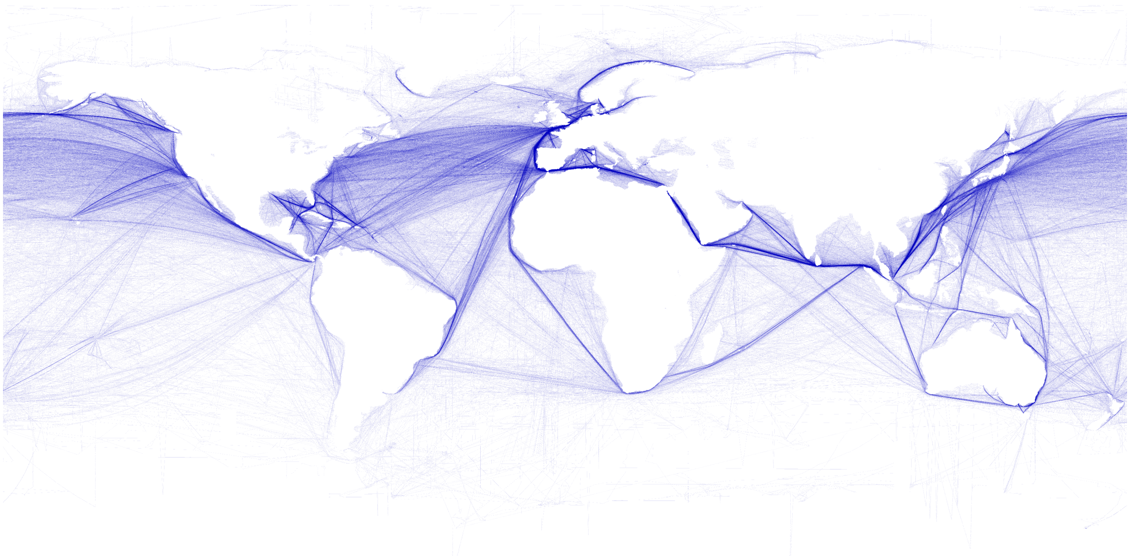

Prospects for renewable marine fuels

A multi-criteria decision analysis of alternative fuels for the maritime sector

Master's thesis in Industrial Ecology

STINA MÅNSSON

Department of Energy and Environment
CHALMERS UNIVERSITY OF TECHNOLOGY
Master's Thesis 2017:04, Gothenburg, Sweden 2017

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Abstract

This study assesses the prospect of renewable fuels in the shipping sector by conducting a multi-criteria decision analysis of selected alternative fuels with a panel of stakeholders. This provides an initial assessment of the importance of different factors influencing the choice of alternative marine fuel from a stakeholder perspective. Four alternative marine fuels, liquefied natural gas (LNG), methanol produced from natural gas (NG-MeOH), methanol produced from biomass (Bio-MeOH), and hydrogen produced from electrolysis by wind power (Elec-H_2), are assessed towards 10 criteria using the analytic hierarchy process. The panel of stakeholders judging the importance of criteria valued economic criteria highest, followed by social criteria, environmental criteria and technical criteria. The relative importance between the criteria are not large, and the most preferred alternative marine fuel turned out to be electrolytic hydrogen from renewable energy sources when considering the joint preference of the stakeholders. The ranking order of fuels changes to some extent when different actors alone judge the importance of criteria, but electrolytic hydrogen turned out to be the most preferred option in most cases. However, international collaboration and technology specific policies and subsidies are most likely needed, and new infrastructure must be built, if electrolytic hydrogen is to be the dominating marine fuel in the future.

Keywords: alternative marine fuels; analytic hierarchy process; AHP; impact assessment; multi-criteria decision analysis; MCDA; shipping

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(ii) Shift – Sustainable Horizons in Future Transport financed by Nordic Energy Research and
(iii) Cost-effective choices of marine fuels under stringent carbon dioxide reduction targets financed by Formas.

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Stina Månsson, Gothenburg, June 2017

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Abbreviations

Decision Analysis

AHP	Analytic hierarchy process
CI	Consistency index
CR	Consistency ratio
MAUT	Multi-attribute utility theory
MCDA	Multi-criteria decision analysis
RI	Random index

Marine Fuels

Bio-MeOH	Methanol produced from biomass
Elec-H_2	Hydrogen produced from electrolysis
FC	Fuel cell
ICE	Internal combustion engine
LHV	Lower heating value
LNG	Liquefied natural gas
MeOH	Methanol
NG-MeOH	Methanol produced from natural gas

Organisations

ICS	International Chamber of Shipping
IEA	International Energy Agency
IGU	International Gas Union
IMO	International Maritime Organisation
IPCC	Intergovernmental Panel on Climate Change
IRENA	International Renewable Energy Agency
UNCTAD	United Nations Conference on Trade and Development
WPCI	World Ports Climate Initiative

Various

CO_2	Carbon dioxide
EJ	10^{18} joule
GDP	Gross domestic product
GHG	Greenhouse gas
MJ	10^{6} joule
NH_3	Ammonia
NMVOC	Non-methane volatile organic carbon
NO_x	Nitrogen oxides

PM	Particulate matter
SO_2	Sulphur dioxide
SO_x	Sulphur oxides

1
Introduction

In this section, a short background of the shipping sector and its environmental challenges are given, along with the aim of the study, and the demarcations.

1.1 Background

The global shipping industry transports 90% of the volume of all goods (ICS, 2015a). The world trade and the global economic growth are therefore highly dependent on the international shipping sector. Over the last four decades, the world seaborne trade, often measured as tonne-miles (moving 1 tonne of cargo a distance of 1 nautical mile), has quadrupled (ICS, 2015b), and the global GDP has grown with 0.5% - 4.5% annually (except for the financial crisis in 2008) (World Bank, 2016). Transport activity and GDP growth have historically been strongly correlated and decoupling transport emissions from GDP growth is one of the largest challenges of today (Sims et al., 2014).

In 2015, the seaborne cargo surpassed 10 billion tonnes, and the estimated trade reached up to 53 600 billion tonne-miles (UNCTAD, 2016).Because of the shipping sector's international nature, and its importance in world trade and economic development, it has been a sector relatively relieved from environmental regulations and taxes in comparison to other sectors (Burman, 2016). If business as usual continues, shipping is estimated to be the most polluting sector within EU in the year 2020, surpassing all land-based air pollution together (Transport & Environment, 2017). There exists a will to change this trend, however, both from the political side and from the industry itself. In 2020, the global sulphur cap that limits the sulphur content in the fuel will be reduced from 3.5% to 0.5% (IMO, 2017c).

Measures in CO_2 reductions are emerging as well. The European Commission's White Paper on strategies towards a competitive and resource efficient transport system, includes a target of a 40% cut in shipping CO_2-emissions below 2005 levels until 2050 (European Commission, 2011), and the international trade association for merchant shipowners, the International Chamber of Shipping, has set the industry goal of a 20% CO_2-reduction per tonne-km by 2020, and a 50% CO_2-reduction per tonne-km 2050 (ICS, 2014).

The maritime sector faces many environmental problems. According to the International Maritime Organisation, the United Nations' agency responsible for shipping, air emissions from shipping contributes to 12% of the global anthropogenic SO_x-emissions, 13% of the global anthropogenic NO_x-emissions, 2.6% of the global anthropogenic CO_2-emissions and 2.5% of the global GHG-emissions, and 1 400 million tonnes of particulate matter (IMO, 2015).

There are technology and energy efficient measures available that decrease air pollution and greenhouse gas emissions, but to succeed with cutting total greenhouse gas emissions, energy efficient measures are not enough, there is also a need for low-emitting alternative fuels (Brynolf, Fridell, & Andersson, 2014). Because of this, there is a growing need for knowledge on alternative marine fuels, expressed by the shipping industry. One such initiative in Sweden is the research project "Prospects for renewable marine fuels", which is a collaboration between IVL Swedish Environmental Research Institute and Chalmers University of Technology, and funded by f3 (The Swedish knowledge centre for renewable transportation fuels) and the Swedish Energy Agency. The future shipping sector is also assessed in the Shift project funded by Nordic Energy Research. This master's thesis is part of those projects and aims to assess the prospect of renewable fuels from a stakeholder perspective using a multi-criteria decision analysis.

1.2 Aim of study

The overall aim of the study is to to assess the prospects of renewable fuels in the shipping sector by conducting a multi-criteria decision analysis of selected alternative fuels with a panel of stakeholders. This provides an initial assessment of the importance of different factors influencing the choice of marine fuel from a stakeholder perspective. To do this, impacts of the alternative fuels are identified, which means the study also includes a synthesis of knowledge on impacts of different criteria such as economic, technical, environmental, and social impacts of respective fuel. The specific objectives to answer are:

- What are the economic, technical, environmental and social impacts of the selected alternative marine fuels?
- What are the relative importance of different criteria in the selection of alternative marine fuels?
- What alternative marine fuel is most preferable considering the stakeholders' preferences?

1.2.1 Demarcations

This study focus on alternative marine fuels for short sea shipping (shipping within EU) and deep sea shipping (cross continental shipping). Very short sea shipping is excluded since it differs from short sea shipping and deep sea shipping both in terms of actors involved and possible alternative fuels. Very short sea shipping is considered to some extent more easily replaced by electrification, which is an alternative fuel that is not analysed in this study.

The alternative marine fuels assessed in this study are; liquefied natural gas (LNG), methanol produced from natural gas (NG-MeOH), methanol produced from biomass (Bio-MeOH), and electrolytic hydrogen, i.e., hydrogen produced from water using electricity in an electrolyser (Elec-H2).

The number of criteria assessed in the study are limited to 10 criteria, and were selected together with the involved stakeholders through a questionnaire. The criteria assessed in this study are; Investment cost for propulsion, Operational cost, Fuel price, Available infrastructure, Reliable supply of fuel, Acidification, Climate change, Health impact, Safety and Upcoming legislation. The time frame considered when weighting criteria and scoring alternatives is a relatively near future approximated with year 2030.

2

Alternative marine fuels

Alternative marine fuels in this study refer to other fuels than the conventional marine fuels (such as heavy fuel oil and marine gas oil). The alternative marine fuels included in this study are liquefied natural gas (LNG), methanol produced from natural gas reforming (NG-MeOH), bio-methanol produced from biomass gasification (Bio-MeOH), and hydrogen produced from electrolysis (Elec-H_2). Regulations, environmental concerns, costs, fuel availability and energy security may be important aspects when choosing alternative fuels. In this section, information about environmental regulations and the selected marine fuels are given. Table 2.1, in the end of the section, summarises some properties of respective fuel.

2.1 Environmental regulations

The International Maritime Organisation (IMO) is the UN agency that is responsible for regulating the shipping industry. The legal framework that regulates air pollution from shipping is the MARPOL Annex VI. It covers regulations on, among others, SO_x- and NO_x-emissions. There exists a global sulphur cap that puts a limit to the sulphur content in the fuel. Today's sulphur limit is set to 3.5%, but on 1 January 2020, the limit will be reduced to 0.5% (IMO, 2017c). This may spur the transition to alternative marine fuels as there are three strategies to meet this new global sulphur cap. These are; 1) heavy fuel oil with scrubbers, 2) distillate fuels with lower sulphur content such as marine fuel oil, and 3) alternative marine fuels (DNV GL, 2016).

Besides a global sulphur cap, there are specific emission control areas with stricter regulation in regions that are more sensitive to pollution. There are sulphur emission control areas (SECAs) with a 0.1% sulphur limit located in the Baltic Sea, North Sea, the English Channel, and waters 200 nautical miles from the coasts of the USA and Canada (DNV GL, 2016).

There are also regulation on levels of NO_x-emissions. For example, engines installed on ships constructed on or after 1 January 2011 need to comply with Tier II NO_x emission standards, and engines installed on ships on or after 1 January 2016 operating in nitrogen emission control areas (NECAs) need to comply with Tier III NO_x emission standards (IMO, 2017c). Tier II NO_x emission standard is between 7.7 - 14.4 g/kWh depending on the engine's rotation per minute (rpm), and Tier III NO_x emission standard is between 2.0 - 3.4 g NO_x/kWh. NECAs are located around North America and the United States Caribbean Sea (IMO, 2017b).

There are no regulations on greenhouse gases, however there is an Energy Efficiency Design Index (EEDI) for all new ships, and a Ship Energy Efficiency Plan (SEEMP) that all ships above 400 gross tonnage must comply with (IMO, 2017a). The international trade association for merchant shipowners, International Chamber of Shipping, has set an industry goal of a 20% CO_2 reduction per tonne-km by 2020, and a 50% CO_2 reduction per tonne-km 2050 below 2005 emission levels (ICS, 2014). And the European Commission's white paper on strategies towards a competitive and resource efficient transport system, includes a target of a 40% cut in shipping CO_2-emissions below 2005 levels until 2050 (European Commission, 2011).

2.2 Liquefied natural gas

Liquefied natural gas (LNG) consists mostly of CH_4 and has the potential to reduce SO_2-emissions and PM_{10} with over 90%, and NO_x-emissions with 80%, and CO_2-emissions 20% (Brynolf et al., 2014; Sames, Clausen, & Andersen, 2011). Therefore it can allow for both SECA and NECA regulations to be met.

