analysis. Theoretical background as well as a description of the employment of the methods is presented in this section. Besides the two methods, a literature review is conducted.

5.1 Literature review

A literature review is conducted within the scope of this study to collect data to be used in the applied models and form a knowledge synthesis on ammonia. Moreover the review is used to find relevant information about the current state of emissions in the shipping sector and what fuels and technologies that are being used as well as what regulations and climate targets that affect or will affect the shipping sector in the future. Information is also gathered regarding potential measures to reduce GHG emissions from the shipping sector including what technological and operational measures, and alternative fuels that are available or being researched. This also allows to identify areas in which there seems to be a lack of research.

5.2 Global Energy Transition Model

The Global Energy Transition model (GET) is an optimisation model developed in the late 1990s by Azar and Lindgren [50] as a tool to investigate the transition of the global energy system while minimising the total system cost limited by a selected atmospheric CO_2 concentration constraint within a specified time frame [51]. The model has been updated several times since then and the GET 10.0 version base the module for shipping on a previous version of the model (GET-RC 6.2) which has been updated to assess the shipping sector more thoroughly [52][53]. The modelled optimisation problems are set up as linear programming problems and analysed in time steps of 10 years within a selected time frame [52].

In this study ammonia is incorporated as marine fuel in GET 10.0 to assess the cost-effectiveness compared to other marine fuels in two different scenarios of CO_2 constraint to be achieved by year 2100: 450 ppm and 550 ppm. The 450 ppm CO_2 scenario imply an atmospheric CO_2 stabilisation level of approximately 480 ppm CO_2-eq and corresponds to an average global temperature increase of about 1.5℃ - 2.0℃ in year 2100 relative to pre-industrial levels (1850-1900) [52][54]. The 550 ppm

CO_2 scenario is analysed to assess the cost-effectiveness of ammonia under a less stringent CO_2 emission constraint. In the following sections the main aspects and assumptions of the GET 10.0 model are described, and more detailed and in-depth information can be found in Lehtveer et al. (2019) [52].

5.2.1 Structure

An overview of the GET 10.0 model is shown in figure 5.1. Included in the model are five sectors; Electricity, Feedstock, Residential and commercial heat, Industrial process heat and Transport (Land, Air and Water). For each sector the energy demand is given exogenously and primary energy sources (Coal, Crude oil, Natural gas, Biomass, Nuclear, Hydro, Solar, Wind) are converted into secondary energy carries (Heat, Electricity, Petroleum based fuels (represented by MGO for ships), Methanol, Natural gas, Biofuels, Ammonia) to be consumed in each sector to meet the demand. As can be seen in figure 5.1, the transport sector is divided into three categories: Land-, Air- and Water transport. Water transport represents the shipping sector which it is denoted as from now on in this thesis. In this thesis ammonia is only allowed as a shipping fuel and can not be used for other applications in the transport sector. In the model the world is divided into 10 regions according to the definition by the International Institute for Applied System Analysis (IIASA) [52] and all primary energy sources are assumed to be available in all regions. Energy sources can be exchanged amongst the regions (except electricity) with costs ascribed to such exchange [52]. In this thesis the regional solutions are aggregated for global results.

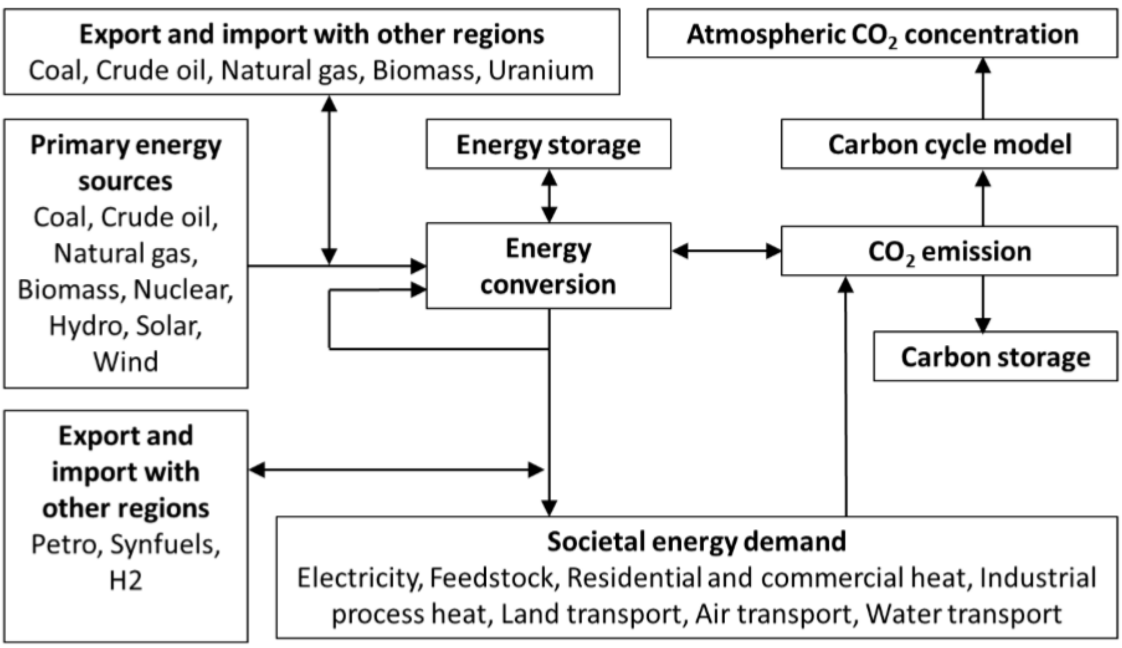

Figure 5.1: Basic flowchart of the model structure of GET 10.0

As mentioned the energy demand is given exogeneously in this thesis and the demand projections for the transport sector is based on scenarios developed by Azar et al.

[55]. The demand projections for the other sectors are based on the B2 scenarios from the International Institute for Applied System Analysis (IIASA) GGI Scenario Database [52] and will not be further discussed in this thesis since the focus in on shipping which is part of the transport sector. The shipping sector is in GET 10.0 represented by three categories of ships; Coast, Ocean and Container, which characteristics are presented in table 5.1. [52]. The division of the shipping sector into three ship categories allows to get a more realistic yet simplified description of the shipping sector capturing some of the main differences in engine size and storage tanks and also the projected increase in shipping by Container which the model accounts for [53].

Table 5.1: Specification of ship types included in the GET model.

	Coast	*Ocean*	*Container*
Engine power [$kW_{mech.output}$]	2400	11000	23000
Voyage range full speed [h]	162	720	360
Tank capacity [GJ]	3500	71300	74600
Life time [years]	30	30	30

Specifications as in study by Lehtveer et al. (2019) [52].

As mentioned GET is a cost optimisation model which imply that the model only considers costs associated to various parameters and actions. Thus, all data included in the model is ascribed a certain cost and as an example emissions of CO_2 is accounted for by ascribing a certain cost associated to emissions of CO_2. Cost data for the assessments performed in this thesis is mainly of two sorts, costs associated to the production of fuel and costs associated to vessels run by different fuels and propulsion systems. Data on the cost of fuel synthesis is presented for 2010 respectively 2050 since a certain future cost reduction is assumed for all fuels. The base case data and assumptions used in the modelling is presented in table 5.1 and table 6.1 in Chapter 6. The application and modelling by GET performed in this thesis is based on data and methodology of previous studies investigating cost-effective transport fuels [3][50][52]. In this thesis Ammonia is incorporated as a shipping fuel while data and assumption for the other fuels included in GET 10.0 are gathered in previous studies [52].

5.2.2 Implementation

The GET 10.0 model is developed in the General Algebraic Modelling System (GAMS) which is a linear programming solver used to optimise various systems. In this thesis, input data and parameter values for are gathered in matrices in excel-files which are uploaded to GAMS.

5.2.3 Model Limitations

The GET 10.0 model represents a simplification of the actual energy system and is not developed to predict future developments of the energy system. Model simplifications include that there is a limited number of primary and secondary energy carriers included, that the energy demand of each sector is given exogenously, that the model base decisions only on cost, that each sector acts rationally and that the model has "perfect foresight" meaning that there is no uncertainty about parameter values in the future such as costs, potentially new energy carriers or energy demand. Another limitation is that the model only considers emissions of CO_2. [52]

5.2.4 Fuels and assumptions

The shipping fuels included in GET in this thesis are listed in table 5.2. The stated primary energy source represents the feedstock and pathway of energy conversion that is included for the fuels (secondary energy carriers) in the model. For some of the fuels, several primary energy sources are stated and this means that the fuel can be produced from different energy sources and the model will choose to produce the fuel by the energy source that minimise the total system cost. For each fuel it is also stated which propulsion technology it can be combined with, and in this thesis the included propulsion technologies are ICEs and FCs. MGO is assumed to represent petroleum based fuels in the shipping sector in this thesis.

Table 5.2: Overview and description of shipping fuel included in GET in this thesis.

Fuel	*Primary energy source*	*Propulsion technology*
Marine Gas Oil (MGO)	Crude oil	ICE/FC
Methanol (MeOH)	Natural gas/Biomass/Coal/Hydrogen	ICE/FC
Biofuels (Bio)	Biomass	ICE/FC
Natural gas (LNG)	Natural gas	ICE/FC
Hydrogen (H_2)	Wind/Solar/Hydro/Coal/Biomass/Natural gas	ICE/FC
Ammonia (NH_3)	Hydrogen	ICE/FC

As stated in Chapter 4, ammonia is in this thesis assumed to be produced by the HB process with nitrogen and hydrogen as feedstock. Nitrogen is not included as an energy carrier in the GET 10.0 model and the cost of nitrogen production is thus incorporated as a part of the HB process. Hydrogen is included in the model as a fuel and energy carrier and thus the hydrogen utilised for ammonia synthesis is assumed to be produced by one or several of the production pathways included for hydrogen. As displayed in table 5.2 there are various energy sources and production pathways included for hydrogen and for instance hydrogen may be produced from fossil fuels such as natural gas and oil, or by electricity using electrolysis. The origin of the hydrogen that goes into ammonia synthesis is determined by the model based on what alternative is most cost-effective and also eventual constraints on hydrogen production and use in other sectors. Also the chosen propulsion system (ICE or FC) is chosen based on costs.

5.2.5 Sensitivity analysis

To assess the sensitivity of the modelling, Monte Carlo analyses are performed evaluating the robustness of the results to the parameter values. Monte Carlo Simulation is a mathematical technique performed to model the probability of different results in a set of data with inherent uncertainties. Monte Carlo Simulations analyse a range of possible results by varying parameter values in a probability distribution by calculating the results using different random parameter values taken from the probability function. The execution of a Monte Carlo Simulation result in distributions of possible outcome parameter values. The probability distribution represents the uncertainty of parameter values and in this study the parameters are varied assuming uniform distribution. Assuming uniform distribution imply that all parameter values have the same chance of occurring and only a set of minimum and maximum values are defined for each parameter. [56][57] In this thesis the distribution of the analysed parameters that are varied is unknown and therefore uniform distribution is chosen giving each value the same chance of occurring.
To assess the sensitivity of the results three parameters are varied:

- *Ammonia synthesis investment cost 2050*
- *Ammonia synthesis efficiency*
- *Additional vessel cost compared to MGO ICE*

These three parameters are chosen because they are believed to affect the cost-effectiveness of ammonia in this method. *Ammonia synthesis investment cost 2050* refer to the CAPEX cost of a HB power plant and in this thesis also includes the cost of nitrogen production as previously mentioned. *Ammonia synthesis efficiency* refer to the energy efficiency of the HB process. The parameter *Additional vessel cost compared to MGO ICE* describes the added investment cost of vessels run on other fuels than MGO to the cost of MGO ICE vessels which is assumed as the reference fuel representing the current cost of vessels operating with conventional fuel. The calculation of vessel cost include estimations of several underlying parameters and the parameters varied to generate the span for vessel cost are tank cost and fuel cell cost. Specific information about the assumptions made and the resulting spans for MC analysis is presented in Chapter 6.

5.3 Multi-Criteria Decision Analysis

When analysing problems with multiple criteria or options, and where there are several stakeholders to take into consideration for a decision, it is suitable to use a Multi-Criteria Decision Analysis (MCDA) to find the most optimal solution. There are a variety of MCDA-methods to chose from depending on the nature of the problem at hand [58]. In this thesis the MCDA that is performed is based on the methodology and result from a former master thesis by Månsson (2017) [7]. An overview of the methodology used is presented in the sections below and further details can be read upon in the thesis report by Månsson [7].

The basis of decision analysis can be divided into five steps [59]:

i) Problem identification.

ii) Structuring the decision problem.

iii) Assessing possible impacts of each option.

iv) Determining preferences of the criteria by the decision makers/stakeholders.

v) Evaluating and comparing the options to make a decision or extension and planning.

Each step of the analysis adds and handles different types of complexity issues such as multiple objective, long time frames, intangibles, value trade offs etc., and iteration between various steps can be necessary [58][60]. In the study by Månsson (2017), the Analytic Hierarchy Process (AHP) is used for determination of the preferences in the involved stakeholders as well as for evaluation and comparison of the fuel options [7]. The AHP is one of the most common MCDA-methods and was developed in the 1980s by Saaty [59]. It is a method that make use of pairwise comparisons of the options considered in the analysis. By relating one option to another, a ratio can be defined to describe the importance of one option compared to another. Usually the ratio is defined as a number on Saaty's fundamental scale (1-9). One of the main advantages of this method is that even intangible options can be handled and given a tangible value. [61]

The aim of the MCDA is to evaluate and compare possible alternative fuels to be used in the shipping sector to reduce GHG emissions. In the structuring part of the analysis, the criteria which the fuels will be assessed against must be specified. Since this thesis is based on the work by Månsson, the same criteria are used. These are economic criteria, technical criteria, environmental criteria and social criteria. The criteria are further specified using ten sub-criteria which are described in detail in table C.16 in Appendix 3. [7]

5.3.1 Analytic hierarchy process

The analytic hierarchy process structures the multi-criteria problem in a hierarchy tree. The crown of the tree is represented by the aim of the MCDA, then followed by the criteria. From each criteria, branches with sub-criteria is formed and grouped. Depending on the problem to be handled by the AHP, it is possible to add or subtract levels in the hierarchy and then at the bottom the options are placed. The criteria and sub-criteria used in this study and how they are connected in the hierarchy is presented in table 5.3. At each level of the hierarchy a pairwise comparison is executed to allocate the importance and weight among the criteria and sub-criteria [62]. The weights of the criteria and sub-criteria are kept the same as in the work by Månsson (2017) which was determined during a workshop with a group of stakeholders associated with the shipping sector. At the workshop the stakeholders were to assess the relative importance of the selected criteria and sub-criteria according to the AHP [7]. In table 5.4 the weights for the criteria and sub-criteria in the MCDA base case is shown. The weights have been normalised so that the sum of the criteria weights is equal to 1 and the sum of the sub-criteria weights for each criteria is equal to 1.

Table 5.3: Overview of the criteria and associated sub-criteria used in the MCDA. The criteria and sub-criteria are arranged in a hierarchy of which the order is structured from left to right.

Aim	*Criteria*	*Sub-criteria*
Most favoured alternative marine fuel	Economic	Investment cost for propulsion Operational cost Fuel cost
	Technical	Reliable supply of fuel Available infrastructure
	Environmental	Climate change Health impact Acidification
	Social	Upcoming legislation Safety

The choice of criteria and sub-criteria is based on [7] and [22].

Table 5.4: Normalised criteria and sub-criteria weights used in the base case MCDA.

	Normalised weight
Economic	**0.316**
Investment cost	0.258
Operational cost	0.162
Fuel cost	0.580
Technical	**0.166**
Available infrastructure	0.294
Reliable supply of fuel	0.706
Environmental	**0.239**
Climate change	0.499
Acidification	0.205
Health impact	0.296
Social	**0.278**
Safety	0.477
Upcoming legislation	0.523

Weights from the study by Månsson (2017) [7]

The options, which in this thesis are the different alternative fuels, are scored based on how well they fulfill the criteria and sub-criteria. Scores for the options except those that includes ammonia is gathered from previous works by Månsson (2017) [7] and Hansson et al. (2019) [22]. Some of the more intangible sub-criteria are scored on a scale 1-4 *(Poor, Moderate, Fairly well, Good)*, these are the technical and social sub-criteria. The scores of the technical and social sub-criteria are calculated as an average performance of a number of related indicators. To evaluate how well the fuels fulfil the indicators of the technical sub-criteria a group of experts from the shipping sector were asked to assign a score of 1-4 to each fuel option. The involved experts for the scoring of the technical sub-criteria indicators are presented in table 5.5.

Table 5.5: Overview of experts participating in indicator scoring for technical sub-criteria in the MCDA.

Stakeholder	*Company/organisation*
Per Stefenson	Stena Teknik
Erik Lewenhaupt	Stena Line
Øystein Kostøl	Yara
Karin Andersson	Chalmers University of Technology
Daniel Berndolf	Preem AB
Daniele Bottino	ABS
Christos Chryssakis	DNV GL - Maritime

A pairwise comparison is then performed for each sub-criterion where the scores of each fuel are compared to one another. More specifically this is conducted by comparing the score of the option in row i to the score of the option in column j, and the result of the comparisons makeup the elements a_{ij} of the pairwise comparison matrix **A**. The element a_{ji} is then given the reciprocal value of a_{ij}. See example of a pairwise comparison matrix in table 5.6 below. From the pairwise comparison matrix the priorities of the fuels can be obtained by calculating the priority vector, $\mathbf{w}=\{w_1....w_n\}$. A common approach to produce the priority vector, which is applied in this thesis, is by using the geometric mean method. This method use the geometric mean of the elements on the corresponding row and divide it by a normalisation term, according to equation 5.1 below, so that the sum of all components in **w** is equal to 1. [7][62]

$$w_i = (\prod_{j=1}^{n} a_{ij})^{\frac{1}{n}} / \sum_{i=1}^{n}(\prod_{j=1}^{n} a_{ij})^{\frac{1}{n}} \tag{5.1}$$

Table 5.6: Example of a pairwise comparison matrix with three alternatives and calculated priorities.

	Alternative 1	Alternative 2	Alternative 3	Priorities
Alternative 1	1	3	1/2	0.309
Alternative 2	1/3	1	1/5	0.109
Alternative 3	2	5	1	0.582
				Sum = 1.00

It is common that there are more than one individual or stakeholder involved when performing a MCDA, and the result will thus be based on a group decision. When AHP is applied there is a need to combine the weights of the criteria and sub-criteria from the involved parts by finding the group priority vector. There are two main ways of doing this, either by aggregation of individual judgements (AIJ) or by aggregation of individual priorities (AIP). [62] In the work by Månsson (2017), the AIP method is used. This part of the MCDA is important for the interpretation of the result, however not performed within this thesis and the global priorities of the criteria and sub-criteria are obtained from Månsson (2017). [7]

To find which alternative marine fuel that is the most preferred among involved stakeholders, the final ranking order must be established. By using linear combination of the priority vectors the global priorities can be found where the fuels are ranked from lowest to highest global priority. [7][62]

5.3.1.1 Consistency check

When performing a pairwise evaluation there is a need to make sure that the matrices are consistent. This can be verified by performing a consistency check where the consistency index (CI) and consistency ratio (CR) of each matrix is calculated. As mentioned earlier, Saaty's fundamental scale of numbers (1-9) is used in the pairwise comparison matrices and for the weighing of the criteria. Because of this the definition of Saaty's consistency ratio is also employed. [7]

The maximum eigenvalue, λ_{max} of the matrix $\mathbf{A}$ can be determined by using equation 5.2, where $\mathbf{I}$ is the identity matrix of the same dimensions as $\mathbf{A}$ [7]. From λ_{max} the CI can be calculated with equation 5.3. When handling pairwise comparison matrices of dimensions that exceeds 3×3, the risk of inconsistency increases as more comparisons are performed. To handle this the CR is calculated with equation 5.4, and if CR($\mathbf{A}$)$\leq$ 0.1, then the matrix can be confirmed to be consistent enough. [7][62][63]

$$det(\mathbf{A} - \lambda\mathbf{I}) = 0 \tag{5.2}$$

$$CI(\mathbf{A}) = \frac{\lambda_{max} - n}{n - 1} \tag{5.3}$$

$$CR(\mathbf{A}) = \frac{CI(\mathbf{A})}{RI_n} \tag{5.4}$$

The RI_n in equation 5.4 represents the average CI generated from a random simulation of comparison matrices of size n × n. Values of RI_n for matrices ranging in size from 3×3 to 12×12 is shown in table 5.7 below [63].