Today there are 196 vessels running on LNG, and another 133 vessels that are ordered and under construction (Calderón, Illing, & Veiga, 2016). The propulsion technology for LNG is considered mature and a wide range of engines are on the market (Calderón et al., 2016; Erhorn et al., 2014). There are 15 ports at which it is possible to bunker LNG, and 31 more ports are planning to build bunkering facilities for LNG, mostly within the European Union (WPCI, 2017).

According to the International Gas Union, the global production potential of LNG in 2015 was 302 million tonnes (15 EJ), and it is estimated to increase to 890 million tonnes (43 EJ/year) in 2021 (IGU, 2016). The nominal production is often lower than the production potential, however, because there is a lack of natural gas, and because plants have to shut down for security reasons in politically unstable regions (IEA, 2016). The amount of LNG produced today can supply 75% of the annual global energy demand (IGU, 2016), assuming a global demand of 20 EJ/year (Taljegård, Brynolf, Grahn, Andersson, & Johnson, 2014b).

Five companies own half the market share of the global LNG production, but the market has become more diversified in recent years (IEA, 2016). According to the International Gas Union, the Middle East is the largest LNG exporter with a market share of 40%, followed by Asia-Pacific with a market share of 34% and Africa with a market share of 15% (IGU, 2016). USA and Australia are the countries expanding their liquefaction capacity the most and are expected to exceed the Middle East's capacity in 2021. The European Union is a net importer of LNG and thus dependent on supply from other regions. To improve energy security, EU plans to increase the storage capacity of LNG (European Commission, 2016).

2.3 NG-methanol

The most common way of producing methanol is through natural gas reforming (Scott, 2016). It is also the cheapest way of producing methanol and therefore the assumed production pathway for fossil methanol in this study. NG-MeOH as a marine fuel has the potential to reduce SO_x-emissions with 99%, NO_x-emissions with 80%, and particular matter with 95% (Andersson & Salazar, 2015; Ellis & Tanneberger, 2015). It complies with SECA and Tier III NO_x emission standards (Andersson & Salazar, 2015; Bengtsson et al., 2012), although some engine types need catalysts to reach Tier III emission standards (Bengtsson et al., 2012).

The first ship to run on methanol was the ro-pax ship, Stena Germanica, that was converted in 2015 (Ellis & Tanneberger, 2015). Since then seven new chemical tankers have been built to run on methanol (Ellis & Tanneberger, 2015). The propulsion technology is considered mature, but the existing infrastructure for bunkering methanol is very limited, for example, methanol is corrosive to various metals and plastics, and the system must be completely free from moisture to use stainless steel (Andersson & Salazar, 2015; Medina & Roberts, 2013).

The annual production of methanol is 130 million tonnes (2.6 EJ/year) (Andersson & Salazar, 2015). If no competing demand is assumed, today's production of methanol can supply 13% of the annual fuel demand (assuming an annual demand of 20 EJ). There are 90 methanol plants around the world, with production in Asia, North and South America, Europe, Africa and the Middle East (Methanol Institute, 2017). The largest company is the Canadian company Methanex with a market share of 14% (Methanex, 2015). Largest production of NG-MeOH takes place in Chile, Russia, Trinidad and Tobago (IRENA, 2013).

2.4 Bio-methanol

Bio-methanol has the same chemical and physical proprieties as methanol, but the production process and the feedstock are different. The cheapest and most common way to produce bio-methanol is through gasification of biomass (Scott, 2016). The biomass can be any type biomass, i.e. municipal wastes, industrial wastes, and agricultural and forest residues.

The advantage of bio-methanol over NG-methanol is that bio-methanol has the possibility to become carbon neutral. It requires, however, that all input energy streams are carbon neutral, and that harvested biomass is replaced and cultivated in a way that does not release carbon from the soil (Grahn, 2016).

Today's production of bio-methanol is around 1 million tonnes per year (IRENA, 2013; Karen Law and Jeffrey Rosenfeld and Michael Jackson, 2013), which is equal to 0.02 EJ/year. Most of the production takes place in Canada, the Netherlands, and in Sweden (IRENA, 2013; Karen Law and Jeffrey Rosenfeld and Michael Jackson, 2013). The amount of bio-methanol produced today can supply 0.1% of today's annual energy demand in shipping if no competing demands are considered and the fuel demand for shipping is assumed to be 20 EJ/year. However, an important aspect to consider regarding bio-methanol is the limit to the future production capacity because of land use constraints. It is estimated by several studies that a sustainable production of biomass is 100 EJ/year (Heyne, Grahn, & Sprei, 2015). The technical potential is higher, 300-500 EJ/year, however the sustainable potential takes into account land needed for food production for an increasing population as well as the preservation of sensitive ecosystems (Heyne et al., 2015). This means the sustainable future production capacity of bio-methanol is limited to 60 EJ/year, if all biomass is allocated to bio-methanol production and assuming a conversion efficiency of 60%.

2.5 Electrolytic hydrogen

The global production of hydrogen is around 65 million tonnes per year (8 EJ/year), of which 4% is produced through electrolysis (Hosseini & Wahid, 2016; IEA, 2007).Hydrogen production from water electrolysis is done by splitting water into O_2-gas and H_2-gas (Holladay, Hu, King, & Wang, 2009; Hosseini & Wahid, 2016). In this study, the production considered is decentralised production at seaports with electricity from renewable energy like wind and sun. Such hydrogen production would avoid the energy losses related to transporting hydrogen and allow for a renewable and carbon neutral marine fuel, however, large investments are needed to put the production and infrastructure in place.

In marine applications, hydrogen powered fuel cells have been tested on smaller ferries and in auxiliary systems, but there are no large ships running on hydrogen today (Royal Academy of Engineering, 2013; Tronstad, Åstrand, Haugom, & Langfeldt, 2017). In contrast to internal combustion engines, fuel cells power the ship through electricity that is generated by feeding H_2 and normal air (O_2) on either side of a specialised material (Krčum, Gudelj, & Žižić, 2010). The hydrogen is ionised into H^+ by a catalyst, and since the specialised material is constructed to only let H^+-ions through, the released electrons travel through an external circuit instead, creating a stream of electrons that is used to power the electric motor (Krčum et al., 2010). On the other side of the material, the H^+-ions and the electrons react with the oxygen ,O_2, and form water, H_2O. Thus, the only local emission from hydrogen powered fuel cells on ships is water vapour.

In table 2.1, some properties of the selected alternative marine fuels are displayed.

Table 2.1: Properties of the alternative marine fuels included in the study.

Properties	*Liquefied natural gas*	*Methanol	*Electrolytic hydrogen*
Energy carrier	CH_4	CH_3OH	H_2
Physical state	Cryogenic liquid	Liquid	**Compressed gas
Density (15 °C, 1 bar)	448 kg/m^3 (-160 °C)	796 kg/m^3	***1.34 kg/m^3
LHV	50 MJ/kg	20 MJ/kg	120 MJ/kg
Flash point	-175 °C	12 °C	-
Auto-ignition temperature	537 °C	464 °C	560 °C
Flammability range	5-15 vol%	6-36 vol%	4-75 vol%
Extinguishing media	Carbon dioxide, Dry chemical, Halon, High expansion foam	Carbon dioxide, Dry powder, Water spray, Alcohol resistant foam	All known
Toxicity	No, but may act asphyxiant in confined spaces if vaporised	****Yes, lethal dose is 30-100 ml/kg body weight	No, but may act asphyxiant in confined spaces
Hazards	Extremely flammable gas. Cryogenic liquid, may cause damage and burns.	Highly flammable liquid and vapors. Toxic. Causes damage to organs.	Extremely flammable gas. Contains gas under pressure, may explode if heated.

Information collected from the European Maritime Safety Agency (Ellis & Tanneberger, 2015), (Tronstad, Åstrand, Haugom, & Langfeldt, 2017), and material safety data sheet for LNG (PGW, 2015), methanol (Methanex, 2016), and compressed hydrogen (LindeGroup, 2005).
*Refers to both NG-MeOH & Bio-MeOH
**Compressed gas is assumed, but liquefied hydrogen is also a possibility. It should be noted that the physical state of hydrogen does not affect the results in this study.
***At 15 °C and 1 bar. Depends on pressure, increases with compression.
****(Ott et al., 2012)

3
Method

In this section, the execution of the multi-criteria decision analysis is described.

3.1 Multi-criteria decision analysis

Multi-criteria decision analysis (MCDA) is a tool for managing complex decision problems. It aims to find an optimal solution, the most consensual solution, by taking into account all stakeholders' interests and preferences as well as practical information (Gamper, Thöni, & Week-Hannemann, 2006; Linkov & Moberg, 2012). The application of MCDA in environmental science has grown significantly over the last decades, and the most commonly used MCDA-model is the analytic hierarchy process (AHP) developed by Thomas Saaty in the 1980s (Linkov & Moberg, 2012). Besides from structuring the decision process, the advantage of MCDA is that it allows for the decision makers to manage multiple conflicting criteria, which means more aspects than purely economical aspects can be considered as well as trade-offs between criteria. MCDA also allows for stakeholders to be involved in the decision making process, contributing to more transparency of the decision process, and better acceptance of the decision.(Gamper et al., 2006; Keeney, 1982)

The selection of alternative marine fuels is a suitable problem for applying the MCDA methodology as it is a complex problem that deals with many technical, environmental and social aspects. Changing marine fuels has the opportunity to reduce air pollution and GHG-emissions, however it does require large investments and introduction of new infrastructure and new propulsion technology. The alternative marine fuels may also cause new environmental problems as they grow in scale. Since the maritime sector is known for having economies of scale, and the ships have long life times, there is a clear need of finding a sustainable solution. Further, changing marine fuels involve many actors and stakeholders, such as authorities, shipowners, and fuel manufacturers and the MCDA is thus a good tool for encouraging collaboration and building trust (Keeney, 1982).

3.1.1 The five steps of MCDA

Performing a multi-criteria decision analysis (MCDA) involves the following five steps (Linkov & Moberg, 2012);

1. Problem identification

2. Problem structuring
3. Model assessment
4. Model application
5. Planning and extension

Below follows a description for what each step of the tool entails.

3.1.1.1 Problem identification

The first step of the MCDA is to define the decision context, which is done through identifying the aim of the decision, and relevant stakeholders affected by the decision. This outlines the rest of the decision analysis, and it is therefore important to conduct a thorough problem identification as the results of the analysis are dependent on this first step.(Gamper et al., 2006; Linkov & Moberg, 2012)

The goal of the MCDA in this study is to analyse the prospects of renewable marine fuels, and give a recommendation based on the stakeholders' preferences. Relevant stakeholders are actors from the maritime sector including authorities, shipowners, and fuel manufacturers.

3.1.1.2 Problem structuring

The second step of the MCDA is to structure the decision problem, which is done through identifying the alternatives and the criteria. The alternatives are different solutions to the problem, or actions, that the decision makers choose between. The criteria are properties of the alternatives, such as costs or environmental impacts, that are needed for solving the problem in a satisfactory way. The criteria need to be measurable, either quantitatively or qualitatively, and should be developed in collaboration with the stakeholders to make sure all their interests are accounted for. The criteria provide the basis for evaluating the alternatives, and may put constraints that exclude some options. Thus, the problem structuring becomes an iterative process where alternatives affect which criteria to include and vice versa.(Gamper et al., 2006; Keeney, 1982; Linkov & Moberg, 2012)

The MCDA in this study focuses on which marine fuel to select for the maritime sector, the alternatives are therefore the selected alternative marine fuels. The criteria are the economic criteria, technical criteria, environmental criteria, and social criteria, divided into sub-criteria, that are regarded as most important to consider according to the involved stakeholders.

3.1.1.3 Model assessment

The third step of the MCDA is to assess the possible impacts of the alternatives with regards to the chosen criteria (Keeney, 1982). The alternatives are then scored against the criteria, and the criteria are weighted according to the stakeholders' values and preferences (Linkov & Moberg, 2012). This tells how well the alternatives perform with respect to the criteria, and how the stakeholders value the chosen criteria. There are various MCDA-models for obtaining these scores and weights to solve the problem in a structured manner, for example, the multi-attribute utility theory (MAUT), and the analytic hierarchy process (AHP). The reasons for scoring and weighting is to compare different types of criteria, such as costs and environmental impacts, and handle trade-offs between criteria (Gamper et al., 2006). For example, it is difficult to compare costs in EURO to Global Warming Potential in kg CO_2eq. in an adequate way by purely relying on intuition. Another reason for scoring is to handle intangible criteria that are difficult to put exact measures on (Brunelli, 2015), such as available infrastructure, or safety.

The analytic hierarchy process (AHP) is a model that handles intangible criteria by pairwise comparisons, it is also the most commonly used MCDA-model (Linkov & Moberg, 2012), and therefore used in this study. More in depth explanation of the AHP model is given in section 3.2.

3.1.1.4 Model application

The fourth step of the MCDA is to apply the selected MCDA model and calculate the results by using the alternative scores and the criteria weights obtained in the model assessment (Linkov & Moberg, 2012). This gives a list of the alternatives based on how well they perform against the criteria (Gamper et al., 2006), or more precisely, how well they fit as a solution to the problem with regard to the criteria and their relative importance. A sensitivity analysis should also be done to understand the underlying causes of the ranking.

In this study the selected alternative marine fuels will be ranked based on their performance with respect to the selected criteria. They will also be ranked according to the relative importance of the criteria based on the preference of the stakeholders from the maritime sector. This ranking order is obtained by applying the analytic hierarchy process.

3.1.1.5 Planning and extension

The fifth and last step of the MCDA is to apply the list of alternatives, based on their ranking order, for final decision making and further planning (Linkov & Moberg, 2012).

The results from this MCDA will be used for further studies in the project *Prospects for renewable marine fuels*, and in the *Shift* project.

3.2 Analytic hierarchy process

The analytic hierarchy process (AHP) is the most commonly used MCDA-model (Brunelli, 2015; Linkov & Moberg, 2012). It has been applied in various areas concerning energy, natural resources, stakeholders, and environmental impact assessments (Linkov & Moberg, 2012), and Tsita and Pilavachi (2013), applied the AHP method for evaluating next generation of biofuels for road transportation. In this section the AHP will be explained in more detail, to give an understanding of the model, and how it is applied in this thesis.

3.2.1 Introduction to AHP as a MCDA-model

In the analytic hierarchy process, the scores and weights are given by pairwise comparisons (Saaty, 2008). Scores refer to comparisons of alternatives; the alternatives are given scores based on how well they perform with regard to a given criteria. While weights refer to comparisons of criteria; the criteria are given weights based on how important they are for achieving the goal of the decision. To ease the process of pairwise comparisons, a decision hierarchy tree is constructed to give the overall structure that decides the number of comparisons to be made (Saaty, 2008). For each comparison, a pairwise comparison matrix is constructed. From the matrices, priorities of the activities (alternative or criteria) are calculated. The final outcome of the process it to obtain global priorities that order the alternatives based on how well they fulfil the goal of the decision. These priorities are based on the pairwise comparisons made between both the alternatives and the criteria. This enables the final decision to be based on both how well the alternatives perform, and on how much the different criteria matter.

3.2.1.1 Decision hierarchy tree

The hierarchy tree for selecting the most preferred alternative marine fuel is found in figure 3.1. The goal is presented at the top of the tree, followed by the criteria divided into the sub-criteria. In the bottom boxes, the selected alternative marine fuels are presented. In this MCDA, the main goal of the AHP is to select the most preferred alternative marine fuel. The criteria considered are; economic criteria, technical criteria, environmental criteria, and social criteria. These are divided into the following sub-criteria; investment cost for propulsion, operational cost, fuel price, reliable supply of fuel, available infrastructure, acidification, health impact, climate change, safety, and upcoming legislation. The alternatives to choose among are; liquefied natural gas (LNG), methanol from natural gas (NG-MeOH), methanol from biomass (Bio-MeOH), and hydrogen from electrolysis by wind power (Elec-H_2). The purpose of the hierarchy tree is to structure the decision process, and visualise how many pairwise comparison matrices that are needed (Saaty, 2008).

In this case there are 15 pairwise comparison matrices in total, one in which the criteria are given weights based on their relative importance for achieving the goal; *how important are the economic, technical, environmental, and social criteria when*

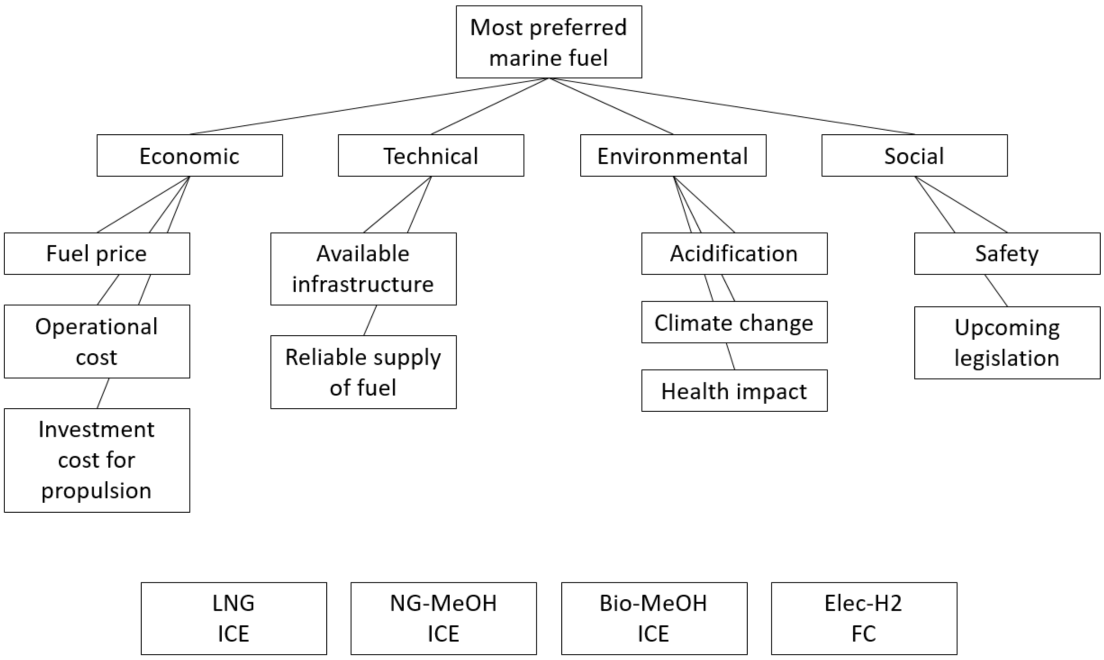


Figure 3.1: Hierarchy tree of the decision problem when selecting the most preferred alternative marine fuel.

selecting an alternative marine fuel? There are four comparison matrices for each group of sub-criteria, for which the sub-criteria are given weights based on their relative importance with respect to the above criteria. For example; *how important are investment costs for propulsion, operational costs, and fuel price with respect to economic criteria when selecting an alternative marine fuel?* Finally, there are 10 pairwise comparison matrices for scoring the relative impacts of the alternative marine fuels with respect to each of the sub-criteria.

3.2.1.2 Pairwise comparisons

In the analytic hierarchy process, the scores and weights are given by pairwise comparison of alternatives and criteria (Saaty, 2008). The criteria are weighted by asking; *how important is criteria c_1 relative to criteria c_2, with respect to the goal?* Sub-criteria are weighted by asking; *how important is sub-criteria $\hat{c_1}$, relative to sub-criteria $\hat{c_2}$, with respect to criteria c_1?* And the selected alternative marine fuels are scored by asking; *how well does alternative marine fuel x_1 perform relative to alternative marine fuel x_2 with regards to sub-criteria $\hat{c_1}$?*

To know what score or weight to give, Saaty (2008), came up with a fundamental scale of absolute numbers for pairwise comparison, see table 3.1. It displays the intensities for scoring and weighting, and how they should be interpreted.

The intensity of 1 is given when two activities (alternatives or criteria) are of equal importance, 3 is given when one activity is slightly more preferred than the other, 5 when one activity is strongly more preferred than the other, 7 when one activity is very strongly more preferred than the other, and 9 is given when there is no doubt that one activity is better than the other. Intensities of 2, 4, 6, and 8 can be seen as intermediate values that are used when the relative judgement is less pronounced (Saaty, 2008).

Table 3.1: Saaty's fundamental scale of absolute numbers (Saaty, 2008).

Intensity of Importance	*Definition*	*Explanation*
1	Equal importance	Two activities contribute equally to the objective
2	Weak or slight	
3	Moderate importance	Experience and judgement slightly favour one activity over another
4	Moderate plus	
5	Strong importance	Experience and judgement strongly favour one activity over another
6	Strong plus	
7	Very strong importance	One activity is favoured very strongly over another
8	Very, very strong	
9	Extreme importance	The evidence favouring one activity over another is of the highest possible order of affirmation
Reciprocals of above	If activity i has one of the above non-zero numbers assigned to it when compared with activity j, then j has the reciprocal value when compared with i	

If one activity is judged as *strongly more important* over another, the practitioner scores the activity with an intensity of 5. If the activity is less favoured, the element becomes 1/3 or 1/5 etc., which means that if the activity is judged as *strongly less important*, the element becomes 1/5. Note that, in the pairwise comparison of two activities, the second activity will always have the reciprocal value of the first, meaning that if activity A is slightly more important than activity B (intensity 3), it follows that activity B must be slightly less important than activity A (intensity 1/3).

3.2.1.3 Pairwise comparison matrix

A pairwise comparison matrix is used to make systematic pairwise comparisons. In table 3.2 is an example of how a pairwise comparison can look. It shows the pairwise comparison matrix for the economic, technical, environmental, and social criteria with respect to selecting the most preferred alternative marine fuel. The intensities are only used as an example.

Table 3.2: Example of a pairwise comparison matrix for criteria when selecting the most preferred alternative marine fuel.

	Economic	Technical	Environmental	Social
Economic	1	5	3	4
Technical	1/5	1	1/3	1/2
Environmental	1/3	3	1	2
Social	1/4	2	1/2	1

The criteria to the left in the matrix is compared with the above criteria in the matrix (Linkov & Moberg, 2012; Saaty, 2008). In this example, the economic criteria is assumed to be judged as *strongly more important* than the technical criteria when selecting alternative marine fuels, hence an intensity of 5. Note that it automatically follows that technical criteria, when compared to economic criteria, is given an intensity of 1/5. This is done for the whole matrix until it is complete.

3.2.1.4 Priority vectors

After constructing the pairwise comparison matrices, the priorities for ranking are obtained by calculating a priority vector for each comparison matrix. There are various ways of calculating the priority vector, $\mathbf{w} = \{w_1, ..., w_n\}$. In this study the geometric mean method is used since it is a method that is easy to interpret and apply in Microsoft Excel. The priorities, w_i, for the pairwise comparison matrix $\mathbf{A}$, are calculated as the geometric mean of the elements on respective row, divided by the sum of all priorities to normalise them (Brunelli, 2015). Below follows the mathematical explanation and an example.

Let $\mathbf{A}$ be a pairwise comparison matrix with elements a_{ij} that are given by Saaty's fundamental scale of absolute number, then the priorities w_i are given by;

$$\mathbf{A} = \begin{pmatrix} a_{11} & a_{12} & \cdots & a_{1n} \\ a_{21} & a_{22} & \cdots & a_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ a_{n1} & a_{n2} & \cdots & a_{nn} \end{pmatrix} \qquad w_i = (\prod_{j=1}^{n} a_{ij})^{\frac{1}{n}} \Big/ \underbrace{\sum_{i=1}^{n}(\prod_{j=1}^{n} a_{ij})^{\frac{1}{n}}}_{\text{Normalisation term}}$$

Below is an example of how the priority vector ,$\mathbf{w}$, is calculated for the pairwise comparison matrix in table 3.2. The number 6.654 is the normalisation term and the calculated priorities are visualised in table 3.3.

$$A = \begin{pmatrix} 1 & 5 & 3 & 4 \\ 1/5 & 1 & 1/3 & 1/2 \\ 1/3 & 3 & 1 & 2 \\ 1/4 & 2 & 1/2 & 1 \end{pmatrix}$$

$$w_1 = \frac{(1 \cdot 5 \cdot 3 \cdot 4)^{\frac{1}{4}}}{6.654} = 0.545 \qquad w_2 = \frac{(1/5 \cdot 1 \cdot 1/3 \cdot 1/2)^{\frac{1}{4}}}{6.654} = 0.084$$

$$w_3 = \frac{(1/3 \cdot 3 \cdot 1 \cdot 2)^{\frac{1}{4}}}{6.654} = 0.233 \qquad w_2 = \frac{(1/4 \cdot 2 \cdot 1/2 \cdot 1)^{\frac{1}{4}}}{6.654} = 0.138$$

$$\mathbf{w} = \begin{bmatrix} 0.545 \\ 0.084 \\ 0.233 \\ 0.138 \end{bmatrix}$$

Table 3.3: Example of pairwise comparison matrix with calculated priorities.

	Economic	Technical	Environmental	Social	Priorities w_i
Economic	1	5	3	4	0.545
Technical	1/5	1	1/3	1/2	0.084
Environmental	1/3	3	1	2	0.233
Social	1/4	2	1/2	1	0.138
					CR = 0.019

Note that the normalised priorities should sum up to 1, however, all calculations in this study are computed in Excel, and for visibility reasons, only three significant figures are displayed throughout the report, which means there are times when it seems like the priorities do not sum up to 1 even if they do. The consistency ratio (CR) tells if the person who made the pairwise comparisons was consistent in the scoring. A description of the consistency check, which gives the CR, is given in section 3.2.2.