Table 5.7: Random Index values used in the calculations of the consistency ratio.

n	3	4	5	6	7	8	9	10	11	12
RI_n	0.525	0.882	1.110	1.250	1.341	1.404	1.451	1.486	1.514	1.536

5.3.2 Model limitations

Multi-criteria decision analysis methodologies are tools to find the best solution or option to a specific and unique problem. This implies that the best option will depend on the palette of criteria and sub-criteria that is used together with which options that are considered. [58] In this MCDA, four criteria, ten sub-criteria and eleven fuel alternatives are included and these are displayed in figure 5.3. The results of this MCDA is only applicable to this specific setup.

5.3.3 Fuels and assumptions

As mentioned, eleven fuel alternatives are included in this MCDA and these are listed in table 5.8. Due to the modelling set-up of the MCDA, ammonia is incorporated as four different fuel alternatives to capture the combinations of the two different production pathways of hydrogen used for ammonia (Electrolysis or SMR) as well as the two alternative propulsion technologies (ICE or FC).

Table 5.8: Overview and description of fuels included in the MCDA.

Fuel short name	*Primary energy source*	*Fuel production*	*Propulsion technology*
LNG ICE	Natural gas	Extraction, liquefaction	ICE
LBG ICE	Biomass residues	Anaerobic digestion, liquefaction	ICE
NG-MeOH ICE	Natural gas	Extraction, natural gas reforming, methanol synthesis	ICE
Bio-MeOH ICE	Forest residues	Biomass gasification	ICE
NG-H_2 FC	Natural gas	Extraction, natural gas reforming, liquefaction	FC
Elec-H_2 FC	Wind power	Electrolysis, liquefaction	FC
HVO	Tall oil	Synthesized from pulp and paper residues	ICE
NG-NH_3 FC	Natural gas	Extraction, natural gas reforming, Haber Bosch	FC
Elec-NH_3 FC	Wind power	Electrolysis, Haber Bosch	FC
NG-NH_3 ICE	Natural gas	Extraction, natural gas reforming, Haber Bosch	ICE
Elec-NH_3 ICE	Wind power	Electrolysis, Haber Bosch	ICE

For the calculation of the economic sub-criteria, the use ofe Ocean ships are assumed for all of the alternative fuels in the MCDA. As previously mentioned the MCDA performed in this thesis is based on preceding work by Månsson (2017) [7], however some changes are made to the sub-criteria *fuel price* and *health impact*. The economic sub-criterion *fuel price* is adjusted and designated *fuel cost* in this thesis because the sub-criterion is changed to also include the fuel demand for an ocean ship capturing the connection of fuel cost and powertrain efficiency. In this thesis the environmental sub-criterion *health impact* is evaluated based on PM instead of DALYs since the major health impacts from shipping originates from emissions of particles and therefore PM is a more generic measure than DALYs [32].

5.3.4 Sensitivity analysis

The global priorities of the alternative marine fuels included in the MCDA are further analysed to be able to interpret and check the robustness of the result. Sensitivity analysis of the fuel ranking is performed in two different ways:

- Alternative scores: Defining different scenarios where the impacts on the sub-criteria are changed.

- Role-play: Using criteria weights from the role-play conducted by Månsson (2017) [7] to check how the opinions from different shipping related stakeholder groups affect the ranking.

5.4 Assessment of alternative fuels

GET and MCDA are applied in this thesis because the two methods exhibit complementing characteristics contributory to the aim. The GET model is used to assess the cost-effectiveness of ammonia compared to other alternative marine fuels and only considers the economic potential of respective fuel. The MCDA method includes assessment of the alternative marine fuels based on not only economic criteria but also technical criteria, environmental criteria and social criteria. The MCDA also take stakeholders interests and preferences into consideration which is suitable for a problem such as alternative marine fuels for shipping which involves several industries, actors and agencies. The MCDA therefore contribute to assess how ammonia perform as an alternative marine fuel based on criteria evaluated by stakeholders within the shipping sector.

5.4.1 Methodological choices

Some assumptions specific for each method have already been presented but this subsection aims to present general methodological choices and assumptions shared by the two methods.

Generally a large share of the data used in both methods represents mean values of gathered data. This is due to the fact that some parameters vary greatly depending on the source of the data and a mean value is chosen to be more representative than specific values.

As previously mentioned the two alternative propulsion technologies available in both methods in this thesis are ICEs and FCs. More specifically, for ammonia, the ICE alternative is assumed to be a dual fuel type of engine. This means that the emission and cost data are based on data for ammonia being used in dual fuel configurations. For the FC technologies available for ammonia, SOFC is assumed in both methods because ammonia can be directly used in this type of FC which eliminates the need of a reformer. This FC technology also seems likely to be a good fit for ammonia according to several studies [37][47][32].

6

Result and analysis

In this chapter the results and analysis from GET and the MCDA is presented separately. For both methods the compiled data used in the assessments is presented followed by base case results as well as results of the sensitivity analyses performed.

6.1 Global Energy Transition Model

In this section the results from the GET model are presented. The cost-effectiveness of the included marine fuels is evaluated as the share of the total energy use within the shipping sector over a time perspective of 2010 - 2100 for the scenarios with CO_2 constraint of 450 ppm and 550 ppm.

6.1.1 Base case data

Base case data is presented for ammonia and MGO which is included as a reference representing conventional fuel used within shipping. In this thesis, NH_3 is incorporated as a shipping fuel while data and assumptions for the other fuels included in GET 10.0 are gathered in previous studies [52].

Table 6.1 displays data of some of the parameters associated to the production cost of NH_3 and MGO. The synthesis investment cost is presented for both year 2010 and 2050. A cost reduction is then assumed for all fuels to be achieved until 2050 compared to the current cost (2010). The synthesis efficiency refer to the production efficiency of respective fuel and calculation of the synthesis efficiency for NH_3 is found in table B.2 in Appendix 2. As can be seen in table 6.1 the synthesis investment cost is assumed to be reduced by 10% at 2050 compared to the 2010 value for NH_3. 10% is chosen to be representative for future improvements in costs of production since the HB-process is mature and other fuels incorporated in the model also assumes 10%. The load factor refers to how well energy is utilised and is calculated by the average load divided by the peak load of the power plants. Data for the other marine fuels included in the model are presented in table B.3 in Appendix 2.

Table 6.1: Parameters related to production cost for NH_3 and MGO.

	NH_3	*MGO*
Synthesis efficiency [%]	74[a]	90
Synthesis investment cost 2010 [USD/kW]	2100[b]	1500
Synthesis investment cost 2050 [USD/kW]	1900[c]	1000
Load factor	0.8[d]	0.7

[a] Calculated from [52] and [64], see Appendix 2.
[b] Calculated from [65], [66] and [67], see Appendix 2.
[c] 10% cost reduction assumed based on 2010 value.
[d] Assumed equal to MeOH.

Table 6.2 display cost specifications for some of the underlying parameters associated to the calculation of the vessel investment cost of NH_3 and MGO ships for the three ship categories Coast, Ocean and Container. Data for the other marine fuels included in the model are presented in table B.4 in Appendix 2.

Table 6.2: Component costs used for NH_3 and MGO ships for the different ship categories in GET.

	Coast	*Ocean*	*Container*
NH_3			
ICE engine [USD/$kW_{mech.output}$] [a]	800	600	600
ICE propulsion efficiency, LHV [a]	45%	40%	40%
FC stack cost [USD/$kW_{mech.output}$] [b]	925	925	925
FC propulsion efficiency, LHV [a]	45%	60%	45%
Storage cost [USD/GJ] [c]	55	35	35
SCR cost for ICEs [USD/$kW_{mech.output}$]	133	133	133
Additional vessel cost compared to MGO (NH_3 ICE) [GUSD/10 000 ships]	11	60	15
Additional vessel cost compared to MGO (NH_3 FC) [GUSD/10 000 ships]	15	80	16
MGO			
ICE engine [USD/$kW_{mech.output}$]	350	350	350
ICE propulsion efficiency, LHV	45%	40%	40%
FC stack cost [USD/$kW_{mech.output}$]	925	925	925
FC propulsion efficiency, LHV	45%	60%	45%
Storage cost [USD/GJ]	20	15	15
SCR cost for ICEs [USD/$kW_{mech.output}$]	133	133	133

[a] Assumed equal to H_2 ICE.
[b] Mean value of the range 350-1500 USD/kW, where the 350 USD/kW is equal to the MGO ICE cost. and 1500 USD/kW is the higher estimate of SOFC cost in [30].
[c] Assumed half of LNG.

6.1.2 450 ppm scenario

In this scenario the atmospheric CO_2 concentration constraint is set to 450 ppm by year 2100. Before the cost-effective fuel choices are presented for the shipping sector, the global primary energy use is presented to be able to understand the results and to get an overview of the development of energy sources summarised for all sectors.

6.1.2.1 Global primary energy use

The global primary energy use in the 450 ppm CO_2 constraint scenario is presented in figure 6.1 where it can be seen that the total energy use has more than doubled by year 2100 compared to 2010. The use of fossil resources (natural gas, oil and coal) dominate the energy mix in the beginning of the century with only a small share of renewable energy sources. The use of oil decrease continuously over the century while the use of coal have two peaks at 2020 respectively 2060 before it decline to nearly 0 EJ at 2100. The use of natural gas increase over the century with two peaks at 2040 respectively 2080 reaching about 140 EJ at 2100. The use of renewable energy sources increase over the century and dominate the energy mix from approximately 2050 and onward for the rest of the studied time period. Thus, to meet the 450 ppm CO_2 constraint, the model introduces solar, wind, hydro and an increasing share of nuclear as alternatives to natural gas, oil and coal. As the use of renewable sources increase, so does the electricity use which grow extensively during the second half of the century.

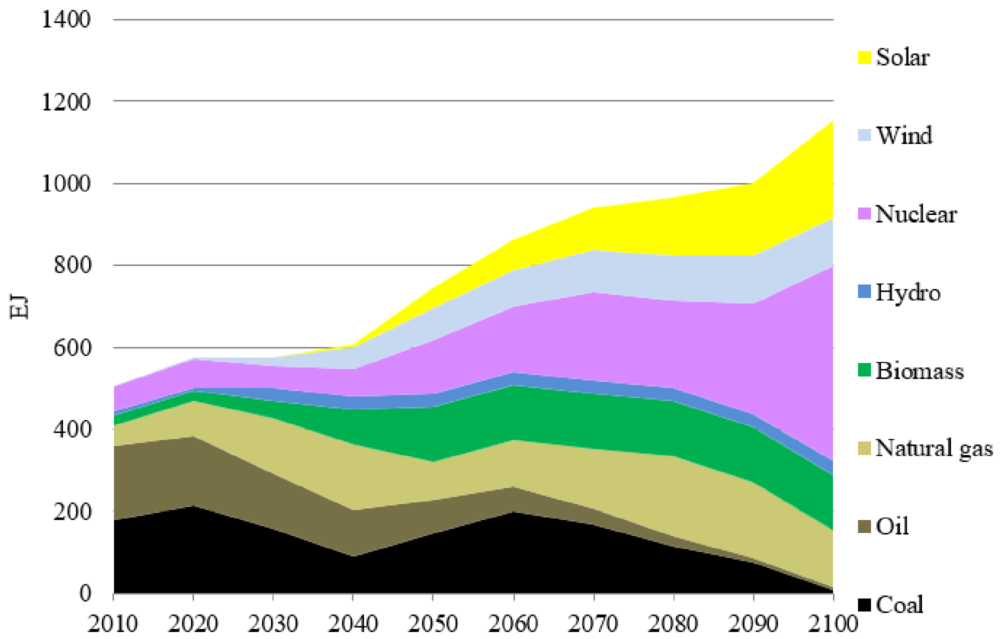

Figure 6.1: Cost-effective global primary energy use at 450 ppm CO_2 constraint.

6.1.2.2 Shipping fuels

Figure 6.2 display the cost-effective fuel choices and corresponding propulsion technologies for the shipping sector under 450 ppm CO_2 constraint. The y-axis correspond to the amount of shipping fuel in EJ and the x-axis represent the studied time period. In the beginning of the studied time period, MGO ICE and LNG ICE dominate as fuel alternatives. At approximately 2040 H_2 FC is introduced as a fuel and at 2020 the use of MGO ICE start to decline and continues to do so until the end of the studied time period reaching nearly 0 at 2100. The use of LNG ICE as fuel peak at approximately 2040 after which it declines continuously as MGO. Shortly after H_2 FC is introduced it increase extensively as a substitute to MGO ICE and LNG ICE. LNG FC is introduced at 2020 and grows modestly before it start to expand at 2040 when LNG ICE start to decline. In the end of the century, at 2100, H_2 FC is the dominating fuel alternative followed by LNG ICE. As can be seen in the figure, the first FC technology alternative is introduced at 2020, but it is not until 2040 and onward that FC technology start out-compete the ICE technology alternatives to dominate as propulsion technology at 2100. As biofuel and methanol is not included in figure 6.2, it can be concluded that biofuel and methanol is not cost-effective as shipping fuels in this assessment. Since the GET model includes several sectors it might be that biofuel and methanol are used to supply demands in other sectors where it is more cost-effective, for example in the heat sector or for land transport. Thus, all sectors are connected and the development of other sectors affect also the cost-effective fuel choices in the shipping sector since the GET model is designed to minimise the total system cost.

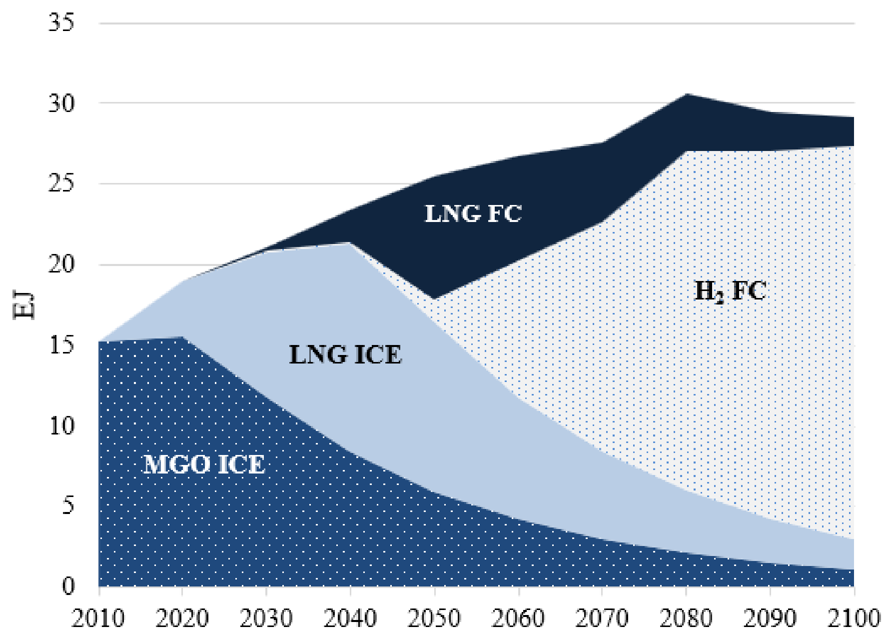

Figure 6.2: Cost-effective shipping fuels and corresponding propulsion technologies in the case of the 450 ppm CO_2 constraint.

In figure 6.2 showing cost-effective fuel choices for the shipping sector under the 450 ppm CO_2 constraint, no amounts of NH_3 are displayed. However small amounts of NH_3 is introduced from year 2060 and thus considered cost-effective (see figure 6.3. The amounts are however to small to be visible in figure 6.2.
As can be seen in the figure, NH_3 FC is introduced at 2060 growing continuously reaching about 120 GJ at 2100, and at 2090 NH_3 ICE is also introduced. As mentioned in regards to figure 6.2, there seem to be a shift in propulsion technology from

ICE to FC and this can also be observed for the cost-effective use of NH_3 which is dominated by FC technology. As presented in table 6.1 for NH_3 and MGO, and in table B.3 in Appendix 2 for the other fuels, the cost of fuel synthesis is decreasing from 2010 to 2050. Thus, over time the cost of production decrease which might be a reason why NH_3 is introduced first in 2060 when the production cost has became cheaper for NH_3 than conventional technology.

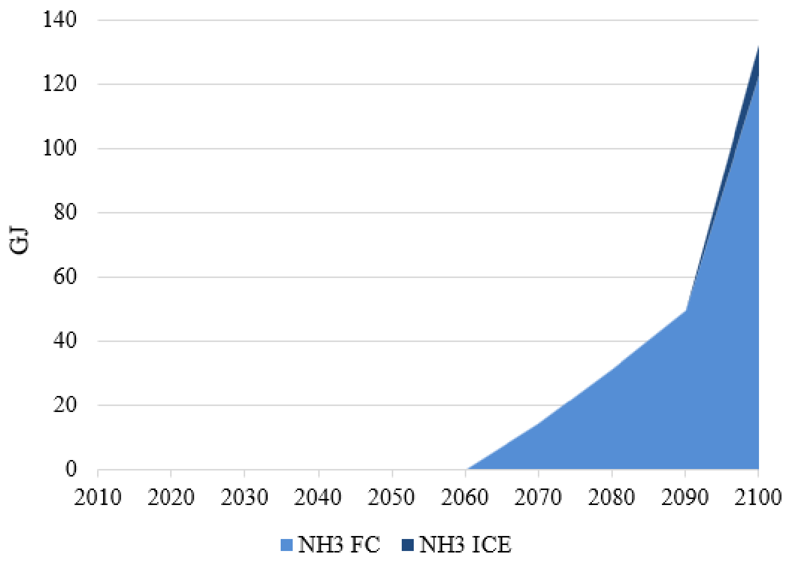

Figure 6.3: Cost-effective use of NH_3 as shipping fuel in the case of the 450 ppm CO_2 constraint.

In figure 6.3 the results are aggregated for all ship types, and in figure 6.4 - 6.6 the penetration of NH_3 and corresponding propulsion technology is presented separately for each ship category. On the left axis, the total energy demand (shipping fuel) of each ship category is displayed in EJ and on the secondary axis to the right the cost-effective use of NH_3 for each ship category is displayed in GJ.

In figure 6.4 it can be seen that freight by Container increases over the century reaching over 11 EJ at 2100. NH_3 combined with FCs is cost-effectively introduced at 2050 and grows to a share of about 700 GJ at 2100. NH_3 combined with ICEs is cost-effectively introduced in 2090 reaching about 20 GJ in 2100. Thus, at 2100 approximately $6.2 * 10^{-6}$ % of the energy demand by Container ships is supplied by NH_3. As can be seen in figure 6.5 shipping by Ocean ships modestly grows during the century reaching about 2.7 EJ at 2100. For Ocean ships, NH_3 is cost-effectively introduced combined with FCs at 2080 reaching approximately 220 GJ at 2100. NH_3 combined with ICEs is not cost-effective for Ocean ships and thus stays on 0 GJ during the whole century. Thus, at 2100 approximately $8.3 * 10^{-6}$ % of the energy demand by Ocean ships is supplied by NH_3. In figure 6.6 the cost-effective use of NH_3 for Coast ships is displayed. As can be seen in the figure, freight by Coast ships are increasing from about 8 EJ in the beginning of the century to 15 EJ at 2100. As for Ocean ships, NH_3 is only cost-effective if combined with FCs and for Coast ships NH_3 is introduced at 2070 reaching about 380 GJ at 2100. This implies that at 2100 approximately $2.5 * 10^{-6}$ % of the energy demand by Ocean ships is supplied by NH_3.

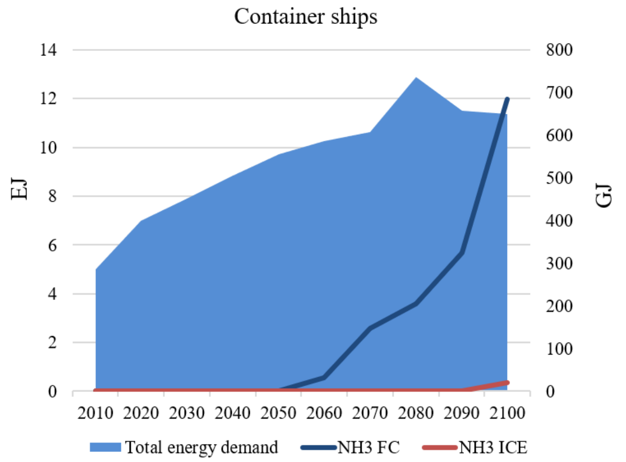

Figure 6.4: Use of NH_3 by Container ships at 450 ppm CO_2 constraint.