In the case of group decisions, there are two ways of combining individual weights to obtain a group priority vector. Either the judgements a_{ij} are aggregated into a common matrix from which the group priority vector is calculated, or the individual priorities are calculated first and then aggregated into a common priority vector (Brunelli, 2015). Methodologically it does not matter which one to select (Wu, Chiang, & Lin, 2008), but in this AHP, aggregation of individual priorities is used since it is of interest to analyse the individual priorities as well. The aggregation is done with the weighted geometric mean, meaning that the priorities of the participants can be rated differently, and allowing for some participants to have a "larger say". In this study, however, the same importance is given to the stakeholders, and hence the geometric mean is used for aggregation.

The final ranking order of the alternative marine fuels are obtained through linear combination of the priority vectors (Brunelli, 2015), the so called global priorities. The alternatives are thus ranked from highest to lowest global priority, and the marine fuel with highest priority is preferred.

3.2.2 Consistency check

To make sure the pairwise comparisons are judged correctly, a consistency check is done. There are various ways to conduct the consistency check, which can be read upon in Brunelli (2015). In this AHP, Saaty's consistency ratio is used in the consistency check because Saaty's fundamental scale of absolute numbers is used for scoring and it is easier to interpret and apply the consistency ratio compared to the other methods. According to Saaty (1980), the consistency ratio should not exceed 0.1, meaning that a 10% inconsistency when performing the pairwise judgements is okay. Any judgement returning a greater inconsistency is revised. The consistency check is done by calculating the consistency ratio (CR). For a given n × n pairwise comparison matrix **A**, the CR is calculated as the consistency index (CI), divided by a random index ($\mathrm{RI_n}$);

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

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

If $CR(\mathbf{A}) \leq 0.1$, the judgement is approved.

The random index, RI_n, depends on the size of the n × n matrix (Brunelli, 2015), see the estimated values in table 3.4. When n is smaller than 3, the consistency index has been used instead of the consistency ratio.

The maximum eigenvalue, λ_{max}, of the pairwise comparison matrix **A**, is obtained by solving the characteristic equation;

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

where **I** is the n × n identity matrix, and λ_{max} is the eigenvalue with greatest absolute value (Brunelli, 2015). Instructions on how the characteristic equation is solved in Excel is provided by (Teknomo, 2015).

Table 3.4: Random index values for calculating the consistency ratio (Brunelli, 2015)

n	3	4	5	6	7	8	9	10
$\mathrm{RI_n}$	0.5247	0.8816	1.1086	1.2479	1.3417	1.4057	1.4499	1.4854

3.2.3 Criticism of the analytic hierarchy process

Criticism directed to the analytic hierarchy process involves the possibility of rank reversal. Rank reversal refers to the situation when adding a new alternative changes the initial ranking of the alternatives (Brunelli, 2015). An example of this is when the three alternatives $X = \{x_1, x_2, x_3\}$ are initially ranked as $x_2 \succ x_1 \succ x_3$, and when adding a fourth alternative x_4, the ranking changes into $x_1 \succ x_2 \sim x_4 \succ x_3$ (Brunelli, 2015). The extent to which the AHP suffers from rank reversal is an ongoing debate.

Criticism is also directed to Saaty's fundamental scale of absolute numbers for the pairwise comparisons, see table 3.1. Some mean that it is not an optimal scale, and difficulty rises when verbal expressions, such as "*slightly more important*", are transformed into numerical values (Brunelli, 2015). On the other hand, making decisions always involves a degree of subjectivity, and people are generally better at making relative judgements than finite ones (Linkov & Moberg, 2012).

3.3 Methodological choices

This section summaries the methodological choices that affect the outline of the multi-criteria decision analysis and the analytic hierarchy process.

3.3.1 Selection of stakeholders

The selection of stakeholders was done by asking people from the reference group to the project *Prospects for renewable marine fuels*. They were selected because they had already shown an interest in assisting the project, and consisted of a mixture of stakeholders and experts including; authorities, shipowners, fuel manufacturers, engine manufacturers, and researchers. This was considered a good mixture for the decision analysis. The stakeholders' task was to help with the selection of sub-criteria and the weighting of criteria and sub-criteria in the analytic hierarchy process.

3.3.2 Selection of alternative marine fuels

The alternative marine fuels in this study are liquefied natural gas (LNG), methanol produced from natural gas (NG-MeOH), methanol produced from biomass (Bio-MeOH), and electrolytic hydrogen from wind (Elec-H_2). The selection of alternative marine fuels was done before the stakeholders got involved in the study.

In the selection of alternative marine fuels, two aspects were considered. First the type of shipping under study, which is short sea shipping (shipping within EU) and deep sea shipping (cross continental shipping). Therefore, the alternative marine fuels selected for this study are those that are believed to suit larger ships and longer distances. Second, a limited amount of alternative marine fuels was selected since the number of fuels included had to be limited to fit a master's thesis time frame. The included marine fuels represent three different energy carriers, with different physical properties. Two alternatives are presently used as alternative marine fuels and two alternatives are renewable marine fuels that are considered as future options.

LNG was selected because it is considered by the European Union to be the alternative fuel that is most suited for shipping. LNG is also the alternative fuel that is used most today. NG-MeOH was selected because it is used as an alternative marine fuel today, and it is an interesting alternative to LNG since it is more similar to conventional fuels. Bio-MeOH was selected because it is a renewable alternative to NG-MeOH, and electrolytic hydrogen from wind power was selected because it is a renewable alternative of hydrogen. Hydrogen from fossil sources are excluded because it is considered to be a too expensive alternative for the marginal environmental benefits.

Table 3.5: Alternative marine fuels.

Alternatives	*Energy carrier*	*Physical state*	*Description*
LNG ICE	Methane	Cryogenic liquid	[a]LNG is obtained by cooling natural gas to -162 ℃ at liquefaction plants, and is assumed to be used in internal combustion engines (ICE).
NG-MeOH ICE	Methanol	Liquid	[b]Production of methanol is assumed to be through natural gas reforming into synthesis gas that is synthesised and processed into methanol, and is assumed to be used in internal combustion engines (ICE).
Bio-MeOH ICE	Methanol	Liquid	[b]Production of bio-methanol is assumed to be through gasification of biomass into synthesis gas that is synthesised and processed into bio-methanol, and is assumed to be used in internal combustion engines (ICE).
Elec-H_2 FC	Hydrogen	Compressed gas	The production of hydrogen is assumed to be through local production by [c]electrolysis that is powered by wind, and is assumed to be used in fuel cells (FC).

[a]LNG production is explained in Shell (2017).
[b]Production methods for methanol and bio-methanol is explained in Scott (2016).
[c]Different production methods for hydrogen is explained in Holladay, Hu, King, and Wang (2009).

3.3.3 Selection of criteria

The selection of criteria was made together with the stakeholders to make sure all their interests were accounted for. This was done by handing out an online multiple-choice questionnaire with the instructions to mark the 10 criteria they think are most important to consider when changing marine fuel. Inspiration for relevant criteria to include in the questionnaire was obtained from Bengtsson et al. (2012), and Tsita and Pilavachi (2013). The option to add other criteria than those stated in the questionnaire was available to avoid influencing the choice of criteria too much beforehand.

The criteria selected for the study were those that obtained more than 40% of the votes. This returned the 10 criteria to include in the study, and was necessary to limit down the scope. The criteria handed out to the stakeholders are listed in table 3.6, the ones in bold are those that obtained more than 40% of the votes and were therefore included in the study. Risk of fire and explosion was later added to safety since it was hard to separate the two in the impact assessment.

Table 3.6: Criteria and sub-criteria in the multiple-choice questionnaire given to the stakeholders.

Criteria	*Sub-criteria*
Economic	**Investment cost for propulsion**
	Operational cost
	Fuel price
	Cost of infrastructure
	Cost of fuel production
Technical	Well-tried technology for propulsion
	Need of technical adaptation at the ship
	Available infrastructure
	Reliable supply of fuel
	Fuel bunkering time
	Fuel bunkering frequency
Environmental	**Acidification**
	Eutrophication
	Health impact
	Climate change
	Impacts from fuel spill
	Other environmental impacts (biodiversity loss, access to fresh water)
Social	**Safety (flammability, toxicity, solubility in water etc.)**
	Job creation
	Competition with food
	Upcoming legislation
	Risk of fire and explosion

3.3.4 Selection of MCDA-model

The analytic hierarchy process (AHP) is the most commonly used MCDA-model (Brunelli, 2015; Linkov & Moberg, 2012). A suitable problem for applying the AHP is one where the aim of the decision is to select the most preferred option between many alternatives that depend on multiple criteria of which some are intangible (Brunelli, 2015; Saaty, 2008). Because of this, the analytic hierarchy process was selected as the MCDA-model in this study. Other reasons for selecting AHP are that it is easily applied in Microsoft Excel, and a relatively easy model to learn, and less time consuming when scoring and weighting compared to more complex models. The multi-attribute utility theory was not selected since it is a more complex and time consuming model unless the utility functions are assumed to be linear. This was, however, considered a too strong assumption since there exists a lot of uncertainty when selecting alternative marine fuels.

3.4 Assessment of alternative marine fuels

The impact assessment of the selected alternative marine fuels is primarily a synthesis of knowledge on the alternative marine fuels with regard to the selected criteria. Information is mainly collected from business associations, interest organisations, scientific papers and previous studies on the alternative marine fuels. It is important to have comparative data for each sub-criteria since the analytic hierarchy process is based on pairwise comparisons. Because of this, the same source of data within sub-criteria has been used as far as possible, assuming that data from the same source is more comparable than data from mixed sources. The comparability between the different sub-criteria is relaxed, however, since different cases have been used in the data collection depending on data availability. An example of this is how the investment cost for propulsion is estimated for building a new container ship with an engine of 23 000 kW and a tank of 71 300 GJ. The environmental impacts, on the other hand, are calculated for a ro-ro ship with an engine of 14 680 kW and a fuel consumption of 0.5189 MJ fuel/tkm. Methodologically, this is not considered to pose a problem, nevertheless, it is an important aspect to consider when reading the report.

3.4.1 System boundaries

All environmental impacts of the alternative marine fuels are from a well-to-propeller perspective, meaning that emissions from raw-material extraction, production, distribution and propulsion are accounted for. Only the fuel itself has been considered, which means emissions from the construction of new infrastructure, new production sites, new engines and new ships are excluded. The same system boundary is applied in the assessment of reliable supply of fuel. The sustainability constraints and energy security only applies to the raw-materials needed for the fuel, and competitive use of the fuel and competitive use of raw-materials are excluded. The availability of other materials, such as platinum in fuel cells, have not been considered either. The system boundary for available infrastructure includes production of the fuel, distribution, storage, and bunkering. The time frame considered when scoring the alternatives is year 2030 to allow for future perspectives. More detailed description of the selected criteria and how they are evaluated are given below. A summary of the criteria is found in table 3.7.

3.4.2 Investment cost for propulsion

The investment cost includes cost of engines, fuel tanks, pipelines, gas alarm systems, and fuel processors etc., depending on the properties of the fuel (Taljegård, Brynolf, Grahn, Andersson, & Johnson, 2014a). The investment cost is important because if too large, it can act as a barrier even if the payback time is short (Brynolf, 2014; Erhorn et al., 2014). Data on investment costs for respective fuel are collected from Taljegård et al. (2014a).

3.4.3 Operational cost

The shipping industry is a very cost-competitive market and it is therefore important to keep operating costs low. In this study, the operational cost refers to crew costs, crew training, insurances, and maintenance cost. Fuel cost is usually included in the operating cost, but is treated separately in this study. Data on operational cost for LNG, NG-MeOH and Bio-MeOH are collected from Bengtsson et al. (2012). The operational cost for Elec-H_2 is assumed to be slightly higher than the operational cost for LNG because of a more complex system with fuel cells (Krčum et al., 2010).

3.4.4 Fuel price

Fuel price refers to the bunker price. The fuel price is important because it makes up a large part (30%-50%) of the operating cost depending on the type of ship (Brynolf, 2014). Data on fuel prices have been collected from Geckoicapital (2017) for LNG and from Methanex (2017) for NG-MeOH. Fuel prices for Bio-MeOH and Elec-H_2 are not available and therefore estimated as the average production cost. Data on production costs for Bio-MeOH are collected from IRENA (2013), and data on production cost for Elec-H_2 is collected from Hosseini and Wahid (2016).

3.4.5 Available infrastructure

Available infrastructure refers to the whole supply chain including the scale production, distribution, storage, and bunkering facilities at ports. There are three ways of bunkering fuel; truck to ship, terminal tank to ship, and bunker vessel to ship, for LNG, portable tank (container) transfer has been used as well (Calderón et al., 2016).

The alternative marine fuels will be evaluated based on the amount of infrastructure available, as well as the compatibility of the alternative marine fuel to the existing infrastructure. Since it is not possible to put an exact value on available infrastructure, an overview of the current situation and trends for respective fuel has been gained from various sources including business associations, interest organisations, scientific papers and other studies on the alternative marine fuels.

Available infrastructure is important because shipowners tend to delay the change to alternative fuels if no infrastructure is in place, and the provider of infrastructure tends to wait until there are sizeable amount of users (Erhorn et al., 2014), and because there is a risk of congestion if there are not enough bunkering opportunities (Calderón et al., 2016).