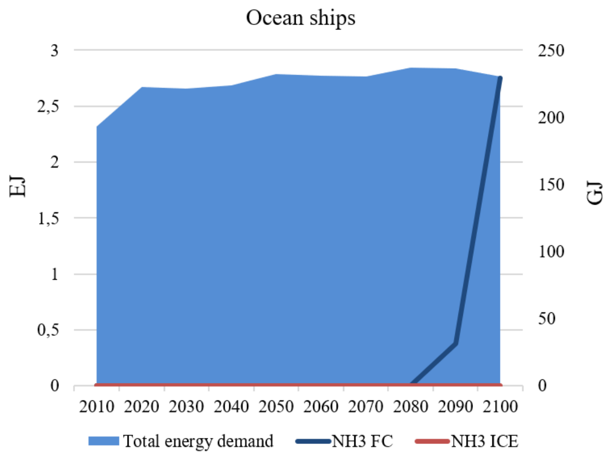

Figure 6.5: Use of NH_3 by Ocean ships at 450 ppm CO_2 constraint.

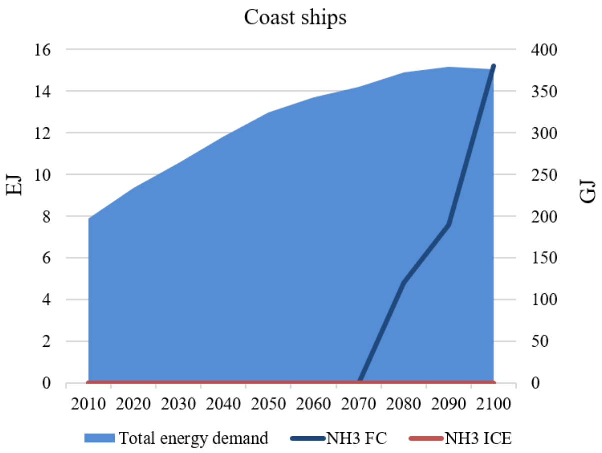

Figure 6.6: Use of NH_3 by Coast ships at 450 ppm CO_2 constraint.

6.1.2.3 Global hydrogen production and use

As mentioned, NH_3 is produced from hydrogen and can only be used as a fuel in the shipping sector. Since hydrogen has several possible applications and can be produced from both fossil and renewable resources, the feedstock used for hydrogen production as well as the global use of hydrogen is presented in figure 6.7 respectively figure 6.8.

As can be seen in the figures, the production and use of hydrogen in significant amounts start at 2030 and increase rapidly reaching about 150 EJ in 2100. In figure 6.7 it can be seen that when hydrogen is introduced at 2030 the dominating feedstock is biomass. At 2100 the primary feedstock is solar followed by biomass, natural gas and finally electricity. As previously presented, only small amounts of NH_3 is cost-effective under 450ppm CO_2 constraint and therefore the share of hydrogen that goes into NH_3 production is barely visible in figure 6.8. However, considering the feedstock used for hydrogen production from 2060 and onward (when NH_3 is cost-effective) it can be assumed that the NH_3 used as shipping fuel is produced from hydrogen produced by on average a minimum of 50% renewable sources.

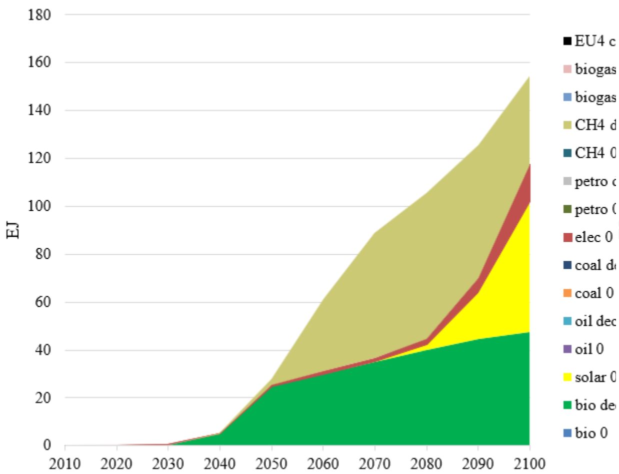

Figure 6.7: Global H_2 feedstock at 450 ppm CO_2 constraint.

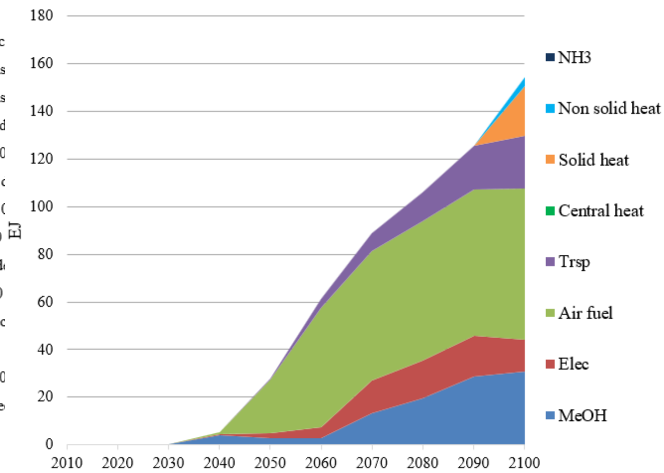

Figure 6.8: Global H_2 use at 450 ppm CO_2 constraint.

6.1.3 550 ppm scenario

In this scenario the atmospheric CO_2 concentration constraint is set to 550 ppm by year 2100 and only the result of cost-effective fuel choices are presented.

6.1.3.1 Shipping fuels

Figure 6.9 display the cost effective fuel choices and corresponding propulsion technologies for the shipping sector under the 550 ppm CO_2 constraint. The y-axis correspond to the amount of shipping fuel in EJ and the x-axis represents the studied time period. The fuel choices in the beginning of the century until 2040 is similar to the cost effective fuel choices and corresponding propulsion technologies for the 450 ppm scenario presented in figure 6.2. A difference is that H_2 FC is introduced in small amounts at 2030 and does not grow significantly until 2080 and onward compared to in the 450 ppm CO_2 scenario where hydrogen act as the main substituting fuel for MGO ICE and LNG ICE. Instead LNG FC grow to dominate and substitute LNG ICE and MGO ICE. In the end of the century, at 2100, LNG FC is the dominating fuel alternative followed by H_2 FC. Thus, under a less stringent CO_2 emission constraint, the use of natural gas increase and the transition from natural gas to hydrogen and NH_3 seem to be delayed compared to the 450 ppm scenario. Also in this scenario, a shift in propulsion technology from ICE to FC can be observed although it is LNG FC and not H_2 FC that dominates as a fuel at 2100.

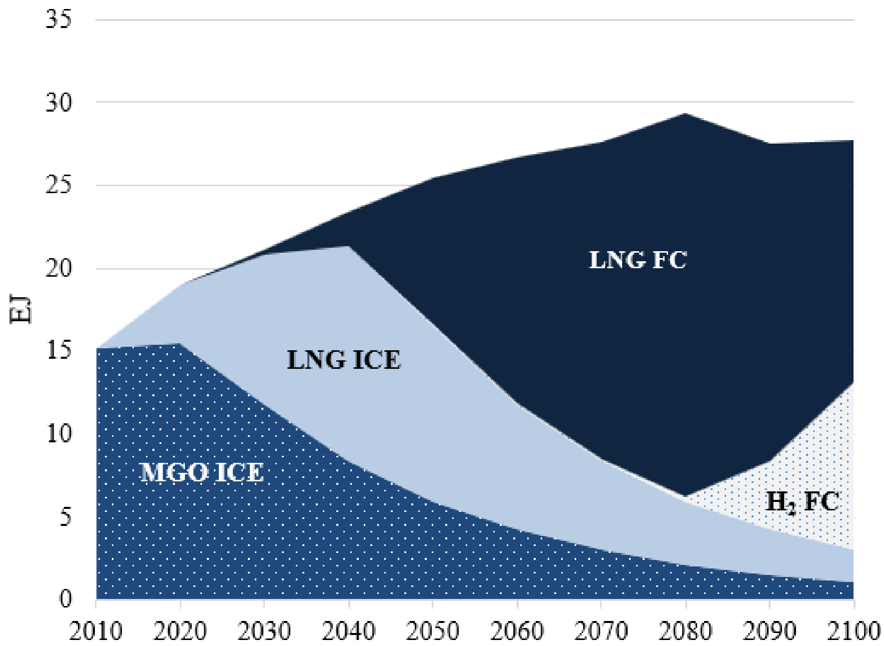

Figure 6.9: Cost-effective shipping fuels and corresponding propulsion technologies in the case of the 550 ppm CO_2 constraint.

Also in this scenario small amounts of NH_3 are introduced (however also here in too small amounts to be visible in the figure 6.9) and thus the cost-effective use of NH_3 under 550 ppm CO_2 constraint is presented separately in figure 6.10 with the amount of shipping fuel in GJ on the y-axis. As can be seen in the figure, NH_3 is introduced as a shipping fuel at 2080 and is only cost-effective combined with FC technology. The difference to the 450 ppm CO_2 scenario seem to be that NH_3 is introduced later in the century and to a lower extent reaching about 55 GJ at 2100 compared to over 120 GJ in the 450 ppm CO_2 scenario. Also, no NH_3 combined with ICE is introduced in the 550 ppm CO_2 scenario.

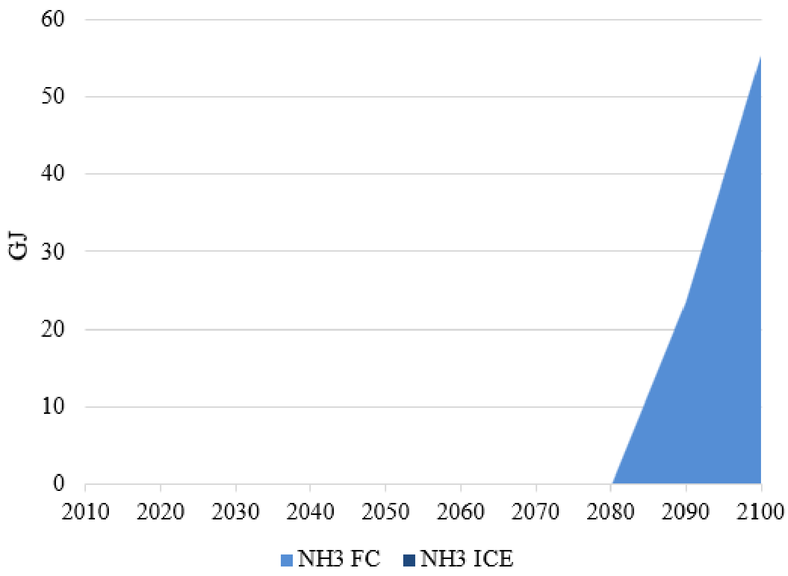

Figure 6.10: Cost-effective penetration of NH_3 in the case of the 550 ppm CO_2 constraint scenario.

In figure 6.10 the results are aggregated for all ship types, and in figure 6.11 and 6.12 the penetration of NH_3 and corresponding propulsion technologies is presented separately for Container and Coast ships. Under 550 ppm CO_2 constraint no NH_3 is cost-effectively introduced for Ocean ships and thus a figure displaying the use of NH_3 by Ocean ships is not included. Similar trends as the outcome of the 450 ppm CO_2 scenario can be observed for the 550 ppm CO_2 scenario and at 2100 approximately $3.5 * 10^{-6}$ % and $1.5 * 10^{-6}$ % of the energy demand by Container- respectively Coast ships is supplied by NH_3. As displayed in figure 6.9 and figure 6.10 the cost-effective use of NH_3 is introduced later in the 550 ppm CO_2 scenario compared to the 450 ppm CO_2 scenario. Thus, under less stringent CO_2 emission constraint there is a delay of cost-effective use of NH_3 as shipping fuel which explain why NH_3 is not cost-effective for Ocean ships in the case of 550 ppm CO_2 constraint.

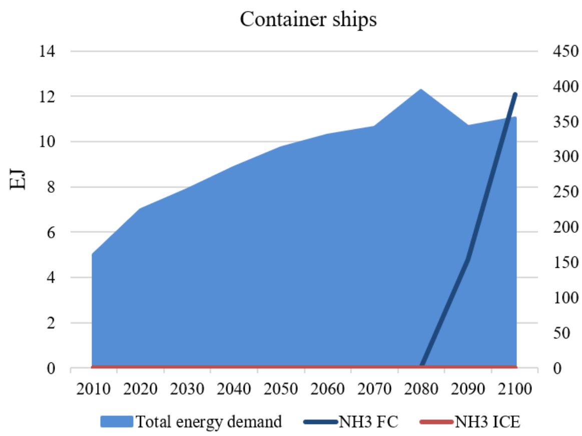

Figure 6.11: Use of NH_3 by Container ships under 550 ppm CO_2 constraint.

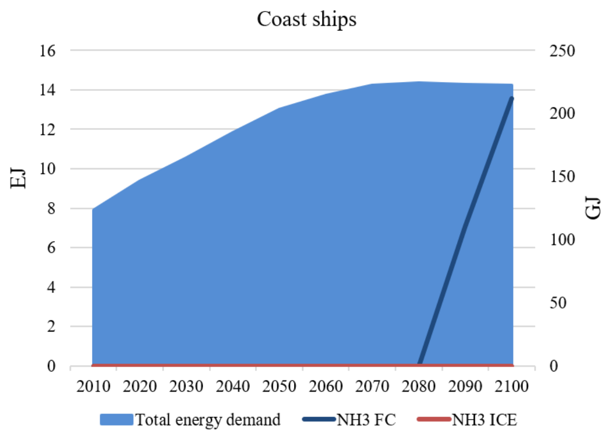

Figure 6.12: Use of NH_3 by Coast ships under 550 ppm CO_2 constraint.

6.1.4 Sensitivity analysis

As mentioned in Chapter 5, three parameters are varied to assess the sensitivity of the results; *ammonia synthesis investment cost 2050*, *ammonia synthesis efficiency* and *additional vessel cost compared to MGO ICE*. The base case data together with the minimum and maximum values of the parameter spans used for the MC analyses are displayed in table 6.3. The Monte Carlo analyses are performed for the 450 ppm CO_2 scenario and the parameters are varied in a simulation of 100 model runs.

The investigated parameter *additional vessel cost compared to MGO ICE* is varied by varying two of the underlying parameters that affect the final value. These parameters are the cost of ICE for NH_3 ships, fuel cell stack cost and the tank cost. The *additional vessel cost compared to MGO ICE* is varied for all fuels and ships using FCs and for the NH_3 ICE alternative. The assumptions made when calculating the span of minimum and maximum values are presented in the following text.

- **NH_3 ICE, minimum value**:
  To find the lower limit of the additional vessel cost compared to MGO ICE span for NH_3 ICE vessels, the ICE engine is assumed to cost the same as the LNG engine (500 USD/kW) for all ship categories. This is combined with an assumed storage cost of 30 USD/GJ_{fuel} for Ocean and Container ships and 40 USD/GJ_{fuel} for Coast ships which corresponds to the storage cost of MeOH.
- **NH_3 ICE, maximum value**:
  For the higher limit of the additional vessel cost compared to MGO ICE span for NH_3 ICE vessels, the ICE engine is assumed to have the same cost as in the base case (600 USD/kW), however the storage cost is assumed to increase to 70 USD/GJ_{fuel} for Ocean and Container ships and to 110 USD/GJ_{fuel} for Coast ships which corresponds to the storage cost of LNG.
- **All FC vessels, minimum values**:
  For the calculation of the additional vessel cost compared to MGO ICE for vessels propelled by FC technology, 350 USD/kW is assumed as the minimum FC cost which is the same cost as for an MGO ICE engine. For NH_3 FC the storage cost is assumed to be 30 USD/GJ_{fuel} for Ocean and Container ships and 40 USD/GJ_{fuel} for Coastal ships which corresponds to the storage cost of MeOH. For the other fuels, the storage cost is assumed to be the same as in base case.
- **All FC vessels, maximum values**:
  For the calculation of the additional vessel cost compared to MGO ICE for vessels propelled by FC technology, 1500 USD/kW is assumed as the maximum FC cost. For NH_3 FC the storage cost is assumed to be 70 USD/GJ_{fuel} for Ocean and Container ships and 110 USD/GJ_{fuel} for Coast ships which corresponds to the storage cost of LNG. For the other fuels, the storage cost is assumed to be the same as in base case.

Table 6.3: Spans used to uniformly vary parameters in the MC analyses.

	Minimum	*Base case*	*Maximum*
NH_3 synthesis energy efficiency	68 %	74%	80 %
NH_3 synthesis investment cost 2050 [USD/kW]	1700	1900	2100
Container ships, additional cost compared to MGO ICE ship [GUSD/10 000 ships]			
MGO FC	2	15	28
MeOH FC	2	15	28
Bio FC	3	16	29
LNG FC	4	17	30
H_2 FC	13	22	31
NH_3 FC	2	15	28
NH_3 ICE	8	11	14
Ocean ships, additional cost compared to MGO ICE ship [GUSD/10 000 ships]			
MGO FC	10	70	130
MeOH FC	10	70	130
Bio FC	20	80	140
LNG FC	35	100	165
H_2 FC	120	160	200
NH_3 FC	10	80	150
NH_3 ICE	50	60	70
Coast ships, additional cost compared to MGO ICE ship [GUSD/10 000 ships]			
MGO FC	2	16	30
MeOH FC	2	16	30
Bio FC	3	15	28
LNG FC	4	17	30
H_2 FC	4	18	32
NH_3 FC	2	16	30
NH_3 ICE	12	15	18

The results from the Monte Carlo analysis of 100 model runs of the 450 ppm CO_2 scenario are plotted as the amount of NH_3 in the system as a function of the sensitivity ranges of the investigated parameters and are displayed in figure 6.13 - 6.16.

In figure 6.13 the Monte Carlo analysis varying the investment cost of NH_3 synthesis is presented. The result show that there is a weak correlation ($R^2 = 0.026$) between the amount of NH_3 in the system and the investment cost of NH_3 synthesis. When the cost of NH_3 synthesis is low, there seems to be a modest trend towards more NH_3 in the system.

In figure 6.14 the Monte Carlo analysis varying the NH_3 synthesis efficiency is presented. The result show that there is a weak correlation ($R^2 = 0.0626$) of synthesis efficiency and the amount of NH_3 in the system. A higher energy efficiency of NH_3 synthesis seem to increase the amount of NH_3 in the system. Thus, in this assessment neither NH_3 synthesis investment cost or NH_3 synthesis energy efficiency seem to be sensitive to the amount of NH_3 that is cost-effective as shipping fuel in the invesigated spans.

In figure 6.15 the Monte Carlo analysis varying the additional cost compared to MGO ICE for Container NH_3 ICE ships is presented. From the figure it can be concluded that there is no correlation of the vessel cost of Container NH_3 ICE ships and the amount of NH_3 in the system. It has previously been shown that NH_3 combined with ICE is not cost-effective and thus this result seem reasonable.

As can be seen in the figure 6.16 there is a modest correlation ($R^2 = 0.1445$) between the amount of NH_3 in the system and the additional vessel cost compared to MGO ICE for Container NH_3 FC ships. Thus, the vessel cost of Container NH_3 FC ships is coupled with the amount of NH_3 in the system and a low vessel cost imply a somewhat higher amount of NH_3 in the system. The result of the Monte Carlo analysis varying the additional vessel cost compared to MGO ICE for Ocean and Coast ships follow the same trends as container ships and are presented in figure B.1 - B.4 in Appendix 2.

When assessing the results of the MC analysis it should be noted that the results are only true for the investigated spans of respective parameter meaning that if a wider or more narrow span is investigated, the outcome might be different.

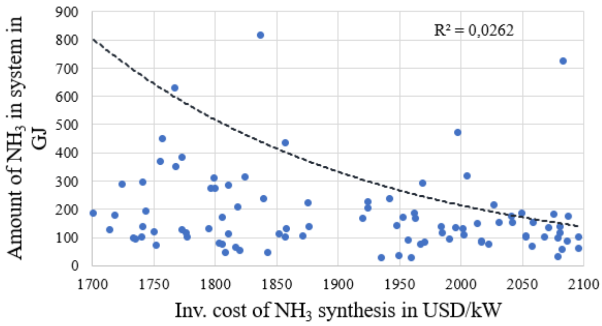

Figure 6.13: MC-variation of investment cost for NH_3 synthesis plant.

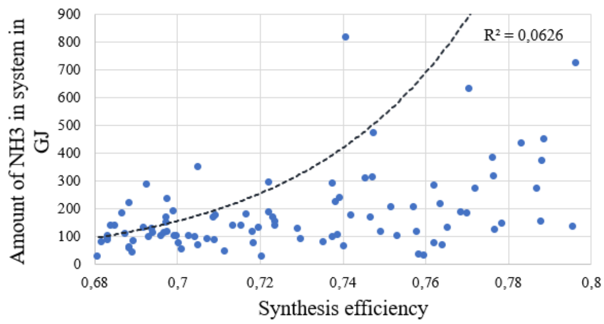

Figure 6.14: MC-variation of NH_3 synthesis energy efficiency.