3.4.6 Reliable supply of fuel

In this study, reliable supply of fuel refers to a sustainable production chain that is not affected by limited raw-material, limited land, nor limited assimilation capacity of emissions. Market characteristics and energy security aspects are considered as well when assessing reliable supply of fuel.

For market conditions, it is assumed that perfect competition is preferred before oligopoly with a few suppliers dictating the terms. It is also assumed that an even distribution of suppliers geographically is preferred to a few countries controlling all production. The stability of the countries are also of interest for energy security reasons since war and conflicts may interfere with the supply of fuel.

From a sustainability perspective, the reliable supply of fuel is dependent on three sustainability constraints; limited availability of non-renewable materials, limited space, and limited assimilation capacity of emissions (Karlsson, Azar, Berndes, Holmberg, & Lindgren, 1997; Lundqvist, 2016). The availability of non-renewable materials depends on the size of reserves and resources, as well as the distribution of resources among countries and the production capacity. Limited space affect biofuels, where the amount of extractable energy is constrained by land for cultivation, the yield, and potential degradation of the land (Lundqvist, 2016). Limited assimilation capacity refers to the amount of emissions that can be managed by nature (Karlsson et al., 1997). Information on future sustainability constraints and market conditions have been collected from companies, business associations and scientific papers.

3.4.7 Acidification

Acidification is assessed as the acidification potential caused by SO_2-emissions, NO_x-emissions, and NH_3-emissions. The exhaust emissions can travel with air for long distances and cause damage to soils, waters, ecosystems, and buildings, even if the emissions are emitted at sea (European Maritime Safety Agency, 2017). Data on acidification potential is collected from Brynolf et al. (2014), and is estimated from a well-to-propeller perspective.

3.4.8 Climate change

Climate change is assessed as the global warming potential, GWP_{100}, from a well-to-propeller perspective. Emissions contributing to climate change are CH_4-emissions, CO_2-emissions and N_2O-emissions. Data on global warming potential is collected from (Brynolf et al., 2014).

Decoupling transport emissions from GDP growth is one of the largest challenges we face today (Sims et al., 2014). Stopping growth of GHG-emissions is not enough to solve climate change. They must stop completely if climate change is to be avoided (Sterman, 2008). It is therefore important for the shipping industry to look for fossil-free alternative fuels as well.

3.4.9 Health impact

Health impact is assessed as the Disability Adjusted Life Years, DALY, which is a measure of life years lost from disability or early death. Health impacts from shipping is connected to the approximately 1 400 million tonnes of particulate matter emitted from shipping every year (IMO, 2015). Particulate matter are extremely small particles or liquids like dust, smog, and soot that cause harm to human health (European Environment Agency, 2017). Secondary particulate matter is formed through chemical reactions in the atmosphere by SO_2, NO_x, NH_3, and Non-methane Volatile Organic Compounds (NMVOC-emissions) (World Health Organisation, 2013). Because the particles are tiny, they can enter lungs and bloodstreams and cause respiratory diseases like asthma and cardiovascular diseases, and it is estimated that this causes 50 000 premature deaths in Europe every year (Transport & Environment, 2017).

Comparative data on DALYs was not available and therefore calculated from the inventory data on emissions from Brynolf et al. (2014). The calculations are based on the life cycle assessment methodology found in Baumann and Tillman (2004). The emissions considered are PM_{10}, SO_2, NO_x, NH_3, and non-methane volatile organic carbon (NMVOC) from a well-to-propeller perspective. The characterisation factors for calculating the DALYs are collected from Zelma et al. (2008), and the fuel consumption is 0.5189 MJ fuel/tkm based on Brynolf et al. (2014). Below is an example on how the DALY was calculated per tonne km for a ro-ro vessel running on NG-MeOH.

$$DALY_{(NG-MeOH)} = (4.62 \cdot 10^{-6} kg.PM_{10}/MJfuel \times 2.6 \cdot 10^{-4} year/kg.PM_{10}$$
$$+2.1 \cdot 10^{-6} kg.SO_2/MJfuel \times 5.1 \cdot 10^{-5} year/kg.SO_2 + 3.26 \cdot 10^{-4} kg.NO_x/MJfuel$$
$$\times 5.7 \cdot 10^{-5} year/kg.NO_x + 5.1 \cdot 10^{-9} kg.NH_3/MJfuel \times 8.3 \cdot 10^{-5} year/kg.NH_3$$
$$+1.1 \cdot 10^{-5} kg.NMVOC/MJfuel \times 3.9 \cdot 10^{-8} year/kg.NMVOC) \times 0.5189 MJfuel/tkm$$

3.4.10 Safety

Safety aspects considered are the risk of fire, explosion, and health hazards connected to handling the fuel (Bengtsson et al., 2012). One thing the alternative marine fuels have in common is that they are all low flash point fuels, which means the temperature at which there is enough vapour to ignite is low (Encyclopaedia Britannica, 2017). This requires new safety measures and has led to the development of the International Code for Ships using Gases and other Low Flash point Fuels (the IGF Code) that was adopted in 2015 (IMO, 2016). Other aspects considered are the auto-ignition point, flammability range, and toxicity. Information on safety has been collected from the European Maritime Safety Agency and material safety data sheets.

3.4.11 Upcoming legislation

Upcoming legislation is evaluated based on the abilities of alternative marine fuels to meet regulations connected to SECA, NECA and CO_2 reductions targets. It is likely that the regulation will become stricter in the future, therefore in scoring the alternative marine fuels, the ability to meet these regulations as well as stricter ones have been considered. Information on exhaust emissions are collected from Brynolf et al. (2014). Only fossil based CO_2-emissions are considered since it is assumed that CO_2-emissions from biomass are circular.

Table 3.7: Criteria for changing marine fuel.

Criteria	*Sub-criteria*	*Description*
Economic	Investment cost for propulsion	Cost for engines, fuel tanks, gas alarm systems, pipelines and fuel processors etc.
	Operational cost	Cost for operation, maintenance, crew manning and training
	Fuel price	Bunker price
Technical	Available infrastructure	Production, distribution, storage, bunkering facilities, and compatibility with existing infrastructure
	Reliable supply of fuel	Production chain that is not affected by limited raw-material, limited land, nor limited assimilation capacity of emissions, market characteristics and energy security aspects
Environmental	Acidification	Well-to-propeller emissions from SO_x, NO_x, and NH_3
	Health impact	Disability adjusted life years due to well-to-propeller emissions from SO_2, NO_x, PM_{10}, NH_3, and NMVOC
	Climate change	Well-to-propeller emissions from greenhouse gases (CO_2, CH_4, and N_2O)
Social	Safety	Risk of fire, explosion, and health hazards from handling fuel
	Upcoming legislation	Regulations connected to SECA, NECA and CO_2 reductions

3.5 Workshop and role-play

The panel of stakeholders was invited to a workshop at which they judged the relative importance of criteria and sub-criteria using the analytic hierarchy process. First, the panel of stakeholders were taught how the analytic hierarchy process worked, then they were asked to give their individual weights from which the final ranking of the alternative marine fuels are calculated.

In the second part of the workshop, the stakeholders took part in a role-play. The purpose of the role-play was to analyse how different actors in the shipping industry may prioritise criteria differently, and how it affects the final ranking of the alternative marine fuels. The stakeholders were therefore asked to divide into three groups and take on the perspective from one of the three following roles; authority, shipowner, and fuel manufacturer, and redo the pairwise comparisons collectively. The group representing the fuel manufacturer perspective did a pairwise comparison from an engine manufacturer perspective as well, which is included in the results. The stakeholders were told to consider short sea shipping within EU and cross continental shipping, and the year 2030 when conducting the comparisons. The participants at the workshop are presented in table 3.8.

Table 3.8: Stakeholders participating at the workshop.

Name	*Organisation*
Selma Brynolf	Chalmers University of Technology
Maria Grahn	Chalmers University of Technology
Fredrik Svensson	Energigas
Olle Hådell	Environmental Analysis Vehicles and Fuels
Zoi Johansson Nikopoulou	Gothenburg University
Fredrik Backman	Preem
Magnus Wallenbert	Preem
Joanne Ellis	SSPA
Martin Svanberg	SSPA
Cecilia Andersson	Stena Line
Julia Hansson	IVL Swedish Environmental Research Institute
Reidar Grundström	Swedish Maritime Administration
Magnus Lindgren	Swedish Transport Administration
Martin Von Sydow	Wallenius Marine
Toni Stojcevski	Wärtsilä

3.6 Analysis of results

The results from the multi-criteria decision analysis are analysed to understand the underlying causes of the final ranking order of alternative marine fuels.

3.6.1 Sensitivity analysis of scores

In the sensitivity analysis of scoring, the strongest and most uncertain assumptions were selected and tested individually by changing the scores given to the alternatives for a specific sub-criteria. This was done because the impacts of technical and social criteria are very subjective since it is not possible to put exact numbers on available infrastructure, reliable supply of fuel, safety and upcoming legislation. A sensitivity analysis of these judgements are therefore done to see how much the final ranking of alternative marine fuels is affected when different perspectives are used in the scoring, and to find out how much the assumptions in this study affected the final ranking of alternative marine fuels.

The assumptions tested are; i) more emphasis on land use constraints than limited availability of fossil fuels and limited assimilation capacity for reliable supply of fuel, ii) more emphasis on the fuels' compatibility with existing infrastructure for available infrastructure, iii) more emphasis on the toxic property of NG-MeOH and Bio-MeOH for safety, iv) more emphasis on the risk of policies restricting the use of biofuels in the future for upcoming legislation.

3.6.2 Sensitivity analysis of criteria weights

In the sensitivity analysis of criteria weights, changes to global priorities and the ranking order of alternative marine fuels are tested by increasing and decreasing the priority of one criteria at a time with $\pm$ 0.1. The reason for this is to test how sensitive the alternative marine fuels are towards changes in the importance of criteria, and it is necessary since the relative judgements made in the pairwise comparison of criteria might differ between different people in terms of how they interpret Saaty's fundamental scale of absolute numbers (Linkov & Moberg, 2012). It also allows for the result to become more general. $\pm$ 0.1 was selected because it is considered large enough to pose an affect to the final ranking.

3.6.3 Analysis of individual priorities

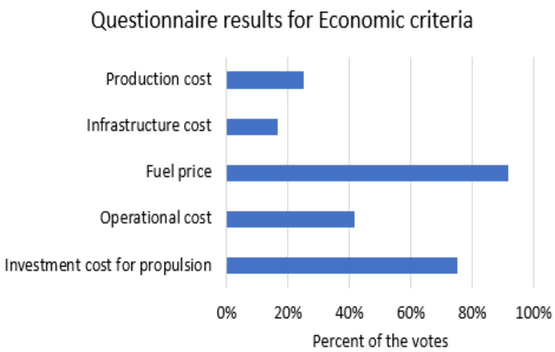
The individual priorities are analysed to find out the extent of agreement between the stakeholders in terms of the importance they place in different criteria when selecting alternative marine fuels. It is also done to see if there are groups that tend to think alike, or tend to think the opposite. This is done by plotting the individual priorities and look for patterns, as well as the span between the highest and lowest priority.

4
Results and analysis

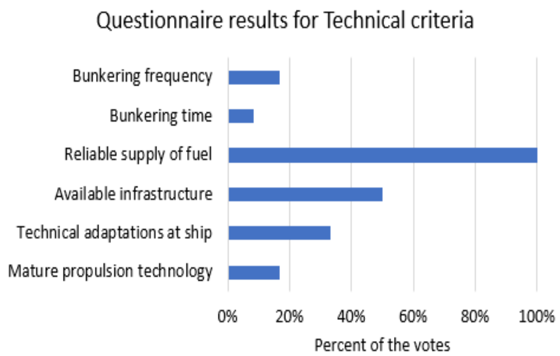
This section includes the results from the questionnaire, the impact assessment of the alternative marine fuels, the pairwise comparison of alternatives and criteria, the final ranking order of the alternative marine fuels and a sensitivity analysis, as well as an analysis of the individual stakeholder priorities and the role-play results.

4.1 Questionnaire

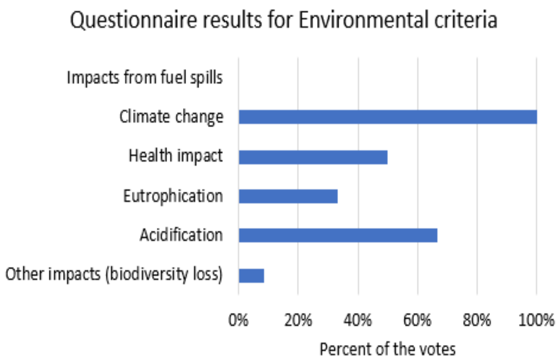
The results from the questionnaire to select what criteria to include in the study are presented in figure 4.1. Criteria with more than 40% of the votes are included in the MCDA.