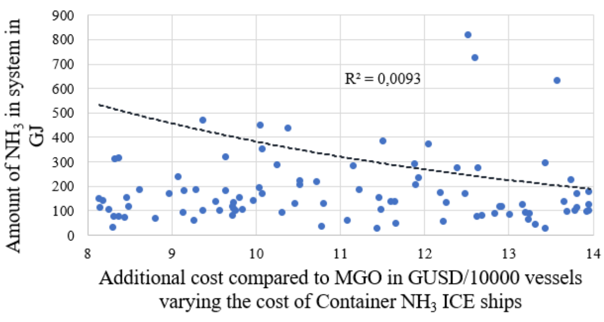

Figure 6.15: MC-variation of investment cost for Container NH_3 ICE ships.

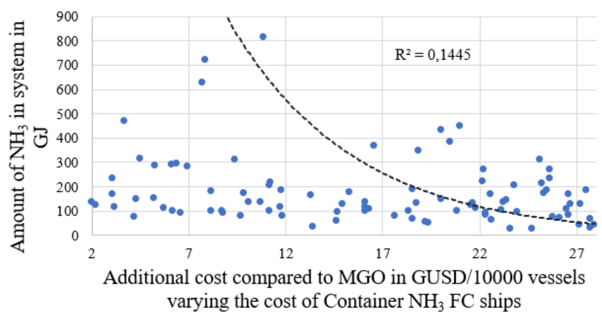

Figure 6.16: MC-variation of investment cost for Container FC ships.

6.2 Multi-Criteria Decision Analysis

In this section the results from the Multi-Criteria Decision Analysis are presented. The result from the evaluation of the impacts of the alternative fuels on the sub-criteria focuses on the ammonia options, while the pairwise comparisons, priorities and global ranking covers all of the fuel options.

6.2.1 Base case data

The base case data is presented as the impacts of the ammonia fuel options as well as LNG is presented for each sub-criteria in table 6.4-6.7. The impacts of the other alternative fuels are found in table C.1-C.8 in Appendix 3.

The impacts of the ammonia alternatives for the economic sub-criteria are presented in table 6.4. The *investment costs* for the fuel cell ships has been calculated to be 200 kUSD/kW higher than the investment cost for the internal combustion engine ships. There are no current studies published where ammonia has been used as fuel for operation regardless the propulsion technology and since the fuel handling and storage system is assumed to be equal among the ammonia alternatives, the *operational cost* are the same. The *fuel cost* is larger for the alternatives where ammonia is produced from electrolysis than from natural gas. This originate from the fact that the fuel price (also displayed in the table) is related to the production method and raw material price where the production of the H_2 feedstock stands for the largest share. Fuel cells have a higher efficiency (about 60% [49]) than internal combustion engines (40% [53]), which can be observed in the difference in *fuel cost* between the ammonia alternatives that originates from the same production method.

Table 6.4: Impact matrix of economic criteria for ammonia alternatives. The impacts of LNG ICE is included as a reference.

Alternative	*Investment cost [kUSD/kW]*	*Operational cost [USD/MWh]*	*Fuel cost [USD/kW]*	*Fuel price [USD/GJ$_{fuel}$]*
NG-NH_3 FC	5300 [a]	10 [b]	53.00	10.14 [c]
Elec-NH_3 FC	5300 [a]	10 [b]	173.17	33.14 [d]
NG-NH_3 ICE	5100 [a]	10 [b]	79.50	10.14 [c]
Elec-NH_3 ICE	5100 [a]	10 [b]	259.75	33.14 [d]
LNG ICE [e]	5100	9	41.03	5.79

[a] Calculated with GET 10.0 for an Ocean ship. SCR technology is applied for the ICE alternatives [133 USD/kW], same ICE engine price as H_2 [600 USD/kW], SOFC price, [925 USD/kW]. Storage cost is assumed to be half of the LNG storage cost [35 USD/GJ] [52].
[b] Assumed to have slightly higher operational cost than LNG, but lower than H_2 in [22].
[c] Raw material price of range of (2.5-7 GUSD/EJ) NG from GET 10.0, up to 90% of the production cost of ammonia originates from the NG price [5].
[d] Calculated from raw material price range for electricity (2.8-13.9 GUSD/EJ) [22].
[e] Impact of LNG ICE from Hansson et al. (2019) [22].

The technical criteria impacts for the ammonia alternatives are presented in table 6.5. The sub-criterion *available infrastructure* is calculated from indicator scores of current bunkering possibilities, compatibility of existing infrastructure, adaptability to existing ships and the maturity of the engine technology associated to the alternative fuel. The indicator scores of all fuels can be found in table C.2 in Appendix 3. The impact on available infrastructure is equal among the ammonia alternatives since the bunkering possibilities remains the same regardless of the production method used or the propulsion technology applied and the same goes for existing infrastructure. Adaptability of existing ships and engine technology maturity is assumed to be the equal since there are no current ammonia powered ships and both propulsion technologies (ICE and FC) are under development but not yet used. Since the impact of *available infrastructure* is using the scale 1-4, it is possible to translate the score of 1.8 for ammonia to the same as a slightly less than moderate infrastructure. Therefore, if ammonia is to be used in practice as fuel in the shipping sector the infrastructure should be developed and improved.

Reliable supply of fuel is used as a proxy and combines judgements on how well the fuels meet requirements on global use of energy source, raw material availability, current size of fuel production and use within the shipping sector as well as two energy security measures; global distribution supply potential and political stability in countries with a large supply potential. In table 6.5 the *reliable supply of fuel* is calculated and presented as the average value of the included requirements while the indicator score can be found in table C.3 in Appendix 3. The electrolysis based fuel options perform better than the natural gas, which is mainly a result from that natural gas is a limited fossil resource [15], while the electrolysis is assumed to run on renewable electricity. This makes electrolysis outperform natural gas in the energy security judgement as well as better raw material availability [15][68]. On the other hand, the majority of the current total production of ammonia originates from natural gas and SMR which gives the natural gas alternatives a higher score on current production [5][24], however when the average value is used the electrolysis reach a higher score.

Table 6.5: Impact matrix for technical criteria for ammonia alternatives on a scale 1-4 representing; (*Poor, Moderate, Fairly well, Good*). The impacts of LNG ICE is included as a reference. The presented impact values are calculated as average indicator scores.

Alternative	*Available infrastructure*	*Reliable supply of fuel*
NG-NH_3 FC	1.8[a]	2.2[b]
Elec-NH_3 FC	1.8[a]	2.8[c]
NG-NH_3 ICE	1.8[a]	2.2[b]
Elec-NH_3 ICE	1.8[a]	2.8[c]
LNG ICE [d]	2.9	2.6

[a] Based on judgement from panel of experts and of current loading infrastructure of ammonia in ports which could be transformed for bunkering operation [48].
[b] Based on information from [68].
[c] Based on aggregated information from [5], [15], [24].
[e] Impact of LNG ICE from Hansson et al. (2019) [22].

The environmental impacts of the ammonia fuel options are presented in table 6.6. The *climate change* sub-criterion is evaluated as the GWP_{100} and includes the entire fuel life cycle emissions of CO_2, CH_4 and N_2O, where the most considerable difference among the ammonia options comes from the production process used for generation of the hydrogen feedstock. It becomes clear that from a purely climate change perspective the ammonia natural gas based options are much worse than the electrolysis ones. If a supplementary fuel is used in the NH_3 ICE options to enhance the combustion characteristics the tailpipe emissions from the combustion in these options might be even higher depending the supplementary fuel used. For the sub-criterion *acidification* only the tailpipe exhaust emissions are included and these include NO_x (produced during combustion in ICEs) and NH_3 (unburnt fuel and slip from the SCR), which are converted to acidification potential as mole H^+/MJ_{fuel}. The acidifying emissions are assumed to only be present in the ammonia alternatives that use ICEs as propulsion technology and the same goes for the health impact sub-criteria. However, the SOFC technology used in the fuel cell alternatives might generate some emissions of NO_x as a result of the high temperature they are operated at [47]. Since there is a lack of studies where ammonia fuel cell technology has been tested in marine operation, the potential NO_x emissions have not been quantified although they are assumed to be low and in compliance with NO_x Tier III without need of SCR-technology. In the *health impact* sub-criterion only the tailpipe exhaust emissions are accounted for and results in that the NH_3 FC options are assumed to not produce any PM emissions while the NH_3 ICEs are assumed to have the same emissions as the MeOH ICEs. The ammonia alternative with the best environmental impact is the Elec-H_2 FC since its impacts in all of the environmental sub-criteria are low.

Table 6.6: Impact matrix for environmental criteria for ammonia alternatives. The impacts of LNG ICE is included as a reference.

Alternative	GWP_{100} [g CO_2-eq./MJ_{fuel}]	*Acidification potential* [mole H^+-eq/MJ_{fuel}]	*Health impact* [mg PM_{10}/MJ_{fuel}]
NG-NH_3 FC	140 (116-158)[a]	0	0
Elec-NH_3 FC	30[b]	0	0
NG-NH_3 ICE	140 (116-158)[a]	8.4×10^{-5} [c]	0.22 (0.0-0.43)[d]
Elec-NH_3 ICE	30[b]	8.4×10^{-5} [c]	0.22 (0.0-0.43)[d]
LNG ICE [e]	80 (78-93)	8.4×10^{-5}	0.40 (0.37-0.43)

[a] Calculated with emission data from [69], [70], [71] and CO_2-eq data from [68].
[b] Calculated with emission data from [69] and CO_2-eq data from [68].
[c] Assumed to give the same level of acidifying emissions as LNG [22].
[d] Assumed produce be the same level of PM_{10} emissions as MeOH ICE [22].
[e] Impact of LNG ICE from Hansson et al. (2019) [22].

In table 6.7 the impacts for the social sub-criteria of the ammonia alternatives are presented. The *safety* sub-criterion is evaluated as a combination of the performance of the fuel towards the safety classifications: risk of fire or explosion, flammability limits in air, auto-ignition temperature, flash point, toxicity classification, related health hazards and if the fuel is classified as a cryogenic liquid. The impact is then calculated as the average of the performance towards the safety classifications and the indicator scores of this sub-criterion can be found in table C.6 in Appendix 3. Since all of the ammonia alternatives use the same chemical compound the safety impact becomes equal among them and the results mainly reflects the toxic nature of ammonia. In the *upcoming legislation* sub-criterion the fuels are evaluated towards their possibility to reach coming legislation on SO_2, NO_x tier III, GHG targets (reduction to 50% tailpipe GHG emission year 2050 and 0% fuel life cycle GHG emissions year 2100 compared to the levels 2008) as well as emissions of PM, CH_4 and NH_3. The indicator score for the *upcoming legislation* sub-criterion can be found in table C.7 in Appendix 3. There are no emissions of SO_2 when using any of the ammonia options since ammonia do not contain any sulphur. Regarding the compliance with NO_x Tier III, the NH_3 FC options will be able to meet this [72], however the NH_3 ICEs need SCR technology [48][73], which results in a lower score. All ammonia options are assumed to be able to meet the 2050 target with a reduction of the tailpipe shipping GHG emissions to 50%, however the two options which use natural gas for the ammonia production are assumed to not be able to meet the 2100 targets where the entire fuel life cycle is included. From this the ammonia option with the best impact on the sub-criterion *upcoming legislation* is thus Elec-NH_3 FC, thereof also has the best performance of the ammonia options in the social criteria.

Table 6.7: Impact matrix for social criteria for ammonia alternatives on a scale 1-4 representing; (*Poor, Moderate, Fairly well, Good*). The impacts of LNG ICE is included as a reference. The presented impact values are calculated as average indicator scores.

Alternative	*Safety*	*Upcoming legislation*
NG-NH_3 FC	2.3[a]	3.5[b]
Elec-NH_3 FC	2.3[a]	3.9[b]
NG-NH_3 ICE	2.3[a]	2.9[c]
Elec-NH_3 ICE	2.3[a]	3.3[c]
LNG ICE [d]	2.5	2.8

[a] Based on safety data from [41], [74], [75], [76], [77], [78].
[b] Based on data from [72].
[c] Based on data from [48], [73].
[d] Impact of LNG ICE from Hansson et al. (2019) [22].

6.2.2 Pairwise comparison matrices and priorities

The results from the pairwise comparisons matrices are presented as the normalised priorities for the sub-criteria in figure 6.17-6.20. The tables of the sub-criteria priorities for all fuel options can be found in table C.9-C.12 Appendix 3.

In figure 6.17 the normalised priorities for the economic sub-criteria are presented. The fuel with the highest priority for the *investment cost* sub-criterion is the HVO ICE while the two H_2 FC options has the lowest priority followed by the NH_3 FCs. When investing in a HVO ICE ship, conventional marine diesel engines can be applied, which results in a lower investment cost than for the other options. FC technology on the other hand is more expensive, less mature and used together with fuel options that needs a more complicated and expensive storage solutions, e.g. hydrogen is stored in cryogenic state. Similar patterns can be observed in the priorities for the *operational cost* sub-criterion where both HVO and methanol are liquid fuels that are easy to handle on-board. The *fuel cost* priorities show that the fuel options that are produced from renewable resources have lower priorities than the fossil based options. All the fossil fuel alternatives are produced from natural gas which gives the LNG ICE option an advantage for lowering the production cost and thus the fuel price since less processing of the natural gas is needed. For the options NG-NH_3 FC and NG-H_2 FC this is compensated for by their higher energy efficiency and smaller fuel energy requirements for the same operating conditions. Therefore NG-H_2 FC becomes the option with the highest priority in the *fuel cost* sub-criterion followed by LNG ICE.

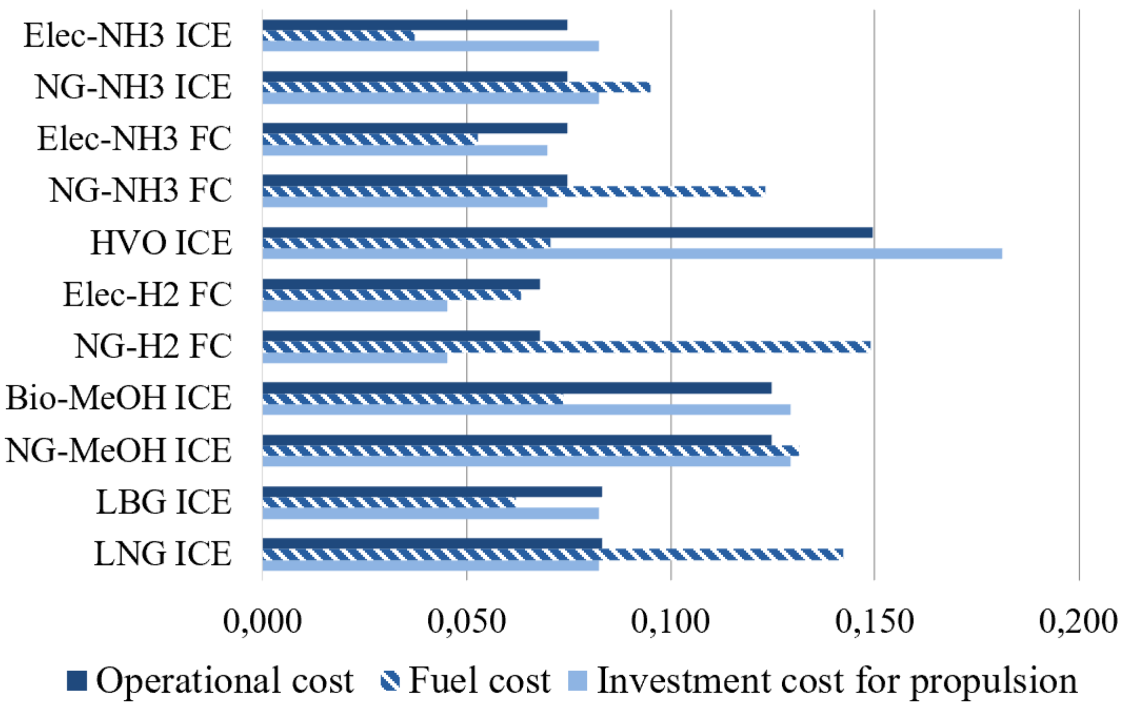

Figure 6.17: Normalised priorities from pairwise comparison matrices of economic sub-criteria. A high priority for an option corresponds to a low cost.

The normalised priorities for the technical sub-criteria are presented in figure 6.18. The pairwise comparison of the *available infrastructure* sub-criterion favours the HVO ICE option followed by LNG ICE. As mentioned before, HVO can be used in conventional marine engines and due to its similarities with diesel it is fairly easy to adapt the current fuel infrastructure to HVO use. LNG ICE also performs well with a high priority which originates from the fact that LNG is already implemented and used in the shipping sector. The H_2 options have the lowest priority due to the large investments that needs to be done in order to have a working H_2 infrastructure. Ammonia is already handled in ports for shipping, although the infrastructure must be adapted to bunkering instead of loading of ammonia which can explain why these options get a higher priority than H_2. However there are other challenges with the maturity of ammonia propulsion technologies compared to the other fuels. In the sub-criterion *reliable supply of fuel* the options that use electrolysis powered by renewable electricity are ranked highest although the current production and use of these fuels is limited. LNG ICE has the second highest priority which mainly originates from its current use as marine fuel and high production rate.

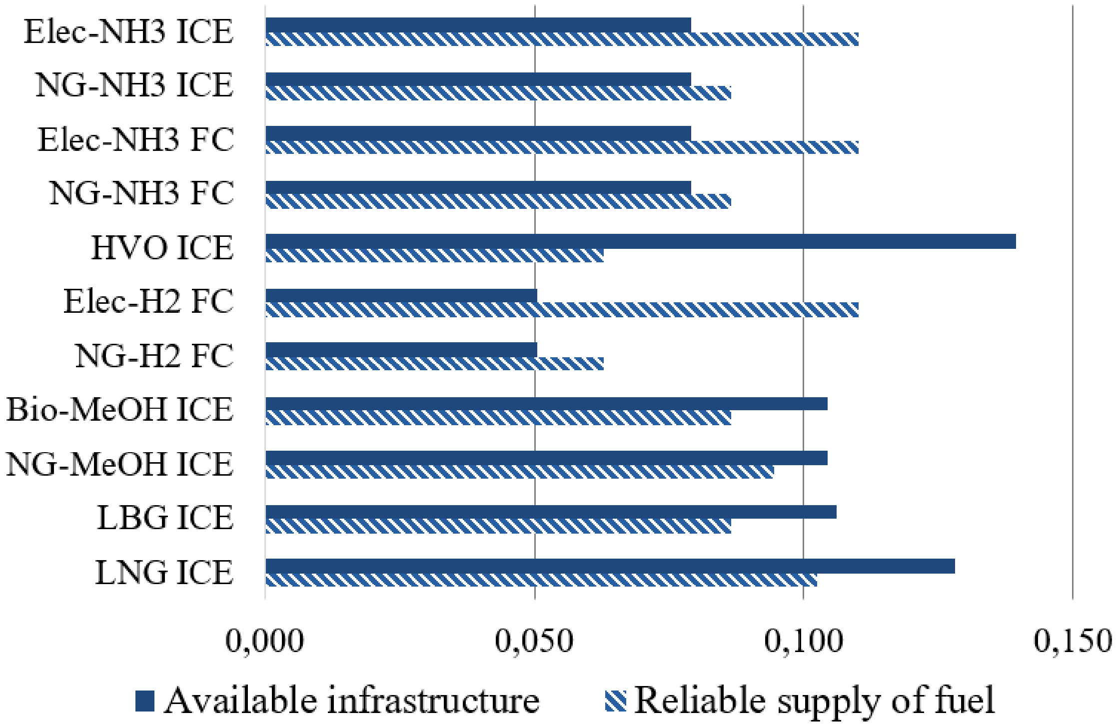

Figure 6.18: Normalised priorities from pairwise comparison matrices of technical sub-criteria. A high priority represents that the option have a good available infrastructure or a reliable supply.

In figure 6.19 the priorities for the environmental sub-criteria are presented. The pairwise comparison of the sub-criterion *climate change* display Bio-MeOH ICE and Elec-H_2 FC as best performing. Bio-MeOH ICE and Elec-H_2 FC both perform well since they originate from renewable resources giving low life cycle GHG emissions. The second best priority is held by HVO ICE and the two Elec-NH_3 options which are also produced from renewable resources. The fuel options originating from fossil resources all perform poorly. Although LBG ICE is produced from biomass residues it performs poorly in this sub-criterion compared to the other biofuels as a result from its high contribution of methane to the GWP which is a stronger GHG than CO_2. The pairwise comparison of sub-criterion *acidification* display priorities of both hydrogen fuel options (NG-H_2 FC, Elec-H_2 FC) and two of the ammonia fuel options (NG-NH_3 FC, Elec-NH_3 FC) as best performing. The common factor is that the mentioned fuels are all combined with FCs as propulsion system and therefore the emissions of acidifying compounds are mitigated compared to the options that utilises ICEs. The remaining ammonia fuel alternatives (NG-NH_3 ICE, Elec-NH_3 ICE) together with LNG ICE and LBG ICE hold the second highest priority. The ICE ammonia alternatives are assumed to be combined with SCR since there is a large uncertainty regarding emissions of NO_x from ammonia utilisation and data from emission testing in marine engines has not been found. The pairwise comparison on the sub-criterion *health impact* display the same four fuels as the pairwise comparison of the sub-criterion *acidification* as best performing. PM as well as NO_x is highly coupled with the high operating temperatures of ICEs and therefore the

FC alternatives hold the highest priorities.