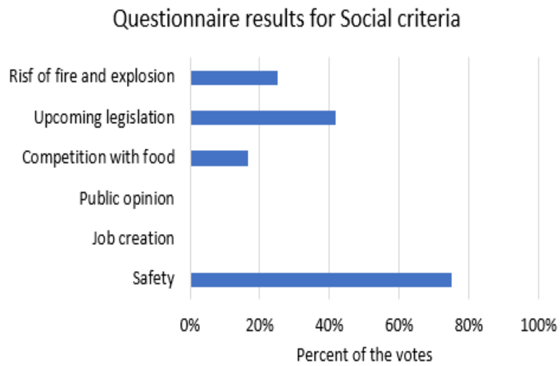
(a) Economic criteria votes



(b) Technical criteria votes



(c) Environmental criteria votes



(d) Social criteria votes

Figure 4.1: Results from the questionnaire handed out to the stakeholders, figure 4.1a) - 4.1d) show the answers for respective criteria.

The criteria with more than 40% of the votes are included in the MCDA, namely; investment cost for propulsion, operational cost, fuel price, available infrastructure, reliable supply of fuel, acidification, climate change, health impact, safety and upcoming legislation. The result shows that climate change and reliable supply of fuel are the only criteria that all participants think are important when selecting alternative marine fuel. The second most important criteria turned out to be safety and fuel price. Criteria excluded from the MCDA because they got less than 40% of the votes are; production cost, infrastructure cost, bunkering frequency, bunkering time, technical adaptations at ship, mature propulsion technology, impacts from fuel spills, eutrophication, biodiversity loss, risk of fire and explosion, competition with food, public opinion, and job creation. Risk of fire and explosion was added to safety, however, because it was difficult to separate the two in the impact assessment.

4.2 Impacts of alternative marine fuels

This section presents the impacts of the alternative marine fuels for each criteria. The impacts are summarised in table 4.1 - 4.4.

4.2.1 Economic impacts

The economic impacts assessed in this study for the selected alternative marine fuels are summarised in table 4.1. Compared to the other alternative marine fuels, the investment cost for propulsion is much higher for hydrogen with fuel cells. The investment cost is estimated for liquefied hydrogen and not compressed hydrogen. It is assumed that the relation between the investment costs is similar for compressed hydrogen and the pairwise comparisons in the AHP are therefore not affected. Of the selected fuels, methanol has the lowest investment cost and operational cost. LNG however, is the cheapest fuel for its energy content. The operational cost is assumed to be slightly higher for hydrogen because of the maintenance of a more complex system (the change of fuel cell stack is included in the investment cost).

Table 4.1: Impact matrix for included economic criteria

Alternatives	*Investment cost [kEuro*/Ship]*	*Operational cost [Euro*/MWh]*	*Fuel price [Euro*/GJ]*
LNG ICE	124 800[a]	3.90-4.40[b]	8[d]
NG-MeOH ICE	117 500[a]	3.25-3.50[b]	17[e]
Bio-MeOH ICE	117 500[a]	3.25-3.50[b]	28[f]
Elec-H_2 FC	206 200[a]	*Slightly higher*[c]	52[g]

[a]Investment costs for LNG, NG-MeOH, Bio-MeOH, and Elec-H_2 are estimated for a container ship with an engine of 23 000 kW and a tank of 71 300 GJ, (Taljegård, Brynolf, Grahn, Andersson, & Johnson, 2014a)
[b]Operational costs for LNG, NG-MeOH, and Bio-MeOH are based on Bengtsson et al. (2012)
[c]Assumed to be slightly higher than operational cost for LNG based on Krčum, Gudelj, and Žižić (2010)
[d]The average LNG price from 1 Mars 2013 to 1 Mars 2017, (Geckoicapital, 2017)
[e]The average NG-MeOH price from 1 Mars 2013 to 1 Mars 2017, (Methanex, 2017)
[f]Fuel price for Bio-MeOH is estimated as the average production cost, (IRENA, 2013)
[g]Fuel price for hydrogen is estimated as the production cost (Hosseini & Wahid, 2016)
*Conversion from USD to Euro was done on 30 Mars 2017 (1 EUR = 1.0721 USD), the LHV was used for energy conversions, 20 MJ/kg.MeOH and 120 MJ/kg.H2

4.2.2 Technical impacts

The included technical impacts, available infrastructure and reliable supply of fuel for the selected alternative marine fuels are summarised in table 4.2. The available infrastructure refers to the whole supply chain of the respective fuels (production, distribution, storage and bunkering opportunities). LNG is rated highest because the infrastructure for LNG is more developed than for the other fuels. It has the largest production volumes as well as more bunkering infrastructure in place. Methanol however, is considered more compatible to the existing conventional fuel infrastructure than the other fuels (Andersson & Salazar, 2015), which decreases the difference in rating between LNG and NG-MeOH and Bio-MeOH from a 2030 perspective. There is no existing infrastructure for decentralised production of Elec-H_2.

Overall, the infrastructure needs to be improved for all fuels. As an example, the production volumes of the alternative marine fuels are too small today to support the annual global energy demand in shipping, even if no competing sectors are considered. Assuming a global energy demand for shipping of 25 EJ/year in 2030 (Taljegård et al., 2014b), today's production of LNG would only be able to meet 60% of the estimated demand (IGU, 2016). However, according to the International Gas Union (2016), the planned expansion of LNG production is supposed to reach 43 EJ/year in 2021, which would be enough to meet the global fuel demand in year 2030 if a sufficient share of production is allocated to the shipping industry. The current production of NG-MeOH would only be able to meet 10% of the estimated year 2030 demand (Andersson & Salazar, 2015) and Bio-MeOH production would only be able to meet 0.08% of demand (IRENA, 2013). In the short term, the production capacity of LNG and NG-MeOH are mostly constrained by available production plants since the natural gas resources are large enough to not be a limiting factor (Holz, Richter, & Eggingy, 2015). In the long term however, raw-material availability of natural gas will be a limiting factor as well.

Electrolytic hydrogen is rated highest in terms of reliable supply of fuel. The long term fuel supply is considered more reliable for Elec-H_2 because it is not as affected

Table 4.2: Impact matrix for included technical criteria

Alternatives	*Available infrastructure*	*Reliable supply of fuel*
LNG ICE	+[a]	− − −[b]
NG-MeOH ICE	−[c]	− − −[d]
Bio-MeOH ICE	− −[e]	−[f]
Elec-H_2 FC	− − −[g]	+ +[h]

[a]Based on Calderón, Illing, and Veiga (2016), European Commission (2016), IGU (2016), WPCI (2017)
[b]Based on European Commission (2016), Holz, Richter, and Eggingy (2015), IEA (2016), IGU (2016)
[c]Based on Andersson and Salazar (2015), Ellis and Tanneberger (2015)
[d]Based on Holz, Richter, and Eggingy (2015), IRENA (2013)
[e]Based on IRENA (2013), Karen Law and Jeffrey Rosenfeld and Michael Jackson (2013)
[f]Based on Heyne, Grahn, and Sprei (2015)
[g]Based on Royal Academy of Engineering (2013)
[h]Based on Hosseini and Wahid (2016)

by the sustainability constraints as the other fuels. The reasons for this are because it is produced through electrolysis from renewable energy sources, and the local production allows for each country and seaport to have control over the production and distribution.

The long term supply of LNG and NG-MeOH are rated less reliable since they are fossil fuels and therefore constrained by the availability in raw-material, both in terms of the limited amount of natural gas, but also because of the uneven distribution of natural gas resources among countries which is problematic from an energy security perspective. 41% of the global reserves of natural gas is owned by the Russian Commonwealth and 31% by the Middle East (Holz et al., 2015). There are times when plants have been shut down for security reasons in politically unstable regions (IEA, 2016). The limited assimilation capacity of emitted carbon is another constraint affecting the reliable supply of LNG and NG-MeOH. The current carbon budget is 800 Gt CO_2 (Global Carbon Project, 2016), and the natural gas resources contain between 1,727-4,127 Gt CO_2 (Holz et al., 2015), which means that if politicians stand by the Paris Agreement, most of the natural gas resources must be left in the ground.

Bio-MeOH is rated more reliable than LNG and NG-MeOH since it is favourable in an energy security perspective. This is because biomass for the production of Bio-MeOH is considered more available than natural gas is to most countries. However, the production capacity of Bio-MeOH is constrained by the available land for biomass production. It is estimated by several studies that the sustainable production of biomass is around 100 EJ/year (Heyne et al., 2015). Assuming a conversion efficiency of 60% (IRENA, 2013), the potential production capacity of Bio-MeOH becomes 60 EJ/year, if all biomass is allocated to Bio-MeOH production.

4.2.3 Environmental impacts

The environmental impacts included in the study are summarised in table 4.3. The environmental impacts are assessed from a well-to-propeller perspective, and the functional unit is 1 tonne cargo transported 1 km with a ro-ro vessel. As can be seen, Bio-MeOH has the highest acidification potential and health impact, and NG-MeOH has the highest global warming potential. Elec-H_2 with fuel cells has no impacts because there are no emissions other than water vapour and the electricity production from wind power is assumed to not emit anything.

4.2.4 Social impacts

Table 4.4 summarises the included social impacts. LNG, NG-MeOH, and Bio-MeOH are rated more safe than Elec-H_2, because LNG and methanol have been handled more extensively in shipping, both as alternative marine fuels and as cargo.

Elec-H_2 with fuel cells is rated higher for upcoming legislation because it has no exhaust emissions other than water vapour and is therefore believed to meet all future regulations on emissions. LNG and NG-MeOH are rated worse because they will not be able to meet future reductions in CO_2 emissions. Bio-MeOH has the potential to meet future targets in CO_2 reductions, but since there is a risk of adverse effects related to climate change from land use change, it is rated worse than Elec-H_2. The sources for which these ratings are based upon are found in the table 4.4.

Table 4.3: Impact matrix for included environmental criteria

Alternatives	*Acidification potential [mole H^+ eq/tkm]*	*GWP_{100} [g CO_2eq/tkm]*	*DALY [year/tkm]*
LNG ICE	0.05[a]	0.9[a]	4.2×10^{-9}[b]
NG-MeOH ICE	0.10[a]	1.1[a]	10.4×10^{-9}[b]
Bio-MeOH ICE	0.15[a]	0.2[a]	13.3×10^{-9}[b]
Elec-H_2 FC	0[c]	0[c]	0[c]

[a]Based on Brynolf, Fridell, and Andersson (2014)
[b]Author's own calculations based on inventory data from Brynolf, Fridell, and Andersson (2014)
[c]Assumed to be zero based on Hosseini and Wahid (2016), Tronstad, Åstrand, Haugom, and Langfeldt (2017)

Table 4.4: Impact matrix for included social criteria

Alternatives	*Safety*	*Upcoming legislation*
LNG ICE	+[a,b]	−[f]
NG-MeOH ICE	+ +[a,c]	− −[f]
Bio-MeOH ICE	+ +[a,c]	+ +[f]
Elec-H_2 FC	−[d,f]	+ + +[g]

[a]Based on Ellis and Tanneberger (2015)
[b]Based on PGW (2015)
[c]Based on Methanex (2016)
[d]Based on Tronstad, Åstrand, Haugom, and Langfeldt (2017)
[e]Based on LindeGroup (2005)
[f]Based on Bengtsson et al. (2012), Brynolf, Fridell, and Andersson (2014)
[g]Based on Hosseini and Wahid (2016), Krčum, Gudelj, and Žižić (2010)

4.2.5 Pairwise comparisons of alternative marine fuels

The pairwise comparison matrices for the alternative marine fuels with regard to the selected criteria are displayed on next page. Table 4.5-4.8 show how the alternative marine fuels are scored with regard to economic sub-criteria, technical sub-criteria, environmental sub-criteria, and social sub-criteria respectively. The pairwise comparison matrices for the weights given to criteria by the panel of stakeholders are found in table A.1-A.13 in appendix A. The aggregated priorities obtained form these weights are presented in section 4.3.

Table 4.5: Pairwise comparison matrices for economic sub-criteria.

Investment cost for propulsion					
	LNG	NG-MeOH	Bio-MeOH	Elec-H_2	Priorities
LNG	1	1/3	1/3	5	0.160
NG-MeOH	3	1	1	7	0.397
Bio-MeOH	3	1	1	7	0.397
Elec-H_2	1/5	1/7	1/7	1	0.047
					λ_{max} = 4.073
					CR = 0.028
Operational cost					
	LNG	NG-MeOH	Bio-MeOH	Elec-H_2	Priorities
LNG	1	1/5	1/5	3	0.103
NG-MeOH	5	1	1	7	0.424
Bio-MeOH	5	1	1	7	0.424
Elec-H_2	1/3	1/7	1/7	1	0.050
					λ_{max} = 4.073
					CR = 0.028
Fuel price					
	LNG	NG-MeOH	Bio-MeOH	Elec-H_2	Priorities
LNG	1	3	5	8	0.573
NG-MeOH	1/3	1	3	5	0.259
Bio-MeOH	1/5	1/3	1	3	0.116
Elec-H_2	1/8	1/5	1/3	1	0.052
					λ_{max} = 4.093
					CR = 0.035

Table 4.6: Pairwise comparison matrices for technical sub-criteria.