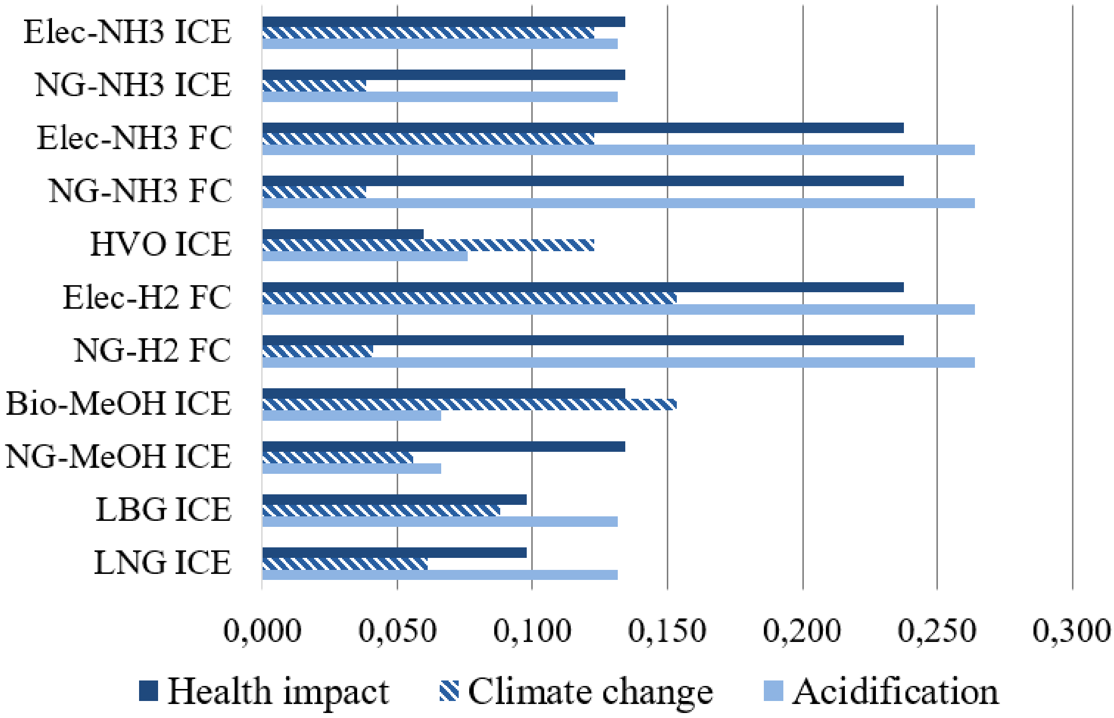

Figure 6.19: Normalised priorities from pairwise comparison matrices of environmental sub-criteria. A high priority represents that the option have small emissions and environmental impact.

The priorities for the social sub-criteria are presented in figure 6.20. The pairwise comparison of the *safety* sub-criterion favours the HVO ICE followed by LNG ICE, LBG ICE and the two hydrogen options. HVO has the highest priority since it is neither classified as explosive, toxic or as cryogenic liquid under CLP criteria. All ammonia options are among the poorest performing fuels. This is due to the fact that ammonia is classified as toxic and hazardous to both humans and aquatic life. However, it can be argued that because ammonia is a well known chemical substance risks associated with ammonia can be somewhat compensated by the extensive handling experience. Yet, ammonia has not been previously demonstrated and used as a marine fuel and therefore new safety regulations need to be developed to handle the safety risks associated with ammonia. The pairwise comparison of *upcoming legislation* display Elec-H_2 FC followed by Elec-NH_3 FC with the highest priorities. Both fuels comply with upcoming SO_x and NO_x legislation as well as GHG emission targets. The priority of Elec-NH_3 FC is slightly lower than the priority of Elec-H_2 because there is an uncertainty regarding ammonia emissions from handling and propulsion. The two other fuel alternatives with FC as propulsion system (NG-H_2 FC, NG-NH_3 FC) also have high priorities due to the fact that they comply with all upcoming legislation and targets except GHGs 2100 0% which they fail due to their fossil origin. All fuel options originating from fossil fuels fail one or more of the included upcoming legislation and GHG targets and the lowest priority is held by LNG ICE together with NG-MeOH ICE which fail both NO_x Tier III and GHGs 2100 0% target.

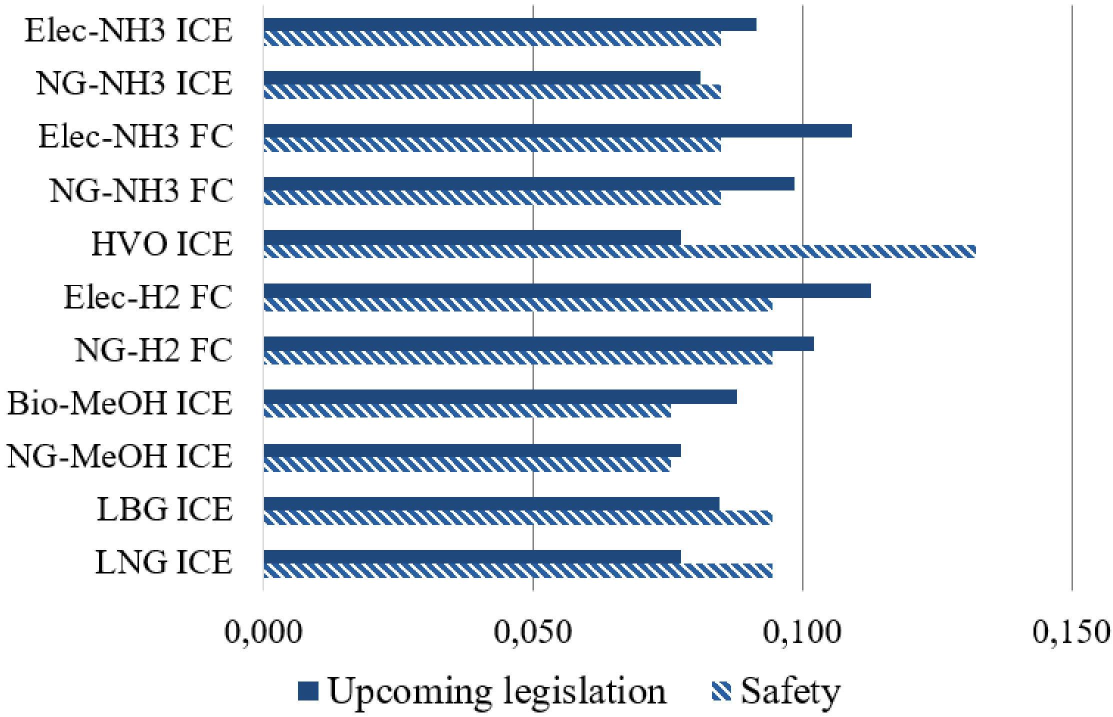

Figure 6.20: Normalised priorities from pairwise comparison matrices of social sub-criteria.

6.2.3 Ranking of alternative fuels

The final ranking by the MCDA of the alternative fuels is presented in figure 6.21, represented by the idealised global priorities. The global priorities are determined by applying linear combination of the sub-criteria priorities with the weights of the criteria and sub-criteria. The idealised global priority is then achieved by dividing the global priorities with the maximum global priority value, which results in the most preferred fuel having an idealised global priority equal to 1. The most preferred alternative fuel is Elec-H_2 FC followed by Elec-NH_3 FC, and on 3rd and 4th place are NG-H_2 FC and NG-NH_3 FC. Thus all of the FC options are the most preferred options in the base case. The NG-NH_3 ICE option is ranked poorest. The HVO ICE alternative is ranked higher than LNG ICE as well as the two MeOH ICE options, where the Bio-MeOH ICE is slightly more preferred than NG-MeOH ICE. Fuel options with hydrogen produced by electrolysis is more preferred than the corresponding options produced by hydrogen originating from natural gas.

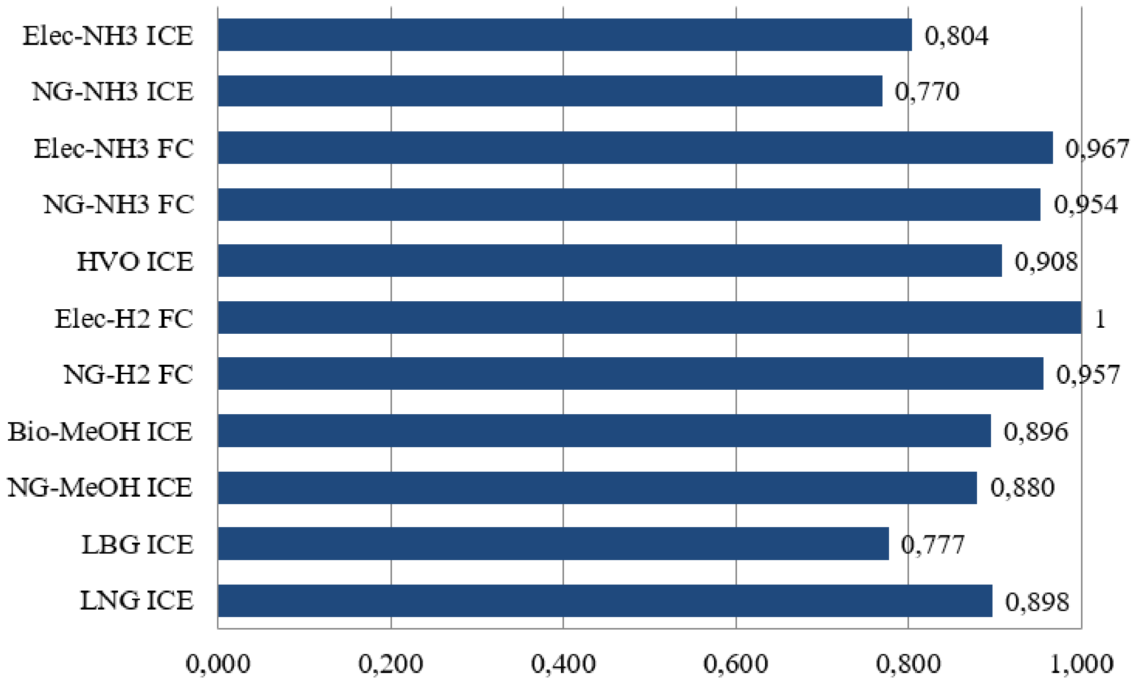

Figure 6.21: Idealised ranking of alternative marine fuels in base case.

6.2.4 Sensitivity analysis

The sensitivity analysis of the result from the MCDA is divided into two parts, alternative score scenarios and alternative weights scenarios (role-play) and are presented separately below.

6.2.4.1 Change of fuel score in sub-criteria scenario descriptions

The first method to test the robustness of the result is by changing the score on how well the different fuels fulfill the sub-criteria. Not all scores or sub-criteria are tested, but the most uncertain and strongest assumptions are tested in 11 scenarios:

1. Increasing the propulsion efficiency of the ICE powered ships from 40% to 50%.

2. Changing the fuel price by including a CO_2-tax of 50 USD/ton of CO_2-eq based on the life cycle GHG emissions of each fuel.

3. Changing the fuel price by including a CO_2-tax of 100 USD/ton of CO_2-eq based on the life cycle GHG emissions of each fuel.

4. Changing the fuel price by including a CO_2-tax of 150 USD/ton of CO_2-eq based on the life cycle GHG emissions of each fuel.

5. Decreasing the cost of H_2 production by electrolysis to the same cost as H_2 production by SMR. Changing so that all ammonia fuel alternatives have the same production cost.

6. Changing the evaluation of the sub-criterion climate change from GWP_{100} to GWP_{20}.

7. Changing reliable supply of fuel to Poor (1) for all fossil fuel based fuels (LNG ICE, NG-MeOH ICE, NG-H_2 FC, NG-NH_3 FC, NG-NH_3 ICE).

8. Assuming the same safety ranking for NH_3 as for H_2 (2.5).

9. Changing upcoming legislation to Poor (1) on all fuels that cannot comply with the IMO 2050 target without complementary solutions (LNG ICE, LBG ICE, NG-MeOH ICE, Bio-MeOH ICE).

10. Changing upcoming legislation to Poor (1) on all fuels that cannot comply with the IMO 2100 target without complementary solutions (LNG ICE, LBG ICE, NG-MeOH ICE, NG-H_2 FC, NG-NH_3 FC, NG-NH_3 ICE).

11. Changing the investment cost for propulsion of the ammonia and hydrogen ship options by both lowering and increasing the FC and ICE costs. The same assumptions are applied as for the calculation of minimum and maximum values in the spans for the GET MC analysis, but only applied to the ammonia and hydrogen Ocean ships.

6.2.4.2 Result from alternative score scenarios

In table 6.8 - 6.12 the sensitivity analysis results from eight of the alternative score scenarios are presented. The results from the remaining three sensitivity scenarios (scenario 6, 8 and 11) can be found in table C.13 - C.15 in Appendix 3. Five of the tested sensitivity scenarios handles the *fuel cost* sub-criterion as it is the sub-criterion with the heaviest weight as well as one of the most uncertain since it is difficult to predict future fuel costs. In each table below, the new normalised priority of the sub-criterion is presented as well as the difference to the normalised priority of the sub-criterion in the base case scenario. Included in the tables are also the new ranking and base case ranking to facilitate comparison.

In table 6.8 the results from scenario 1 is presented where the assumed propulsion efficiency for ICE has been changed from 40% to 50% which affect the sub-criterion *fuel cost*. Small changes can be observed in the sub-criterion priorities, and the ranking is only affected for two of the fuel options (HVO ICE and LNG ICE swap places).

Table 6.8: Result from alternative score scenario 1.

	Sub-criterion priority	*Difference in sub-criterion priority*	*New global ranking*	*Base case ranking*
Propulsion efficiency	Fuel cost			
Elec-NH_3 ICE	0.038	+0.001	9	9
NG-NH_3 ICE	0.100	+0.005	11	11
Elec-NH_3 FC	0.045	-0.008	2	2
NG-NH_3 FC	0.113	-0.010	4	4
HVO ICE	0.073	+0.003	**6**	5
Elec-H_2 FC	0.054	-0.009	1	1
NG-H_2 FC	0.141	-0.008	3	3
Bio-MeOH ICE	0.077	+0.003	7	7
NG-MeOH ICE	0.140	+0.009	8	8
LBG ICE	0.064	+0.002	10	10
LNG ICE	0.153	+0.011	**5**	6

The results from the sensitivity scenarios 2, 3 and 4 are presented in table 6.9 where a CO_2 tax of 50, 100 and 150 USD/ton CO_2-eq has been introduced. The addition of the taxes affect the sub-criterion *fuel cost* and results in some changes of the ranking. In all CO_2 tax scenarios, the fuels that are produced from renewable resources receives higher priorities in the sub-criterion than in the base case, except Elec-NH_3 ICE which remains intact in scenario 2 and 3 but marginally disfavoured in scenario 4. The priorities of the fossil based fuels is lowered, except for LNG ICE which is improved. Since the priorities are calculated from the pairwise comparison matrices of the sub-criterion it is the relative fuel cost between the fuels that affects the deterioration or improvement of the priority of an option. This could explain the changes in priorities of LNG ICE and Elec-NH_3 ICE. The higher the CO_2 tax the more drastic changes in the ranking order can be observed. However the most preferred fuel option Elec-H_2 FC is also having the smallest GHG emissions, a further increase in CO_2 tax should strengthen its top ranking since the priority is continuously increasing throughout scenario 2, 3 and 4.

Table 6.9: Results from alternative score scenarios 2, 3 and 4.

	Sub-criterion priority	*Difference in sub-criterion priority*	*New global ranking*	*Base case ranking*
CO_2-tax 50 USD/ton	Fuel cost			
Elec-NH_3 ICE	0.037	0.000	9	9
NG-NH_3 ICE	0.075	-0.020	11	11
Elec-NH_3 FC	0.056	+0.003	2	2
NG-NH_3 FC	0.114	-0.009	4	4
HVO ICE	0.078	+0.007	5	5
Elec-H_2 FC	0.071	+0.008	1	1
NG-H_2 FC	0.146	-0.003	3	3
Bio-MeOH ICE	0.084	+0.011	**6**	7
NG-MeOH ICE	0.128	-0.004	8	8
LBG ICE	0.063	+0.001	10	10
LNG ICE	0.148	+0.006	**7**	6
CO_2-tax 100 USD/ton	Fuel cost			
Elec-NH_3 ICE	0.037	0.000	9	9
NG-NH_3 ICE	0.060	-0.035	11	11
Elec-NH_3 FC	0.060	+0.008	2	2
NG-NH_3 FC	0.103	-0.021	**6**	4
HVO ICE	0.087	+0.017	5	5
Elec-H_2 FC	0.082	+0.019	1	1
NG-H_2 FC	0.137	-0.012	**4**	3
Bio-MeOH ICE	0.101	+0.027	**3**	7
NG-MeOH ICE	0.119	-0.012	8	8
LBG ICE	0.065	+0.003	10	10
LNG ICE	0.149	+0.006	**7**	6
CO_2-tax 150 USD/ton	Fuel cost			
Elec-NH_3 ICE	0.036	-0.001	9	9
NG-NH_3 ICE	0.047	-0.048	11	11
Elec-NH_3 FC	0.064	+0.012	2	2
NG-NH_3 FC	0.088	-0.035	**7**	4
HVO ICE	0.099	+0.029	**4**	5
Elec-H_2 FC	0.099	+0.035	1	1
NG-H_2 FC	0.123	-0.026	**5**	3
Bio-MeOH ICE	0.127	+0.053	**3**	7
NG-MeOH ICE	0.107	-0.024	8	8
LBG ICE	0.065	+0.003	10	10
LNG ICE	0.145	+0.002	6	6

In scenario 5 the cost for electrolysis is tested by lowering the raw material price of electricity to the same level as natural gas. Further the production cost for all the ammonia alternatives are assumed to be equal. The results from this scenario is presented in table 6.10. The sub-criterion priorities are significantly improved for the options that make use of the electrolysis technology however the ranking of these are not affected. Some changes can be observed in the places 5-8, yet they are small.

Table 6.10: Results from alternative score scenario 5.

	Sub-criterion priority	*Difference in sub-criterion priority*	*New global ranking*	*Base case ranking*
Electrolysis price low	Fuel cost			
Elec-NH_3 ICE	0.063	+0.025	9	9
NG-NH_3 ICE	0.067	-0.028	11	11
Elec-NH_3 FC	0.095	+0.043	2	2
NG-NH_3 FC	0.102	-0.021	4	4
HVO ICE	0.044	-0.027	**6**	5
Elec-H_2 FC	0.148	+0.085	1	1
NG-H_2 FC	0.148	-0.001	3	3
Bio-MeOH ICE	0.047	-0.027	**8**	7
NG-MeOH ICE	0.115	-0.016	**7**	8
LBG ICE	0.037	-0.025	10	10
LNG ICE	0.134	-0.008	**5**	6

In table 6.11 the results from scenario 7, where the sub-criterion score of *reliable supply of fuel* has been changed to Poor (1) for all the fossil based fuels, is presented. All of the priorities are affected. The options that are based on renewable resources are strengthened by the change while the fossil based alternatives receives a weakened priority. Several changes in the global ranking in places 4-9 can be identified where the renewable options Elec-NH_3 ICE, HVO ICE and Bio-MeOH ICE climbs one step in the ranking.

Table 6.11: Result from alternative score scenario 7.

	Sub-criterion priority	*Difference in sub-criterion priority*	*New global ranking*	*Base case ranking*
Poor fossil supply	Reliable supply of fuel			
Elec-NH_3 ICE	0.144	+0.034	**8**	9
NG-NH_3 ICE	0.052	-0.035	11	11
Elec-NH_3 FC	0.144	+0.034	2	2
NG-NH_3 FC	0.052	-0.035	**6**	4
HVO ICE	0.082	+0.019	**4**	5
Elec-H_2 FC	0.144	+0.034	1	1
NG-H_2 FC	0.052	-0.011	3	3
Bio-MeOH ICE	0.113	+0.027	**5**	7
NG-MeOH ICE	0.052	-0.042	**9**	8
LBG ICE	0.113	+0.026	10	10
LNG ICE	0.052	-0.050	**7**	6

In table 6.12 the results from the sensitivity scenarios 9 and 10 are presented where the sub-criterion *upcoming legislation* has been changed. In scenario 9 the fuels that cannot comply with the IMO 2050 target of halving the tailpipe exhaust GHG emissions without complementary solutions has been given the score Poor (1) (LNG ICE, LBG ICE, NG-MeOH ICE, Bio-MeOH ICE, HVO ICE). The IMO 2100 target of 0% life cycle emissions of GHG is tested in scenario 10 where the score of the alternatives that cannot comply with this target without complementary solutions has been changed to Poor (1) (LNG ICE, LBG ICE, NG-MeOH ICE, NG-H_2 FC,

$NG\text{-}NH_3$ FC, $NG\text{-}NH_3$ ICE). The changes from the base case score to poor results in distinct changes of the sub-criterion priorities and changes in the global ranking in both scenario 9 and 10. In scenario 9 where only the tailpipe emissions are considered changes in the ranking can be observed in 6th-11th place where the options with an improvement of their sub-criterion priority are favoured. When the fuel life cycle emissions are taken into consideration in scenario 10 the ranking order change for seven of the eleven options, where the options produced from renewable resources are promoted.

Table 6.12: Results from alternative score scenarios 9 and 10.

	Sub-criterion priority	*Difference in sub-criterion priority*	*New global ranking*	*Base case ranking*
Upcoming legislation 2050	Upcoming legislation			
Elec-NH_3 ICE	0.124	+0.033	**6**	9
NG-NH_3 ICE	0.110	+0.029	**10**	11
Elec-NH_3 FC	0.148	+0.039	2	2
NG-NH_3 FC	0.134	+0.035	4	4
HVO ICE	0.038	-0.039	5	5
Elec-H_2 FC	0.153	+0.040	1	1
NG-H_2 FC	0.139	+0.037	3	3
Bio-MeOH ICE	0.038	-0.050	**8**	7
NG-MeOH ICE	0.038	-0.039	**9**	8
LBG ICE	0.038	-0.047	**11**	10
LNG ICE	0.038	-0.039	**7**	6
Upcoming legislation 2100	Upcoming legislation			
Elec-NH_3 ICE	0.141	+0.049	**7**	9
NG-NH_3 ICE	0.043	-0.038	11	11
Elec-NH_3 FC	0.168	+0.059	2	2
NG-NH_3 FC	0.043	-0.055	**5**	4
HVO ICE	0.120	+0.042	**3**	5
Elec-H_2 FC	0.174	+0.061	1	1
NG-H_2 FC	0.043	-0.059	**6**	3
Bio-MeOH ICE	0.136	+0.048	**4**	7
NG-MeOH ICE	0.043	-0.034	**9**	8
LBG ICE	0.043	-0.041	10	10
LNG ICE	0.043	-0.034	**8**	6

6.2.4.3 Stakeholder-group role-play weights

In the second part of the sensitivity analysis of the MCDA, the weights from the role-play in the study by Månsson (2017) is used and shown in table 6.13 below [7]. This is to evaluate how sensitive the global ranking of the alternative fuels is towards the perspectives from different stakeholder-groups. The stakeholder-groups included are; i) government authorities, ii) ship owners, iii) fuel manufacturers and iv) engine manufacturers.

Table 6.13: Criteria and sub-criteria weights from base case and stakeholder group role-play.

	Base case	*Authorities*	*Ship owner*	*Fuel manufacturer*	*Engine manufacturer*
Economic	**0.316**	**0.113**	**0.538**	**0.472**	**0.472**
Investment cost	0.258	0.250	0.199	0.230	0.230
Operational cost	0.162	0.250	0.068	0.122	0.122
Fuel cost	0.580	0.500	0.733	0.648	0.648
Technical	**0.166**	**0.073**	**0.165**	**0.285**	**0.285**
Available infrastructure	0.294	0.167	0.200	0.200	0.200
Reliable supply of fuel	0.706	0.833	0.800	0.800	0.800
Environmental	**0.239**	**0.407**	**0.045**	**0.073**	**0.073**
Climate change	0.499	0.731	0.674	0.582	0.105
Acidification	0.205	0.188	0.101	0.109	0.258
Health impact	0.296	0.081	0.266	0.309	0.637
Social	**0.278**	**0.407**	**0.251**	**0.170**	**0.170**
Safety	0.477	0.250	0.800	0.167	0.167
Upcoming legislation	0.523	0.750	0.200	0.833	0.833

Weights from Månsson (2017) [7]

6.2.4.4 Results from stakeholder role-play scenarios

The results from the sensitivity analysis with the criteria weights based on different stakeholder group perspective are presented as idealised global priorities in figures 6.22-6.25 respectively.

The final ranking of alternative marine fuels by the distribution of criteria weights from an authority perspective is presented in figure 6.22. The most preferred fuel is Elec-H_2 followed by Elec-NH_3 FC, Bio-MeOH ICE and on fourth place Elec-NH_3 ICE. The relative ranking order is similar to the final ranking of alternative fuels presented for base case in figure 6.21 with some exceptions. LNG ICE has dropped from its 5th place to 9th, while LBG ICE has improved from 10th to 8th. Generally the fossil based fuel options perform poorly. The criteria priorities of the stakeholder group authority display that the most important criteria are environmental and social criteria strongly prioritised over economic and technical criteria. Within the environmental and social criteria, sub-criteria *climate change* respectively *upcoming legislation* dominate. Thus, more weight is put on fuel performance regarding emissions aggregated to GWP_{100} and whether the fuel will reach upcoming climate targets, and this mainly affect the fossil fuel option rankings held in the base case.

The final ranking of alternative marine fuels by the distribution of criteria weights from a ship owner perspective is presented in figure 6.23. The most preferred fuel is LNG ICE followed by NG-MeOH ICE, NG-H_2 FC and HVO ICE on 4th place. The bottom placements are held by the fuels produced by electrolysis (Elec-NH_3 ICE, Elec-NH_3 FC and Elec-H_2) together with LBG ICE. The criteria priorities of the ship owner stakeholder group display that the dominating criteria is the economic criteria. Within the economic criteria, the sub-criterion *fuel cost* dominate. Since the fuel price of LNG and the other natural gas based fuels is lower compared to the fuel price of the electrolysis based fuels, there is a shift towards top-placements for fossil based fuels compared to the base case ranking.

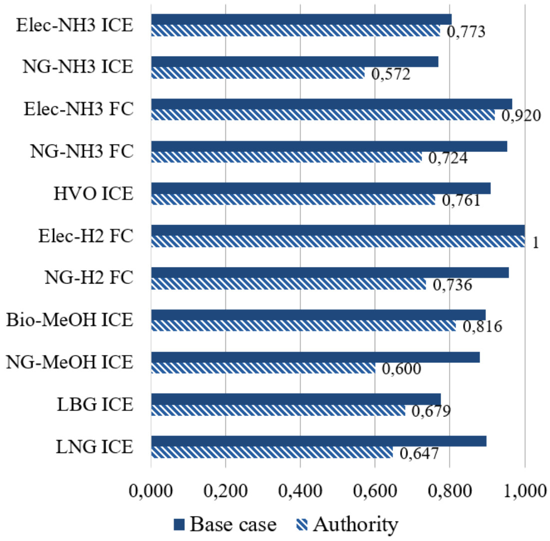

Figure 6.22: Authority ranking.

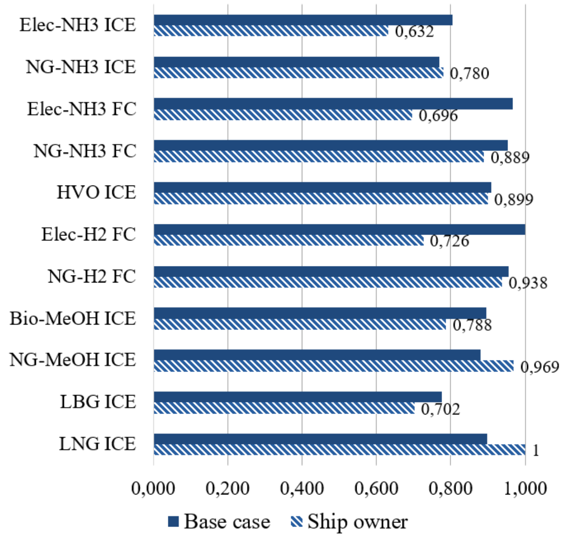

Figure 6.23: Ship owner ranking.

The final ranking of alternative marine fuels by distribution of criteria weights from a fuel manufacturer perspective is presented in figure 6.24. The most preferred fuel is NG-MeOH ICE followed by LNG ICE, NG-NH_3 FC and NG-H_2 FC. The criteria priorities of the fuel manufacturer stakeholder group display that the most important criteria is the economic criteria followed by the technical criteria. The most important sub-criteria is *fuel cost* respectively *reliable supply of fuel*. Like the scenario of ship owner ranking of criteria, the sub-criterion *fuel cost* is most important and the same trend favouring fossil based fuels can be observed. In the bottom of the ranking the Elec-NH_3 ICE, LBG ICE and NG-NH_3 ICE options can be found, which is similar to the base case ranking with the swapping of places by NH_3 ICE options.

The final ranking of alternative marine fuels by distribution of criteria weights from an engine manufacturer perspective is presented in figure 6.25. The most preferred fuel is NG-MeOH ICE followed by LNG ICE, NG-NH_3 FC and NG-H_2 on 4th place. The criteria priorities of the engine manufacturer stakeholder group display that the most important criteria is the economic criteria followed by the technical criteria, and the dominating sub-criterion in each of these is *fuel cost* respectively *reliable supply of fuel* as for the criteria ranking by the fuel manufacturer previously presented. Only slight changes can be observed compared to the ranking by the fuel manufacturer, where Elec-NH_3 FC climbs from 8th to 6th place. This is a result from the changes of importance in the environmental sub-criteria where the engine manufacturers put more focus on *health impact*. The least preferred fuel options according to the engine manufacturer perspective are Elec-NH_3 ICE and LBG ICE.

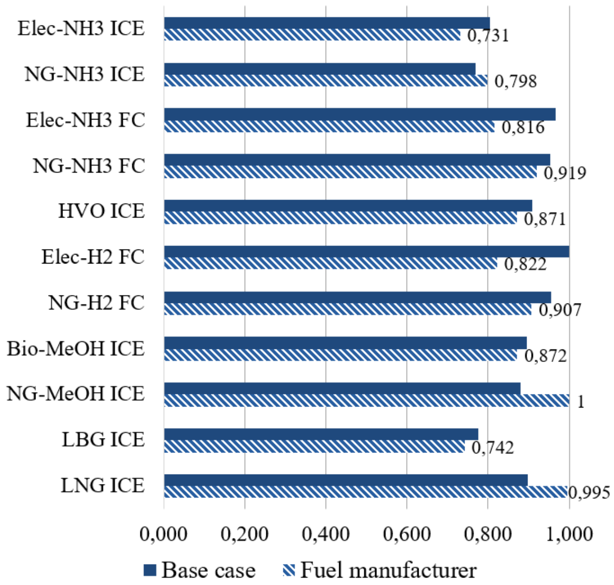

Figure 6.24: Fuel manufacturer ranking

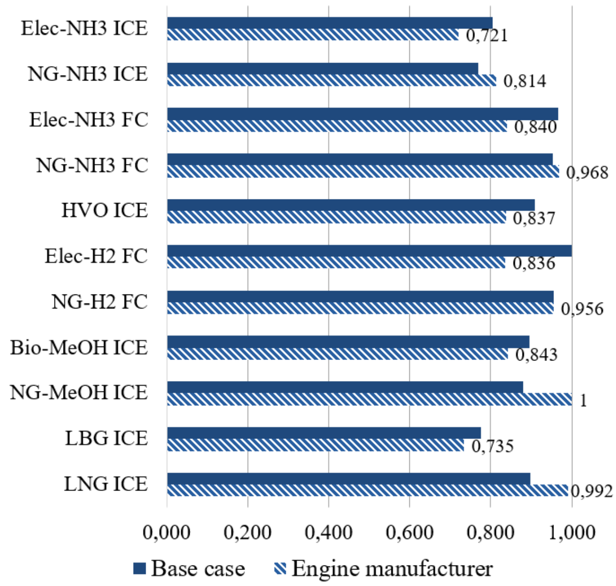

Figure 6.25: Engine manufacturer ranking

7
Discussion

In this chapter the results of the two applied methods are discussed and future work is suggested. Included is also a section discussing the reliability of the results.

7.1 Potential of ammonia as marine fuel

One of the main reasons for considering ammonia as an alternative marine fuel is that it is a carbon-free molecule allowing the potential of zero emissions of GHGs from a tailpipe perspective. However, in order to achieve low GHG emissions from a life cycle perspective the utilised ammonia has to be produced from renewable sources. As previously mentioned, it is possible to use ammonia as a fuel for both ICEs and FCs and the tailpipe emissions depend on which technology that is used. As no sulphur is present in ammonia, there will be no SO_x emissions regardless of which propulsion system that is applied.

Another potential carbon-free alternative fuel is hydrogen, and because of this ammonia is often compared to hydrogen when assessed. Ammonia is a well known chemical substance produced and traded globally with significant infrastructure, handling experience and safety regulations for production and distribution in place. Hydrogen distribution infrastructure is on the other hand not yet available in significant amounts. Because of the extensive risk of explosion when hydrogen is mixed with air, considerable safety systems must be designed. When comparing the existing infrastructure of ammonia to LNG, LNG is mainly favoured by already being introduced as a fuel in the shipping sector and important infrastructure has already started to be developed.

One of the main disadvantages of ammonia is that it is a toxic substance and hazardous both to humans and aquatic life. The toxicity must be considered when designing the fuel handling system for both bunkering as well as during operation to ensure the safety of people and environment. A barrier for implementation of ammonia as an alternative marine fuel is the lack of regulations in place managing the use of ammonia as a marine fuel. Also there is a lack of research and real projects on ammonia as a fuel for marine applications. Because research about ammonia fuelled marine engines is very limited it is unclear how much NO_x is emitted when ammonia is combusted. Nonetheless it is probable that SCR is needed to meet emission regulations which is what has been assumed for the assessments performed in this thesis.

Another important aspect to have in mind when assessing the potential of ammonia as an alternative marine fuel is its other applications. The currently largest market for ammonia is the fertiliser industry where about 80% of the produced ammonia is used. This raises the concern that there could be a risk of affecting the food prices if the demand for ammonia increase which would be the case if ammonia is to be used as a shipping fuel. The majority of the currently produced ammonia originates from natural gas which entail that the price of natural gas highly governs the price of ammonia. Since natural gas is a fossil resource the price of ammonia could be vulnerable in the future considering the potential of gas depletion or carbon taxes. However if a larger share of ammonia is produced by renewable resources the price would not be as coupled with the feedstock supply.

7.2 Global Energy Transition Model

The results obtained from the GET model suggest that for both assessed CO_2 constraint scenarios, it would be cost-effective with a shift in applied propulsion technology from ICE which dominates in the beginning of the century to FC technology which constitute approximately 90% at 2100 in both scenarios. One of the reasons that FCs out-compete ICEs towards the end of the studied time period is believed to be that FC propulsion systems emit less CO_2/kW than ICEs, and this is needed to meet the constraint of CO_2 at 2100. Another key parameter is believed to be the difference in efficiency of ICEs and FCs. As FCs have a higher efficiency they require less fuel than ICEs for the same distance which imply a decreased fuel cost and this also affect the required amount of storage which is an important vessel cost parameter especially for the fuels in need of cryogenic storage. As the model make the choice of fuel and propulsion system based on costs, the results thus suggests that FC is the cost-effective propulsion technology in the future.

Since combustion technology is the most commonly used propulsion technology worldwide within shipping today, there is a need of incentives to realise the transition towards FC technology. Ships generally have a long life time and thus it is important that policymakers incentivise FC technology in the near future towards shipping investors for new ships to be built with FC propulsion systems, however it may also be an alternative to change the propulsion system of existing ships. As FC propulsion systems within shipping is still a new technology there is also a need of more research towards the use of FCs for marine purposes before the transition from ICEs can be realised. The results also suggest that the new fuels (hydrogen and ammonia) mainly are cost-effective with FCs as propulsion system.

The results obtained from the GET model display that under a 450 ppm CO_2 constraint, LNG ICE act as a transition fuel substituting the declining use of MGO. The use of LNG ICE is in turn substituted with H_2 FC which seem to be the long term cost-effective fuel for the shipping sector. The results obtained from the GET model under 550 ppm CO_2 constraint display that the major difference to the 450 ppm CO_2 scenario is that LNG FC acts as a transition fuel for LNG ICE instead of H_2 FC as in the 450 ppm CO_2 scenario. Thus, the share of hydrogen is significantly lower and even though it penetrates in 2030 it does not reach significant amounts until 2080 and onward. This also result in a smaller penetration of ammonia. Consequently the use of non carbon based alternative fuels are delayed under a less stringent CO_2 constraint.

Since both ammonia and hydrogen are carbon-free fuels by their molecular structure, it is interesting to compare the two fuels. The additional vessel cost compared to MGO ICE is lower for ammonia vessels than hydrogen vessels, yet, ammonia is not near as cost-effective as hydrogen. An explanation to this might be that the production cost is significantly lower for hydrogen than for ammonia and the production pathway for ammonia as implemented in the model uses hydrogen as a precursor. Thus, the fuel cost seems to be an important parameter to the cost-effectiveness of ammonia. However, this is contradictory to the results of the MC analysis analysing the sensitivity of ammonia synthesis investment cost and ammonia synthesis energy efficiency which both affect the fuel cost. The MC analysis display that there is almost no correlation to the ammonia synthesis investment cost and ammonia synthesis energy efficiency to the amount of ammonia in the system for the investigated spans. These conflicting results indicate that the ammonia synthesis investment cost and ammonia synthesis energy efficiency probably do have an impact on the cost-effectiveness of ammonia as a shipping fuel but that the investigated spans in the MC analysis were not chosen wide enough to realise this. That the ammonia synthesis energy efficiency have an impact on the amount of ammonia in the system seem reasonable since the energy efficiency is coupled to the production cost of ammonia which is considerably high for ammonia compared to the other included fuels and an increase in synthesis efficiency thus slightly improve the cost-effectiveness of ammonia.

The total vessel cost of ammonia ships with FC system also seem to be an important parameter to the cost-effectiveness of ammonia and for this parameter there is a modest correlation to the amount of ammonia in the system. However, both the FC stack cost and the storage cost which are the two underlying parameters that are varied in the MC analysis are uncertain parameters. The FC stack cost is varied in a large range and therefore the FC stack cost might be over- or underestimated in the model.

As presented in the results, there is no correlation of the cost of ammonia ICE ships to the amount of ammonia in the system and this seems reasonable since it has been established that ICE as propulsion technology is not cost-effective in the future and ammonia penetrates in the mid century gaining its share in the end of the century when FCs dominate as propulsion technology. The total vessel cost for ICE ammonia ships is lower than FC ammonia ships for all ship categories. However the lower efficiency of ICEs and the need of more fuel is believed to make FC engines more cost-effective as previously discussed.

7.3 Multi-Criteria Decision Analysis

The alternative marine fuel that is ranked highest in the MCDA base case is Elec-H_2 FC which is a renewable option with small emissions of GHGs, NO_x and PM. The second most preferred alternative marine fuel is Elec-NH_3 FC which have similar emission characteristics as the Elec-H_2 FC option. The options that use ammonia performs both really well with a high ranking but also very poorly in the MCDA. According to the results in the base case it is only feasible to use ammonia in combination with FC, while the ICEs are ranked to be among the least preferred options. LNG ICE which is ranked in 6th place is an option which has already been introduced in the shipping sector and has possibilities to lower the emissions of GHG, SO_x, NO_x and PM compared to conventional fuels. The corresponding renewable option LBG ICE however is assigned a much lower ranking with its 10th place although having similar impacts as LNG in many of the sub-criteria.

Renewable alternative marine fuels are more preferred than their corresponding fossil option according to the base case ranking of the MCDA, except for the LBG/LNG case. All of the four top-ranked alternative fuels use FC technology, showing the potential use of this type of technology in the shipping sector. Characteristics of the FC that makes this possible are their low emissions of GHG, acidic- and PM emissions as well as high efficiency, which in combination with fuels produced from renewable electrolysis achieves a high ranking.

When analysing how the priorities of the sub-criteria are distributed it is possible to see that Elec-H_2 FC have the highest priority in five of the sub-criteria. The option in 5th place, HVO ICE, have the highest priority in four of the sub-criteria which is one more than Elec-NH_3 which has top priorities in three of the sub-criteria. This shows that the distribution of weights combined with the priorities of the sub-criteria and the difference in priorities among the option are important aspects to get a high ranking. The sub-criteria where HVO ICE is highly prioritised have a small weight when combined to find the global priority.