Available infrastructure					
	LNG	NG-MeOH	Bio-MeOH	Elec-H_2	Priorities
LNG	1	3	5	7	0.564
NG-MeOH	1/3	1	3	5	0.263
Bio-MeOH	1/5	1/3	1	3	0.118
Elec-H_2	1/7	1/5	1/3	1	0.055
					λ_{max} = 4.117
					CR = 0.044
Reliable supply of fuel					
	LNG	NG-MeOH	Bio-MeOH	Elec-H_2	Priorities
LNG	1	1	1/5	1/7	0.068
NG-MeOH	1	1	1/5	1/7	0.068
Bio-MeOH	5	5	1	1/3	0.283
Elec-H_2	7	7	3	1	0.580
					λ_{max} = 4.073
					CR = 0.028

Table 4.7: Pairwise comparison matrices for environmental sub-criteria.

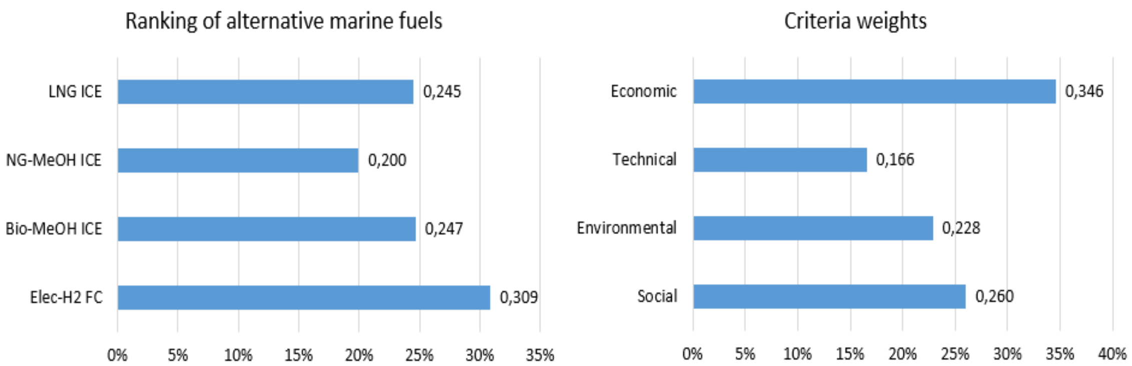
	LNG	NG-MeOH	Bio-MeOH	Elec-H_2	Priorities
Acidification					
LNG	1	3	5	1/3	0.263
NG-MeOH	1/3	1	3	1/5	0.118
Bio-MeOH	1/5	1/3	1	1/7	0.055
Elec-H_2	3	5	7	1	0.564
					λ_{max} = 4.117
					CR = 0.044
Climate change					
LNG	1	2	1/5	1/6	0.083
NG-MeOH	1/2	1	1/7	1/8	0.050
Bio-MeOH	5	7	1	1/3	0.302
Elec-H_2	6	8	3	1	0.565
					λ_{max} = 4.131
					CR = 0.050
Human health damage					
LNG	1	3	5	1/3	0.269
NG-MeOH	1/3	1	3	1/5	0.120
Bio-MeOH	1/5	1/3	1	1/6	0.058
Elec-H_2	3	5	6	1	0.553
					λ_{max} = 4.150
					CR = 0.057

Table 4.8: Pairwise comparison matrices for social sub-criteria.

	LNG	NG-MeOH	Bio-MeOH	Elec-H_2	Priorities
Safety					
LNG	1	1/2	1/2	2	0.189
NG-MeOH	2	1	1	3	0.351
Bio-MeOH	2	1	1	3	0.351
Elec-H_2	1/2	1/3	1/3	1	0.109
					λ_{max} = 4.010
					CR = 0.004
Upcoming legislation					
LNG	1	2	1/5	1/6	0.085
NG-MeOH	1/2	1	1/6	1/7	0.055
Bio-MeOH	5	6	1	1/3	0.298
Elec-H_2	6	7	3	1	0.561
					λ_{max} = 4.145
					CR = 0.055

4.3 Multi-criteria decision analysis

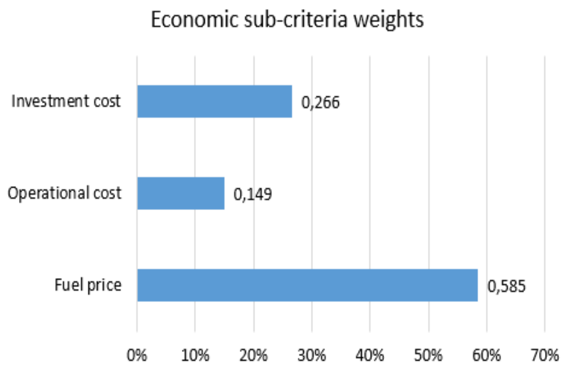
The final ranking order of the selected alternative marine fuels are presented in figure 4.2a. The most preferred fuel is electrolytic hydrogen with fuel cells, followed by bio-methanol and LNG, which are equally preferred. Methanol from natural gas is the least preferred alternative in this MCDA. Figure 4.2b shows the aggregated priorities of criteria when selecting alternative marine fuel, based on the pairwise comparisons of criteria made by the stakeholders. It shows that the most important criteria when selecting alternative marine fuel is economic criteria, followed by social criteria, environmental criteria, and technical criteria.



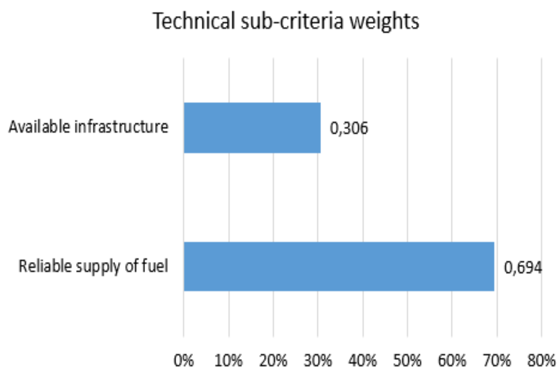
(a) Ranking of marine fuels **(b)** Criteria importance

Figure 4.2: The final ranking of alternative marine fuels, figure 4.2a) shows the ranking order, and 4.2b) shows the aggregated importance of the included criteria.

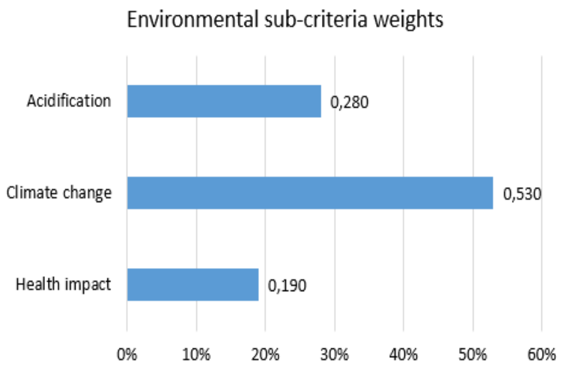
The aggregated priorities of the included sub-criteria from the stakeholders' pairwise comparisons are shown in figure 4.3. For economic sub-criteria, fuel price is most prioritised when selecting alternative marine fuel, followed by the investment cost and then the operational cost, see figure 4.3a. For technical sub-criteria, reliable supply of fuel is prioritised twice as much as available infrastructure, see figure 4.3b. For environmental sub-criteria, climate change is prioritised the most, followed by acidification and health impact, see figure 4.3c. For social sub-criteria, upcoming legislation is a little bit more prioritised by the stakeholders than safety is, see figure 4.3d.



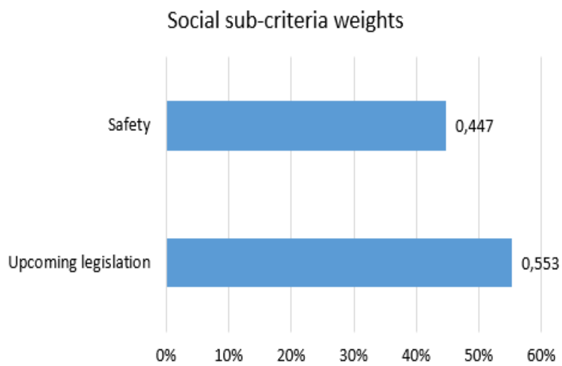
(a) Economic sub-criteria



(b) Technical sub-criteria



(c) Environmental sub-criteria



(d) Social sub-criteria

Figure 4.3: Aggregated priorities of sub-criteria based on the stakeholders' pairwise comparisons.

4.3.1 Sensitivity analysis of alternative scores

The impacts of technical and social criteria are very subjective since it is not possible to put exact numbers on available infrastructure, reliable supply of fuel, safety and upcoming legislation. The judgements are based on an overall view that is obtained from studying the shipping industry and the fuels. A sensitivity analysis of these judgements are therefore done to see how much the final ranking of alternative marine fuels are affected when different perspectives are used in the scoring. Four cases are tested and the resulting order of alternative marine fuels are shown in figure 4.4. The four cases and the new scores given in the sensitivity analysis are explained below, and displayed in table 4.9.

Case 1: Reliable supply of fuel, in the sensitivity analysis more emphasis is put on the land use constraints than the limited availability of fossil fuels and the limited assimilation capacity. This favours LNG and NG-MeOH and is tested by letting LNG and NG-MeOH switch scores with Bio-MeOH for reliable supply of fuel.

Case 2: Available infrastructure, in the sensitivity analysis more emphasis is put on the compatibility with existing infrastructure than on existing infrastructure for respective fuel. This favours NG-MeOH and Bio-MeOH, and is tested by letting NG-MeOH switch scores with LNG, and give Bio-MeOH the old scores of NG-MeOH.

Case 3: Safety, in the sensitivity analysis more emphasis is put on the toxic property of NG-MeOH and Bio-MeOH. This favours LNG, and is tested by letting LNG switch scores with NG-MeOH and Bio-MeOH.

Case 4: Upcoming legislation, in the sensitivity analysis more emphasis is put on the risk of policies restricting the use of biofuels. This affects Bio-MeOH, and is tested by letting Bio-MeOH score lower.

The sensitivity analysis shows how different perspectives in scoring alter the ranking order of alternative marine fuels in three of the cases, for which LNG becomes more preferred than Bio-MeOH, see figure 4.4. The only case that does not change the original ranking order is case 2 when a larger emphasis is put on compatibility to existing infrastructure when judging the available infrastructure.

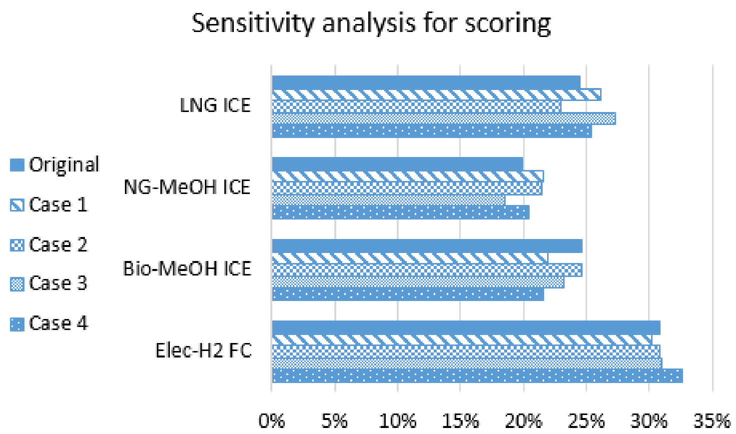


Figure 4.4: Sensitivity analysis for evaluating how different perspectives in scoring affect the ranking order of alternative marine fuels.

Table 4.9: Pairwise comparison matrices for the sensitivity analysis.

	LNG	NG-MeOH	Bio-MeOH	Elec-H_2	Priorities
Case 1: Reliable supply of fuel					
LNG	1	1	5	1/3	0.212
NG-MeOH	1	1	5	1/3	0.212
Bio-MeOH	1/5	1/5	1	1/7	0.051
Elec-H_2	3	3	7	1	0.525
					λ_{max} = 4.073
					CR = 0.028
Case 2: Available infrastructure					
LNG	1	1/3	3	5	0.263
NG-MeOH	3	1	5	7	0.564
Bio-MeOH	1/3	1/5	1	3	0.118
Elec-H_2	1/5	1/7	1/3	1	0.055
					λ_{max} = 4.117
					CR = 0.044
Case 3: Safety					
LNG	1	2	2	3	0.423
NG-MeOH	1/2	1	1	2	0.227
Bio-MeOH	1/2	1	1	2	0.227
Elec-H_2	1/3	1/2	1/2	1	0.122
					λ_{max} = 4.010
					CR = 0.004
Case 4: Upcoming legislation					
LNG	1	2	2	1/6	0.149
NG-MeOH	1/2	1	1	1/7	0.085
Bio-MeOH	1/2	1	1	1/7	0.085
Elec-H_2	6	7	7	1	0.681
					λ_{max} = 4.037
					CR = 0.014

4.3.2 Sensitivity analysis of criteria weights

The sensitivity analysis of criteria priorities (± 0.1) shows that the preference of LNG and NG-MeOH is sensitive to changes in economic priority, and the preference of Elec-H_2 is sensitive to changes in technical, environmental, and social priorities, and the preference of Bio-MeOH is sensitive to changes in social priority. The ranking order of alternative marine fuels is more sensitive to a decrease in criteria priority than to an increase in criteria priority. The ranking order changes when increasing the economic priority with +0.1, or when the technical, environmental or social criteria priority is decreased with -0.1.