In the sensitivity analysis of the MCDA two different approaches was used to test the robustness of the result. The two approaches tested different aspects of the robustness, where the alternative score scenarios focused on the influence of the impacts in the sub-criteria and the role-play focused on the distribution of criteria and sub-criteria weights. In table 7.1 the average ranking of the fuels in the two sensitivity analysis approaches are presented. The average ranking in the alternative score scenarios is very similar to the ranking of the base case, while the average ranking differs more in the stakeholder group role-play. This indicates that how stakeholders prioritise the criteria and sub-criteria have a larger influence on the resulting ranking than changes of the score in a certain sub-criterion. The biggest difference from the base case ranking is that the economic criteria as well as the fuel cost sub-criterion is much more prioritised by three of the four stakeholder-groups favouring more known and mature fuels which to some extent already has been tested or introduced in the shipping sector.

Table 7.1: Average ranking in MCDA sensitivity analysis. Range of ranking in parenthesis.

	Alternative score scenarios	*Stakeholder group role-play*	*Base case ranking*
Elec-NH_3 ICE	8.6 (6-9)	9.3 (4-11)	9
NG-NH_3 ICE	10.7 (10-11)	9.0 (7-11)	11
Elec-NH_3 FC	2.0 (2)	6.5 (2-10)	2
NG-NH_3 FC	4.3 (3-7)	4.5 (3-7)	4
HVO ICE	5.1 (3-7)	5.5 (4-7)	5
Elec-H_2 FC	1.0 (1)	6.0 (1-8)	1
NG-H_2 FC	3.7 (3-6)	4.3 (3-6)	3
Bio-MeOH ICE	5.8 (3-8)	4.8 (3-6)	7
NG-MeOH ICE	8.1 (7-9)	3.5 (1-10)	8
LBG ICE	10.2 (10-11)	9.3 (8-10)	10
LNG ICE	6.4 (5-8)	3.5 (1-9)	6

The results from the MCDA depend on which criteria and sub-criteria that are included. The ones incorporated here as well as their weights in both base case and role-play scenarios were considered to be the most important in the study by Månsson (2017)[7]. However which criteria that should be included as well as their importance might change in the future and thus affecting which alternative fuel that is most preferred. For instance new regulations and legislation's could be introduced, but also new propulsion technologies developed. Since 2017 the IMO has declared their goal and strategy of halving the GHG emissions from the shipping sector until 2050 which potentially could change how the stakeholders weighs the importance of the environmental criteria relative to the other criteria.

The distribution of criteria and sub-criteria weights has shown to be important for the global ranking of the alternative fuels. The weighting was performed by a limited group of stakeholder representatives and experts, but the shipping sector is an international transportation sector with both national and international actors. To find the most optimal alternative marine fuel for the entire shipping sector is thus very difficult and probably a combination of fuels is needed to meet requirements from different actors as well as possibilities around the world.

7.4 Reliability of results

7.4.1 Data uncertainty

Much of the data gathered on ammonia in this thesis contain uncertainties since the performed literature review found that there has been little or no testing of ammonia in real marine engines. Therefore parameters such as investment cost of propulsion systems, operational cost and emissions related to ammonia operation are based on uncertain data. Especially data regarding emissions of NO_x, NH_3 and PM are uncertain. The future ammonia ICE engine cost will depend on which concept that will become most successfully developed: dual fuel or single fuel, as well the choice of ignition mechanism: spark or compression. The cost of FC technology is assumed to be reduced in the future, however how much depend on the type of FC and how quickly they can be acknowledged as mature and produced in large volumes. As mentioned, the data on emissions when using ammonia as fuel in marine applications is uncertain and limited, and depends largely on which type of ICE or FC that are being used. If further research is performed developing propulsion technologies for ammonia operation, it is probably possible to reduce tailpipe emissions further than what has been assumed in the assessments in this thesis, but more research needs to be performed to quantify this.

As mentioned ammonia is a very common commodity mainly produced with the HB process which is a well known and mature production method. Despite this it has been difficult to find relevant data associated to the specific production steps of ammonia, e.g. the energy efficiency of only the HB process where the production of the feedstock is not included. If HB is combined with SMR, part of the heat that is released by the exothermic reaction between H_2 and N_2 to form NH_3 can be used to heat or generate steam to be used in the SMR-reaction. Also the energy efficiency depends largely on the age and type of the production plant.

7.4.2 GET

The GET 10.0 model is an optimisation model developed to examine possible cost-effective developments of the global energy system under an atmospheric CO_2 concentration constraint. It is a tool that has been developed for many years, but it is important to note that it still represents a simplification of the actual energy system since the global energy system is very complex. The results from the GET 10.0 model gives an indication of how the energy system could be developed in a cost-effective way, however it does not give a prediction of how the future energy system actually will develop. In GET 10.0 only emissions of CO_2 is included, no other GHG emissions are taken into consideration. It is known that current LNG ICE engines have a problem with methane slip which is a much stronger GHG than CO_2 [4], but these emissions are not included in the model.

As previously mentioned, 100 model runs are performed for the MC analysis of the 450 ppm CO_2 scenario. Since the result of the MC analysis to some extent is conflicting to the result of the base case as formerly presented, it can be questioned if 100 model runs is enough to draw firm conclusions. Performing more model runs would increase the reliability of the MC analysis results and also investigating wider spans would be interesting to assess the robustness of the results.

7.4.3 MCDA

The *fuel cost* is the most important sub-criterion in the base case as well as in three of the four role-play stakeholder groups. The fuel cost is based on both estimations on fuel prices as well as how much fuel that is required to run an Ocean ship with an 11 000 kW engine for 720 h which in turn depends on the efficiency of the propulsion technology. Future fuel prices are difficult to estimate since there are many aspects influencing how the fuel price develops. The price depends on the production method but also competition among multiple utilisation purposes, e.g. with agriculture for ammonia. The price development can to some extent be observed in the GET-model but since it represents a simplification of the energy system and not how the system actually will develop it is not possible to find the real future fuel prices.

7.5 Future work

The energy efficiency of ammonia synthesis is as discussed believed to affect the fuel cost and thus also the cost effectiveness of ammonia in the GET model. In this thesis only ammonia synthesis by the HB process has been considered, but it would also be interesting to include other production pathways for ammonia. Electrochemical processes for ammonia synthesis are being developed which potentially could have a significantly higher energy efficiency and thus be interesting to include.

The difference in powertrain efficiency between FCs and ICEs influence the amount of fuel needed and thus the fuel cost. Since the fuel cost make up a large share of the operational cost of a ship it seems that the efficiency of the powertrain affect which type of ships that the GET model finds cost-effective to invest in. Therefore it would be interesting to investigate how future developments of the efficiency of the included propulsion technologies affect the cost-effectiveness of the alternative marine fuels. Currently only emissions of CO_2 is included in the GET model, but it is not only CO_2 that is affecting the climate and global warming. It would thus be interesting to include other GHG emissions in the model to achieve a more thorough evaluation of the cost-effectiveness of the included fuels. Mainly, it would be interesting to include emissions of methane since it is a strong GHG and also a feed-stock used for several of the included fuel alternatives.

In this thesis only the results from the GET model directly related to the shipping sector has been analysed due to time constraints. Since there are several sectors included in the GET model it would be interesting to analyse the results of the other sectors to draw more firm conclusions about the cost-effective fuel choices in the shipping sector. The sectors are connected and the development of one sector might influence the development of other sectors which is why assessing the other sectors included in the GET model further would provide a deeper understanding of the obtained results. To further elaborate on the potential of ammonia as a shipping fuel it would also be interesting to assess a stricter CO_2 emission constraint.

The selection of criteria and sub-criteria and their weights was established 2017 in a previous thesis work [7]. In the future other criteria might be more relevant and their relative importance change depending on the development of the shipping sector. If performing future MCDAs of alternative marine fuels, the selection and weighting should be carried out again and such studies could possibly include more criteria and fuel options. Further sensitivity analyses with different alternative score scenarios should also be conducted since not all sub-criteria were tested in this thesis.

As previously mentioned, there is a lack of reliable data on the emissions of mainly NO_x, NH_3 and PM from marine ammonia operation by both ICEs and FCs. Thus, there is a need for research and tests to quantify these types of emissions. Further, regulations need to be developed if ammonia is to be safely used as a marine fuel.

8

Conclusion

What are economic, technical, environmental and social impacts of the investigated alternative marine fuels, and particularly of ammonia?

There are several alternative marine fuels that could be incorporated in the future shipping sector. Each of the fuels investigated in this thesis have its own potential as well as its challenges. LNG has the advantage of already being used in the shipping sector and is used together with a proven propulsion technology which can extensively mitigate emissions compared to conventional fuels, while its main challenge is the ability to meet future climate targets. LBG which is the renewable alternative of LNG have the potential to meet climate targets considering the fuel life cycle if the methane slip from the engines is mitigated, however LBG has a much higher fuel price than LNG. MeOH is also already in use, but to a lesser extent than LNG. An advantage of MeOH is that it can be produced from both fossil and renewable resources allowing to reduce GHGs emissions also in a life cycle perspective. An advantage of HVO is that it has similar operational properties as conventional marine fuels making it easy to start using, however, the small current production capacity is a barrier for implementation. The biggest potential of using hydrogen as a shipping fuel is the mitigation of tailpipe GHG and air polluting emissions, although there are major challenges with storage and infrastructure. Like hydrogen, ammonia does not contain carbon giving it the possibility to achieve zero tailpipe GHG emissions. Further it is a well known and globally traded commodity. Depending on the origin of the feedstock used for ammonia synthesis, the life cycle emissions can have large environmental impacts. The main challenges of ammonia is related to its toxicity together with the lack of regulations to be used as a marine fuel as well as the absence of studies and tests on actual marine engines and FCs.

Under which conditions is ammonia cost-effective compared to other alternative marine fuels?

Assessing cost-effective fuel choices for the shipping sector in the case of 450 ppm and 550 ppm CO_2 constraints show that ammonia is cost-effective to a limited extent compared to the other investigated fuels. The results from the MC analysis suggests that the synthesis efficiency of ammonia might be an important parameter that affect the cost-effectiveness of ammonia as a shipping fuel. Since the additional vessel cost compared to MGO ICE is lower for ammonia ships compared to hydrogen ships and the production cost is lower for hydrogen than ammonia, ammonia ships could be cost-effective to a greater extent if there is a restrain on hydrogen due to for example implementation problems or security concerns.

Considering the cost-effective fuel choices for both 450 ppm and 550 ppm CO_2 constraint it can be concluded that it is likely that several fuels are to be cost-effective in the future of the shipping sector and that it is not a choice of one fuel to dominate as marine fuel. There is a considerable difference in cost-effective fuel choices for the two CO_2 scenarios in the end of the century where hydrogen have a significantly higher share under 450 ppm than 550 ppm. Thus, the CO_2 constraint proves to be important to what fuel alternatives that are cost-effective in the future and a less stringent CO_2 emission constraint seem to delay the transition towards zero carbon fuels.

The results of cost-effective fuel choices for both CO_2 emission constraint scenarios suggest that FC technology is likely to be cost-effective in the future. This also imply that ammonia combined with FC technology is cost-effective compared to ammonia combined with ICE according to the GET model.

How does ammonia perform as an alternative marine fuel when multiple criteria, prioritised by stakeholders within the shipping sector, are taken into consideration?

Ammonia produced by electrolytic hydrogen combined with FC technology is the second most preferred fuel option according to the base case ranking in the MCDA. If ammonia is produced by hydrogen from NG and used together with FCs, the performance is impaired but still rather good and this fuel option is ranked in 4th place. The combination of ammonia and ICEs on the other hand are not feasible to use according to the MCDA since these options are ranked in 9th and 11th place in the base case as well as having poor average ranking in the sensitivity analyses. Thus, ammonia generally perform better in the MCDA where several aspects as well as weighting performed by stakeholders is considered compared to the GET model where it is only cost-effective to a limited extent and only economic impacts are considered.

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A

Appendix 1

Table A.1: General properties of ammonia.

Properties	*Ammonia*
Energy carrier	NH_3
Physical state	Liquid
Liquid density	0.682 kg/dm^3 (at -33.43°C, 101.3 kPa)[a]
LHV	18.6 MJ/kg, 12.7 MJ/dm^3 [b]
HHV	22.5 MJ/kg, 15.3 MJ/dm^3 [b]
Flashpoint	132 °C [c]
Auto-ignition temperature	651 °C [a]
Explosive limits (NH_3-air mixture)	16-27% (at 0°C, 101.3 kPa)[a]
Extinguishing media	Water spray, Dry powder Foam [d]
Toxicity	Immediately dangerous to life and health limit: 300 ppm [47] LC50 (Rat, 4h): 2000 ppm [77]
Hazards	H221: Flammable gas. H280: Contains gas under pressure, may explode if heated. H331: Toxic if inhaled. H314: Causes severe skin burns and eye damages. H318: Causes serious eye damage. H400: Very toxic to aquatic life. H411: Toxic to aquatic life with long lasting effects. [e]
Global production	180 Mt/year[f]

[a] [42], [b] [33],[c] [76], [d] [77], [e] [77] [78], [f] [35]

Table A.2: Heating values of alternative marine fuels.

Fuel	*LHV [MJ/dm³]*	*HHV [MJ/dm³]*
MGO	37.5	40.1
LNG	23.6	27.1
MeOH	15.7	17.9
Liq. H_2	8.5	10.1
HVO	15.7	17.9
Liq. NH_3	12.7	15.3

All heating values gathered from GET 10.0 except for Liq. NH_3 which is from [33].

B

Appendix 2

Table B.1: Parameters values for the calculation of ammonia synthesis investment cost.

Description	*Parameter*	*Value*
Annual NH_3 capacity [tonnes/year] [a]	C_{NH3}	12000000
CAPEX H_2 synthesis [USD/kW] [b]	I_{H2}	452
CAPEX NH_3 synthesis (incl. feedstock prod.) [USD/tonne annual capacity] [c]	$IC_{NH3+feedstock}$	1500

[a] [66]
[b] [65], Assuming 1 Euro = 1.13 USD
[c] [67]

Calculation ammonia synthesis investment cost, I_{NH3}:

The annual NH_3 capacity, C_{NH3}, multiplied by the CAPEX of NH_3 synthesis (including feedstock), $IC_{NH3+feedstock}$, gives the cost of NH_3 synthesis in USD, $I_{NH3+feedstock}$.

$$I_{NH3+feedstock} = C_{NH3} * IC_{NH3+feedstock} = 18000000000USD$$

The CAPEX of NH_3 synthesis (including feedstock), $IC_{NH3+feedstock}$, times the LHV value of ammonia gives the energy content of the annual NH_3 capacity in MJ/year. This is converted to power (kW).

$$IC_{NH3+feedstock} * 18600MJ/tonne(LHV) = 223200000000MJ/year = 7077625kW$$

$$I_{NH3+feedstock} = \frac{I_{NH3+feedstock}}{7077625kW} = \frac{18000000000USD}{7077625kW} = 2543USD/kW$$

The calculated ammonia synthesis investment cost also includes the cost of feedstock production which is why the CAPEX of H_2 is subtracted to $I_{NH3+feedstock}$ to find the ammonia synthesis investment cost, I_{NH3} .

$$I_{NH3} = I_{NH3+feedstock} - I_{H2} = \mathbf{2091\ USD/kW}$$

Table B.2: Parameters values for the calculation of ammonia synthesis investment cost.

Description	*Parameter*	*Value*
SMR synthesis efficiency [%] [a]	e_{H2-SMR}	80
Electrolysis synthesis efficiency [%] [b]	$e_{H2-Elec}$	80
NH_3 synthesis efficiency (incl. SMR H_2 synthesis) [%] [c]	$e_{NH3+SMR-H2}$	64
NH_3 synthesis efficiency (incl. Elec H_2 synthesis) [%] [d]	$e_{NH3+Elec-H2}$	54
NH_3 synthesis efficiency (HB calculated average) [%]	e_{NH3}	74

[a] From GET 10.0 [52]
[b] From GET 10.0 [52]
[c] Assumed from span of 61-66% [64]
[c] [64]

Calculation ammonia synthesis efficiency, e_{NH3}:
First, the efficiency of ammonia synthesis assuming hydrogen produced from SMR is calculated.

$$e_{NH3,SMR-H2} = \frac{e_{NH3+SMR-H2}}{e_{H2}} = 0.800$$

Then, the efficiency of ammonia synthesis assuming hydorgen produced from electrolysis is calculated.

$$e_{NH3,Elec-H2} = \frac{e_{NH3+Elec-H2}}{e_{H2}} = 0.675$$

Since ammonia is assumed to be produced by hydrogen produced from both SMR and electrolysis in the GEt model, an average is calculated to represent the ammonia synthesis efficiency. Average NH_3 efficiency:

$$\frac{0.800 + 0.675}{2} = 0.74 = \mathbf{74\ \%}$$

Table B.3: Parameters related to production cost of alternative marine fuels included in GET.

	MeOH	*LNG*	*H_2*	*Bio*
Synthesis efficiency [%]	50-90	100	40-100	50
Synthesis investment cost 2010 [USD/kW]	625-3300	20	800-7000	32000-33000
Synthesis investment cost 2050 [USD/kW]	375-1900	20	500-5000	18000-19000
Load factor	0.8	1.0	0.8-1.0	0.8

Table B.4: Component costs of ships fuelled with alternative marine fuels for the different ship categories in GET in base case.

	Coast	*Ocean*	*Container*
MeOH			
ICE engine [USD/kW$_{mech.output}$]	370	370	370
ICE propulsion efficiency, LHV	45%	40%	40%
FC stack cost [USD/kW$_{mech.output}$]	925	925	925
FC propulsion efficiency, LHV	45%	60%	45%
Storage cost [USD/GJ]	40	30	30
SCR cost for ICEs [USD/kW$_{mech.output}$]	-	-	-
Additional vessel cost compared to MGO ICE (MeOH ICE) [GUSD/10 000 ships]	15	20	2
Additional vessel cost compared to MGO ICE (MeOH FC) [GUSD/10 000 ships]	16	70	15
LNG			
ICE engine [USD/kW$_{mech.output}$]	500	500	500
ICE propulsion efficiency, LHV	45%	40%	40%
FC stack cost [USD/kW$_{mech.output}$]	925	925	925
FC propulsion efficiency, LHV	45%	60%	45%
Storage cost [USD/GJ]	110	70	70
SCR cost for ICEs [USD/kW$_{mech.output}$]	-	-	-
Additional vessel cost compared to MGO ICE (LNG ICE) [GUSD/10 000 ships]	7	60	8
Additional vessel cost compared to MGO ICE (LNG FC) [GUSD/10 000 ships]	17	100	17
H_2			
ICE engine [USD/kW$_{mech.output}$]	800	600	600
ICE propulsion efficiency, LHV	45%	40%	40%
FC stack cost [USD/kW$_{mech.output}$]	740	740	740
FC propulsion efficiency, LHV	45%	60%	45%
Storage cost [USD/GJ]	300	225	225
SCR cost for ICEs [USD/kW$_{mech.output}$]	-	-	-
Additional vessel cost compared to MGO ICE (H_2 ICE) [GUSD/10 000 ships]	21	210	24
Additional vessel cost compared to MGO ICE (H_2 FC) [GUSD/10 000 ships]	18	160	22
Bio			
ICE engine [USD/kW$_{mech.output}$]	370	370	370
ICE propulsion efficiency, LHV	45%	40%	40%
FC stack cost [USD/kW$_{mech.output}$]	890	890	890
FC propulsion efficiency, LHV	45%	45%	45%
Storage cost [USD/GJ]	40	30	30
SCR cost for ICEs [USD/kW$_{mech.output}$]	-	-	-
Additional vessel cost compared to MGO ICE (Bio ICE) [GUSD/10 000 ships]	1	20	2
Additional vessel cost compared to MGO ICE (Bio FC) [GUSD/10 000 ships]	15	80	16

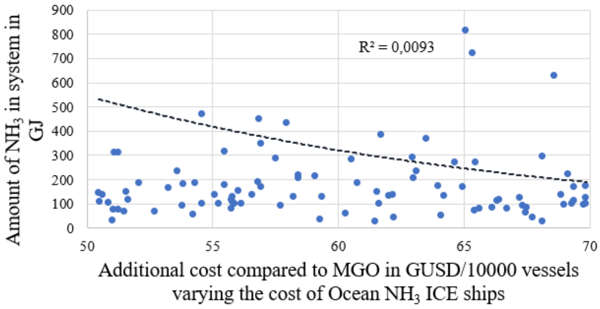

Figure B.1: MC-variation of investment cost for Ocean NH_3 ICE ships.

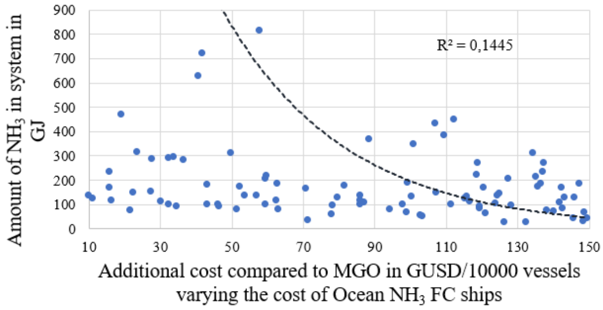

Figure B.2: MC-variation of investment cost for Ocean FC ships.

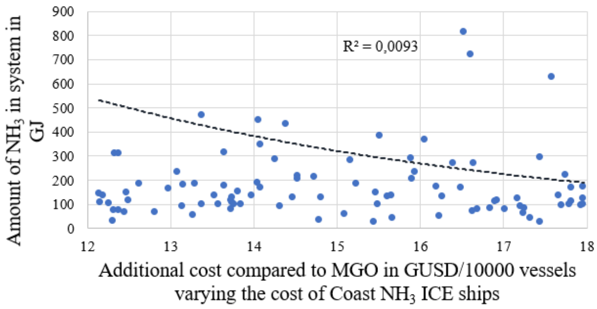

Figure B.3: MC-variation of investment cost for Coast NH_3 ICE ships.

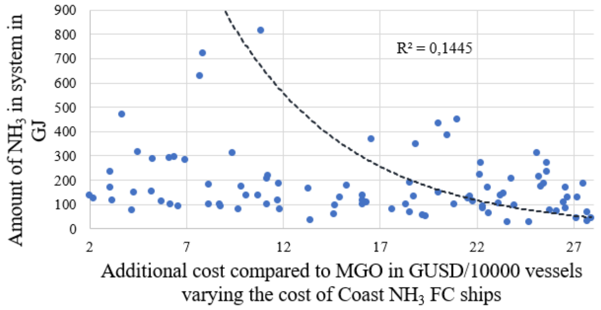

Figure B.4: MC-variation of investment cost for Coast FC ships.

C

Appendix 3

Table C.1: Complete impact matrix of economic criteria.

Alternative	*Investment cost [kUSD/kW]*	*Operational cost [USD/MWh]*	*Fuel cost [USD/kW]*	*Fuel price [USD/GJ_{fuel}]*
LNG ICE	5100	9	41.03	5.79
LBG ICE	5100	9	141.67	19.70
NG-MeOH ICE	4700	6	47.40	6.45
Bio-MeOH ICE	4700	6	113.24	15.40
NG-H_2 FC	6000	11	37.50	7.33
Elec-H_2 FC	6000	11	138.06	27.01
HVO ICE	4500	5	119.75	16.28
NG-NH_3 FC	5300	10	53.00	10.14
Elec-NH_3 FC	5300	10	173.17	33.14
NG-NH_3 ICE	5100	10	79.50	10.14
Elec-NH_3 ICE	5100	10	259.75	33.14

Values for the impacts of the non-ammonia based fuels from [22]

Table C.2: Expert input for indicator scores used to determine impacts of the technical sub-criterion *Available infrastructure*. The scale 1-4 *(Poor, Moderate, Fairly well, Good)* is applied. Average indicator scores presented with range in parenthesis.

	Compatibility of the alternative marine fuel to existing infrastructure	*Adaptability to existing ships*	*Engine technology maturity*
LNG ICE	2.29 (2-3)	2.43 (1-3)	3.86 (3-4)
LBG ICE	2.29 (2-3)	2.43 (1-3)	3.86 (3-4)
NG-MeOH ICE	2.71 (1-3)	2.86 (2-3)	2.86 (2-3)
Bio-MeOH ICE	2.71 (1-3)	2.86 (2-3)	2.86 (2-3)
NG-H_2 FC	1 (1)	1.29 (1-2)	1.29 (1-2)
Elec-H_2 FC	1 (1)	1.29 (1-2)	1.29 (1-2)
HVO ICE	3.86 (3-4)	3.71 (3-4)	4 (4)
NG-NH_3 FC	1.86 (1-3)	1.57 (1-2)	1.71 (1-3)
Elec-NH_3 FC	1.86 (1-3)	1.57 (1-2)	1.71 (1-3)
NG-NH_3 ICE	1.86 (1-3)	1.57 (1-2)	1.71 (1-3)
Elec-NH_3 ICE	1.86 (1-3)	1.57 (1-2)	1.71 (1-3)

Table C.3: Indicator scores for the technical sub-criterion *Reliable supply of fuel*. The scale 1-4 *(Poor, Moderate, Fairly well, Good)* is applied.

	Raw material availability	*Current production*	*Current use in shipping sector*	*Energy security 1: Global distribution of supply potential*	*Energy security 2: Political stability in countries with large supply potential*
LNG ICE	3	4	3	1	2
LBG ICE	3	1	1	2	4
NG-MeOH ICE	3	4	2	1	2
Bio-MeOH ICE	3	1	1	2	4
NG-H_2 FC	3	1	1	1	2
Elec-H_2 FC	4	1	1	4	4
HVO ICE	1	1	1	1	4
NG-NH_3 FC	3[a]	4[c]	1	1[e]	2[e]
Elec-NH_3 FC	4[b]	1[d]	1	4[f]	4[f]
NG-NH_3 ICE	3[a]	4[c]	1	1[e]	2[e]
Elec-NH_3 ICE	4[b]	1[d]	1	4[f]	4[f]

[a] Based on a total supply potential of 7400 EJ [15] and primary energy source production of 121.5 EJ in 2015 [24].
[b] Assumed to have same raw material availability as Elec-H_2 in [22].
[c] Based on NH_3 world production of 140 Mt [79] and 72% of feed-stock produced from NG [5].
[d] Based on NH_3 world production of 140 Mt [79] and 1% of feed-stock produced from other fractions [5].
[e] Energy security 1 assumed to poor and energy security 2 moderate based on [15].
[f] Assumed good based on [68].
Indicator scores for non-ammonia options gathered from [22].

Table C.4: Complete impact matrix for technical criteria on a scale 1-4 representing: *Poor, Moderate, Fairly well, Good*

Alternative	*Available infrastructure*	*Reliable supply of fuel*
LNG ICE	2.9	2.6
LBG ICE	2.4	2.2
NG-MeOH ICE	2.4	2.4
Bio-MeOH	2.4	2.2
NG-H_2 FC	1.1	1.6
Elec-H_2 FC	1.1	2.8
HVO ICE	3.1	1.6
NG-NH_3 FC	1.8	2.8
Elec-NH_3 FC	1.8	2.2
NG-NH_3 ICE	1.8	2.8
Elec-NH_3 ICE	1.8	2.2

Values for the impacts of the non-ammonia based fuels from [22] and calculated from expert indicator scores

Table C.5: Complete impact matrix for environmental criteria.

Alternative	*GWP_{100} [g CO_2-eq./MJ_{fuel}]*	*Acidification potential [mole H^+-eq/MJ_{fuel}]*	*Health impact [mg PM_{10}/MJ_{fuel}]*
LNG ICE	80 (72-93)	8.4×10^{-5}	0.40 (0.27-0.43)
LBG ICE	50 (49-57)	8.4×10^{-5}	0.40 (0.27-0.43)
NG-MeOH ICE	90 (89-92)	2.5×10^{-4}	0.22 (0.0-0.43)
Bio-MeOH	20	2.5×10^{-4}	0.22 (0.0-0.43)
NG-H_2 FC	130 (119-134)	0	0
Elec-H_2 FC	20	0	0
HVO ICE	30	2.1×10^{-4}	0.84
NG-NH_3 FC	140 (119-159)	0	0
Elec-NH_3 FC	29	0	0
NG-NH_3 ICE	140 (119-159)	8.4×10^{-5}	0.22 (0.0-0.43)
Elec-NH_3 ICE	29	8.4×10^{-5}	0.22 (0.0-0.43

Values for the impacts of the non-ammonia based fuels from [22]

Table C.6: Indicator scores for the social sub-criterion *Safety*. The scale 1-4 *(Poor, Moderate, Fairly well, Good)* is applied.

	Risk of explosion or fire	*Toxicity*	*Health hazards*	*Cryogenic liquid*
LNG ICE	1	4	4	1
LBG ICE	1	4	4	1
NG-MeOH ICE	2	1	1	4
Bio-MeOH ICE	2	1	1	4
NG-H_2 FC	1	4	4	1
Elec-H_2 FC	1	4	4	1
HVO ICE	4	4	2	4
NG-NH_3 FC	3	1	1	4
Elec-NH_3 FC	3	1	1	4
NG-NH_3 ICE	3	1	1	4
Elec-NH_3 ICE	3	1	1	4

Safety indicator scores for ammonia options based on information of hazards stated in table A.1. Indicator scores for non-ammonia options gathered from [22].

Table C.7: Indicator scores for the social sub-criterion *Upcoming legislation*. The scale 1-4 *(Poor, Moderate, Fairly well, Good)* is applied.

	Compliance with SO_2 2020 cap	*Compliance with NO_x Tier III*	*IMO 2050 target*	*IMO 2100 target*	*Particle mass*	*Particle number*	*Methane emissions*	*NH_3 emissions*
LNG ICE	4	4	3	1	3	2	1	4
LBG ICE	4	4	3	3	3	2	1	4
NG-MeOH ICE	4	3	3	1	3	2	3	3
Bio-MeOH ICE	4	3	3	4	3	2	3	3
NG-H_2 FC	4	4	4	1	4	4	4	4
Elec-H_2 FC	4	4	4	4	4	4	4	4
HVO ICE	4	2	2	4	2	2	3	3
NG-NH_3 FC	4[a]	4[b]	4	1	4[d]	4[d]	4[d]	3[f]
Elec-NH_3 FC	4[a]	4[b]	4	4	4[d]	4[d]	4[d]	3[f]
NG-NH_3 ICE	4[a]	2[c]	4	1	3[e]	2[e]	4[e]	3[g]
Elec-NH_3 ICE	4[a]	2[c]	4	4	3[e]	2[e]	4[e]	3[g]

[a] Fuel does not contain any sulphur
[b] Emissions of NO_x assumed well below constraint [72].
[c] Emissions of NO_x will be present from combustion [73].
[d] Assumed to have same indicator scores as the H_2 FC options in [22].
[e] Assumed to have same indicator scores as LNG ICE in [22].
[f] Could possibly be some emissions during transport, handling, risk of spills etc.
[g] Risk of emissions of unburnt NH_3 and slip from SCR if not correctly calibrated.
Indicator scores for non-ammonia options gathered from [22].

Table C.8: Complete impact matrix for social criteria on a scale 1-4 representing: *Poor, Moderate, Fairly well, Good*

Alternative	*Safety*	*Upcoming legislation*
LNG ICE	2.5	2.8
LBG ICE	2.5	3.0
NG-MeOH ICE	2.0	2.8
Bio-MeOH	2.0	3.1
NG-H_2 FC	2.5	3.6
Elec-H_2 FC	2.5	4.0
HVO ICE	3.5	2.8
NG-NH_3 FC	2.3	3.5
Elec-NH_3 FC	2.3	3.9
NG-NH_3 ICE	2.3	2.9
Elec-NH_3 ICE	2.3	3.3

Values for the impacts of the non-ammonia based fuels from [22]

Table C.9: Normalised priorities from pairwise comparison matrices for economic sub-criteria for the MCDA base case.

Alternative	*Investment cost priorities*	*Operational cost priorities*	*Fuel cost priorities*
LNG ICE	0.082	0.083	0.142
LBG ICE	0.082	0.083	0.062
NG-MeOH ICE	0.129	0.125	0.131
Bio-MeOH ICE	0.129	0.125	0.074
NG-H_2 FC	0.045	0.068	0.149
Elec-H_2 FC	0.045	0.068	0.063
HVO ICE	0.181	0.150	0.071
NG-NH_3 FC	0.070	0.075	0.123
Elec-NH_3 FC	0.070	0.075	0.053
NG-NH_3 ICE	0.082	0.075	0.095
Elec-NH_3 ICE	0.082	0.075	0.037

Table C.10: Normalised priorities from pairwise comparison matrices for technical sub-criteria for the MCDA base case.

Alternative	*Available infrastructure priorities*	*Reliable supply of fuel priorities*
LNG ICE	0.128	0.102
LBG ICE	0.106	0.087
NG-MeOH ICE	0.104	0.094
Bio-MeOH ICE	0.104	0.087
NG-H_2 FC	0.051	0.063
Elec-H_2 FC	0.051	0.110
HVO ICE	0.139	0.063
NG-NH_3 FC	0.079	0.087
Elec-NH_3 FC	0.079	0.110
NG-NH_3 ICE	0.079	0.087
Elec-NH_3 ICE	0.079	0.110

Table C.11: Normalised priorities from pairwise comparison matrices for environmental sub-criteria for the MCDA base case.

Alternative	*Climate change priorities*	*Acidification priorities*	*Health impact priorities*
LNG ICE	0.062	0.132	0.098
LBG ICE	0.088	0.132	0.098
NG-MeOH ICE	0.056	0.066	0.135
Bio-MeOH ICE	0.154	0.066	0.135
NG-H_2 FC	0.041	0.264	0.238
Elec-H_2 FC	0.154	0.264	0.238
HVO ICE	0.123	0.076	0.059
NG-NH_3 FC	0.038	0.264	0.238
Elec-NH_3 FC	0.123	0.264	0.238
NG-NH_3 ICE	0.038	0.132	0.135
Elec-NH_3 ICE	0.123	0.132	0.135

Table C.12: Normalised priorities from pairwise comparison matrices for social sub-criteria for the MCDA base case.

Alternative	*Safety priorities*	*Upcoming legislation priorities*
LNG ICE	0.094	0.077
LBG ICE	0.094	0.085
NG-MeOH ICE	0.075	0.077
Bio-MeOH ICE	0.075	0.088
NG-H_2 FC	0.094	0.102
Elec-H_2 FC	0.094	0.113
HVO ICE	0.132	0.077
NG-NH_3 FC	0.085	0.099
Elec-NH_3 FC	0.085	0.109
NG-NH_3 ICE	0.085	0.081
Elec-NH_3 ICE	0.085	0.092

Table C.13: Results from alternative score scenario 6 = Changing how climate change is evaluated from GWP_{100} to GWP_{20}.

	Sub-criterion priority	*Difference in sub-criterion priority*	*New global ranking*	*Base case ranking*
GWP_{20}	Climate change			
Elec-NH_3 ICE	0.133	+0.010	9	9
NG-NH_3 ICE	0.045	+0.007	**10**	11
Elec-NH_3 FC	0.133	+0.010	2	2
NG-NH_3 FC	0.045	+0.007	**3**	4
HVO ICE	0.113	-0.010	**6**	5
Elec-H_2 FC	0.162	+0.008	1	1
NG-H_2 FC	0.040	-0.001	**4**	3
Bio-MeOH ICE	0.160	+0.006	**5**	7
NG-MeOH ICE	0.065	+0.009	8	8
LBG ICE	0.048	-0.040	**11**	10
LNG ICE	0.055	-0.006	**7**	6

Table C.14: Result from alternative score scenario 8 = Assuming the same safety ranking for NH_3 as for H_2 (2.5).

	Sub-criterion priority	*Difference in sub-criterion priority*	*New global ranking*	*Base case ranking*
Safety of NH_3=H_2	Safety			
Elec-NH_3 ICE	0.091	+0.006	9	9
NG-NH_3 ICE	0.091	+0.006	**10**	11
Elec-NH_3 FC	0.091	+0.006	2	2
NG-NH_3 FC	0.091	+0.006	**3**	4
HVO ICE	0.127	-0.005	**6**	5
Elec-H_2 FC	0.091	-0.003	1	1
NG-H_2 FC	0.091	-0.003	**4**	3
Bio-MeOH ICE	0.073	-0.003	7	7
NG-MeOH ICE	0.073	-0.003	8	8
LBG ICE	0.091	-0.003	**11**	10
LNG ICE	0.091	-0.003	**5**	6

Table C.15: Results from alternative score scenario 11 = Changing the investment cost for propulsion of the ammonia ship alternatives by both lowering and increasing the costs in the same way as in the MC analysis of GET.

	Sub-criterion priority	*Difference in sub-criterion priority*	*New global ranking*	*Base case ranking*
FC investment high	Investment cost			
Elec-NH_3 ICE	0.093	+0.011	9	9
NG-NH_3 ICE	0.093	+0.011	11	11
Elec-NH_3 FC	0.056	-0.013	2	2
NG-NH_3 FC	0.056	-0.013	4	4
HVO ICE	0.166	-0.015	**7**	5
Elec-H_2 FC	0.042	-0.004	1	1
NG-H_2 FC	0.042	-0.004	3	3
Bio-MeOH ICE	0.132	+0.003	**6**	7
NG-MeOH ICE	0.132	+0.003	8	8
LBG ICE	0.093	+0.011	10	10
LNG ICE	0.093	+0.011	**5**	6
ICE investment high	Investment cost			
Elec-NH_3 ICE	0.067	-0.015	9	9
NG-NH_3 ICE	0.067	-0.015	11	11
Elec-NH_3 FC	0.072	+0.003	2	2
NG-NH_3 FC	0.072	+0.003	**3**	4
HVO ICE	0.188	+0.007	5	5
Elec-H_2 FC	0.047	+0.002	1	1
NG-H_2 FC	0.047	+0.002	**4**	3
Bio-MeOH ICE	0.134	+0.005	**6**	7
NG-MeOH ICE	0.134	+0.005	8	8
LBG ICE	0.085	+0.003	10	10
LNG ICE	0.085	+0.003	**7**	6
FC investment low	Investment cost			
Elec-NH_3 ICE	0.054	-0.029	9	9
NG-NH_3 ICE	0.054	-0.029	11	11
Elec-NH_3 FC	0.107	+0.037	2	2
NG-NH_3 FC	0.107	+0.037	**3**	4
HVO ICE	0.214	+0.033	5	5
Elec-H_2 FC	0.071	+0.026	1	1
NG-H_2 FC	0.071	+0.026	**4**	3
Bio-MeOH ICE	0.107	-0.022	**6**	7
NG-MeOH ICE	0.107	-0.022	8	8
LBG ICE	0.054	-0.029	10	10
LNG ICE	0.054	-0.029	**7**	6
ICE investment low	Investment cost			
Elec-NH_3 ICE	0.089	+0.007	9	9
NG-NH_3 ICE	0.089	+0.007	**10**	11
Elec-NH_3 FC	0.069	-0.001	2	2
NG-NH_3 FC	0.069	-0.001	4	4
HVO ICE	0.178	-0.003	5	5
Elec-H_2 FC	0.045	-0.001	1	1
NG-H_2 FC	0.045	-0.001	3	3
Bio-MeOH ICE	0.127	-0.002	7	7
NG-MeOH ICE	0.127	-0.002	8	8
LBG ICE	0.081	-0.001	10	10
LNG ICE	0.081	-0.001	6	6

Table C.16: Description and delimitation of the sub-criteria included in the MCDA.

Criteria	*Sub-criteria*	*Description*
Economic	Fuel cost	Calculated from fuel price [USD/GJ$_{fuel}$] and the energy [EJ$_{fuel}$] required to run an Ocean ship on full speed for 720 h with a 11 000 kW engine. Power train efficiencies are included when calculating the energy requirement. The fuel prices are compiled from data on production cost, raw material cost, conversion efficiencies and bunker price.
	Operational cost	Costs of crew, insurances, maintenance cost etc.
	Investment cost for propulsion	Cost of an Ocean ship per kW of installed engine mechanical output. Includes cost of engine, fuel storage systems, etc. Ship specifications used are the same as in GET and specified in table 5.1, engine of 11000 kW and driving range of 720 h.
Technical	Reliable supply of fuel	Takes into account the raw material availability, existing production facilities and capacity, current use in shipping applications and energy security coupled to global supply and distribution networks.
	Available infrastructure	Compatibility to existing infrastructure with bunkering vessels, storage and distribution possibilities. Other factors also included are adaptability of current marine vessels and engine technology maturity.
Environmental	Climate change	Evaluated as GWP_{100} and includes emissions of CO_2, CH_4 and N_2O on a 100-year basis and includes emissions from the well-to-propeller perspective.
	Health impact	Emissions of particulate matter (PM) in the exhaust gas from propulsion.
	Acidification	Includes the tailpipe NO_x, SO_x and NH_3 emissions from combustion of the fuels and is evaluated as acidification potential.
Social	Upcoming legislation	Current and upcoming legislation that can affect the use of the alternative fuels related to emissions.
	Safety	Combines several safety aspects such as risk of explosion or fire. Hazards related to handling of the fuel auto-ignition temperature, flammability range, toxicity and flash point.

The definitions used are the same as in the study by Hansson et al. (2019) [22], except for how fuel cost is calculated.