The changes to global priorities and the ranking order of alternative marine fuels when increasing the priority of one criteria at a time with +0.1 can be seen in table 4.10. The difference between the new global priorities and the original ones are displayed both in numbers and in percentages.

Table 4.10: Changes to global priority and ranking order of the alternative marine fuels when increasing the priority of one criteria at a time with +0.1.

	Original global priority				
LNG ICE	0.245				
NG-MeOH ICE	0.200				
Bio-MeOH ICE	0.247				
Elec-H_2 FC	0.309				
Economic +0.1	**New global priority**	**Difference in priority**	**Difference in %**	**New ranking**	**Original ranking**
LNG ICE	0.285	0.039	16.1 %	2	3
NG-MeOH ICE	0.232	0.032	16.1 %	4	4
Bio-MeOH ICE	0.270	0.024	9.6 %	3	2
Elec-H_2 FC	0.314	0.005	1.6 %	1	1
Technical +0.1	**New global priority**	**Difference in priority**	**Difference in %**	**New ranking**	**Original ranking**
LNG ICE	0.267	0.022	9.0 %	3	3
NG-MeOH ICE	0.212	0.013	6.4 %	4	4
Bio-MeOH ICE	0.270	0.023	9.4 %	2	2
Elec-H_2 FC	0.351	0.042	13.6 %	1	1
Environmental +0.1	**New global priority**	**Difference in priority**	**Difference in %**	**New ranking**	**Original ranking**
LNG ICE	0.262	0.017	6.9 %	3	3
NG-MeOH ICE	0.208	0.008	4.2 %	4	4
Bio-MeOH ICE	0.265	0.019	7.6 %	2	2
Elec-H_2 FC	0.365	0.056	18.5 %	1	1
Social +0.1	**New global priority**	**Difference in priority**	**Difference in %**	**New ranking**	**Original ranking**
LNG ICE	0.258	0.013	5.4 %	3	3
NG-MeOH ICE	0.218	0.019	9.4 %	4	4
Bio-MeOH ICE	0.279	0.032	13.1 %	2	2
Elec-H_2 FC	0.344	0.036	11.6 %	1	1

The original ranking order of the alternative marine fuels is Elec-H_2 $\succ$ Bio-MeOH $\succ$ LNG $\succ$ NG-MeOH. The order changes, however, when increasing the priority of economic criteria, see figure 4.10. The new rank becomes Elec-H_2 $\succ$ LNG $\succ$ Bio-MeOH $\succ$ NG-MeOH, and the breaking point happens at an increase of 0.01, at which LNG becomes more preferred than Bio-MeOH. The next breaking point happens at an increase of 0.19, at which LNG becomes more preferred to Elec-H_2 as well. A continuous increase in economic priority ranks the alternatives according to the fuel price.

A continuous increase in the importance of technical criteria, environmental criteria, and social criteria does not change the original ranking, and the result is thus robust towards changes within chosen range of criteria uncertainties.

Table 4.11: Changes to global priority and ranking order of the alternative marine fuels when decreasing the priority of one criteria at a time with -0.1.

	Original global priority				
LNG ICE	0.245				
NG-MeOH ICE	0.200				
Bio-MeOH ICE	0.247				
Elec-H_2 FC	0.309				
Economic -0.1	**New global priority**	**Difference in priority**	**Difference in %**	**New ranking**	**Original ranking**
LNG ICE	0.206	-0.039	-16.0 %	3	3
NG-MeOH ICE	0.168	-0.032	-16.0 %	4	4
Bio-MeOH ICE	0.223	-0.024	-9.6 %	2	2
Elec-H_2 FC	0.303	-0.005	-1.7 %	1	1
Technical -0.1	**New global priority**	**Difference in priority**	**Difference in %**	**New ranking**	**Original ranking**
LNG ICE	0.223	-0.022	-8.9 %	2	3
NG-MeOH ICE	0.187	-0.013	-6.4 %	3	4
Bio-MeOH ICE	0.223	-0.023	-9.4 %	2	2
Elec-H_2 FC	0.267	-0.042	-13.6 %	1	1
Environmental -0.1	**New global priority**	**Difference in priority**	**Difference in %**	**New ranking**	**Original ranking**
LNG ICE	0.228	-0.017	-6.9 %	2	3
NG-MeOH ICE	0.191	-0.008	-4.1 %	3	4
Bio-MeOH ICE	0.228	-0.019	-7.6 %	2	2
Elec-H_2 FC	0.252	-0.056	-18.2 %	1	1
Social -0.1	**New global priority**	**Difference in priority**	**Difference in %**	**New ranking**	**Original ranking**
LNG ICE	0.232	-0.013	-5.3 %	2	3
NG-MeOH ICE	0.181	-0.019	-9.4 %	4	4
Bio-MeOH ICE	0.214	-0.032	-13.1 %	3	2
Elec-H_2 FC	0.273	-0.036	-11.7 %	1	1

The changes to global priorities and the ranking order of alternative marine fuels when decreasing the priority of one criteria at a time with -0.1 is displayed in table 4.11. It shows that a decrease of -0.1 in social criteria changes the ranking into Elec-H_2 $\succ$ LNG $\succ$ Bio-MeOH $\succ$ NG-MeOH (LNG becomes more preferred than Bio-MeOH). A larger decrease in social priority does not change the ranking any further, thus the ranking stays at Elec-H_2 $\succ$ LNG $\succ$ Bio-MeOH $\succ$ NG-MeOH.

Decreasing the priority of technical and environmental criteria with -0.1 changes the ranking marginally as LNG becomes equally preferred to Bio-MeOH. Decreasing environmental priority further, however, changes the ranking order of the alternative marine fuels. The breaking point occurs at a decrease of -0.17 at which the ranking order changes into LNG $\succ$ Bio-MeOH $\succ$ Elec-H_2 $\succ$ NG-MeOH.

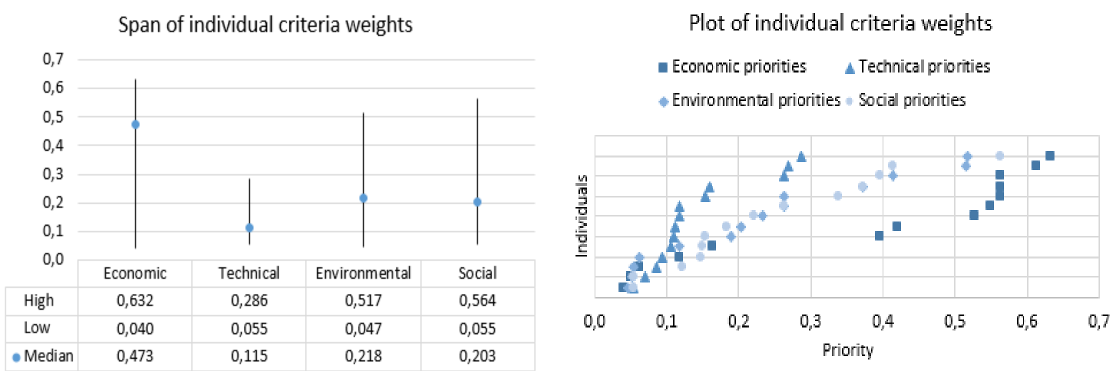
A continuous decrease in the priority of economic criteria does not change the original ranking order, the result is thus robust towards decreases in the importance of economic criteria within the chosen range of criteria uncertainties.

4.3.3 Analysis of individual weights

The individual priorities from the pairwise comparisons of economic, technical, environmental and social criteria are displayed in figure 4.5. Figure 4.5a shows that the stakeholders' priorities vary over large span for economic, environmental and social criteria. The stakeholders seem to be more consistent in their weighting of technical criteria as the span of priorities is smaller. The medians, however, tell us that the majority seem to think rather alike.

The plot with individual priorities, see figure 4.5b, shows that the stakeholders are divided into two groups regarding the importance of economic criteria. Most prioritise economic criteria high, but a third prioritise economic criteria low. For technical criteria, three stakeholders prioritise it a bit higher than the other stakeholders do. Generally speaking, technical criteria is prioritised rather low by all stakeholders.

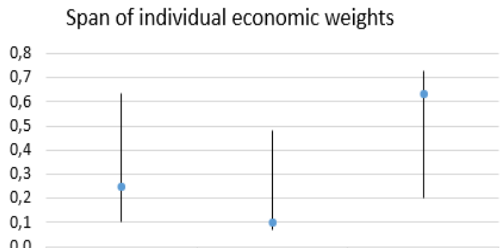
The individual priorities of environmental criteria are spread, and no specific groups can be distinguished. However, there is a tendency towards lower priority than higher priority which confirms the third place in the aggregated criteria priorities seen in figure 4.2b. Social criteria shows a spread in individual priorities as well. There is one person that prioritises social criteria much higher than the rest, which increases the span between the highest and lowest priority.



(a) Span of criteria priorities **(b)** Individual priorities

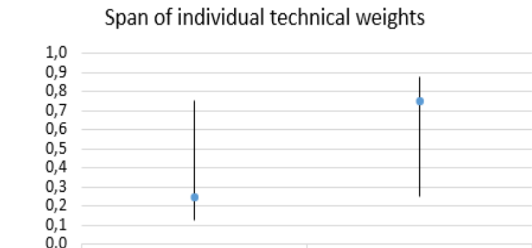
Figure 4.5: The distribution of stakeholders' individual priorities for economic, technical, environmental and social criteria, figure 4.5a) shows the span between the highest and lowest priority and the median, figure 4.5b) plots the individual priorities.

The span of individual priorities for the sub-criteria is displayed in figure 4.6. It shows that the preferences in sub-criteria vary over large spans as well. The medians, however, tell us that the majority of the group tend to think alike. Explanations for the large spans can be found in figure 4.7, as it plots the individual priorities for respective sub-criteria. For each sub-criteria, there are some persons who think the opposite to the majority, except for social sub-criteria, for which the group is split in two when it comes to which one of safety and upcoming legislation is most important.



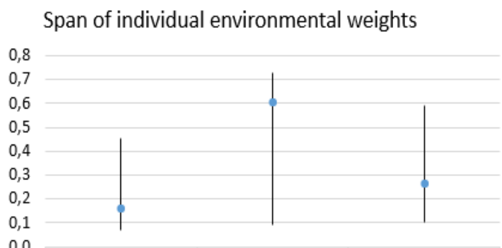
	Investment cost	Operational cost	Fuel price
High	0,637	0,481	0,731
Low	0,105	0,072	0,200
• Median	0,250	0,105	0,637

(a) Economic priorities



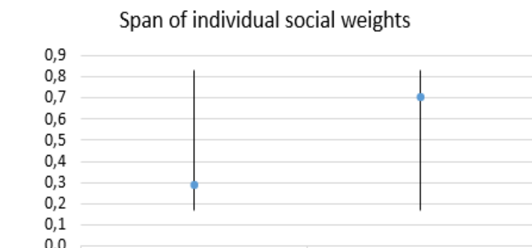
	Available infrastructure	Reliable supply of fuel
High	0,750	0,875
Low	0,125	0,250
• Median	0,250	0,750

(b) Technical priorities



	Acidification	Climate change	Health impact
High	0,455	0,731	0,594
Low	0,069	0,091	0,105
• Median	0,163	0,610	0,269

(c) Environmental priorities



	Safety	Upcoming legislation
High	0,833	0,833
Low	0,167	0,167
• Median	0,292	0,708

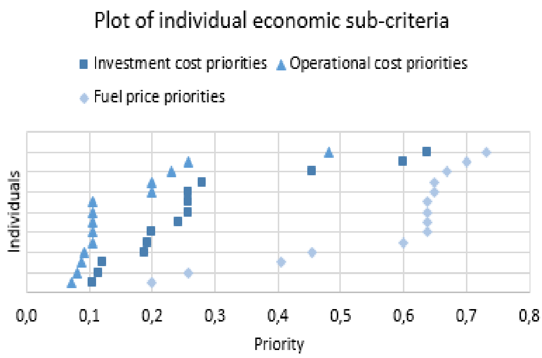
(d) Social priorities

Figure 4.6: The distribution of stakeholders' individual priorities in sub-criteria.

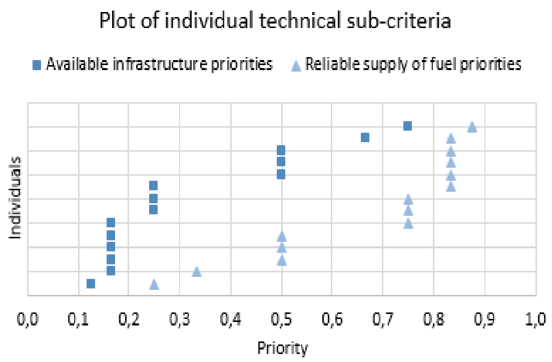
For economic sub-criteria, the majority of the group think investment costs and operational costs are of low priority (there are three persons who think that investment cost is of high priority and only one person who thinks operational cost is of high priority), see figure 4.7a. Further, the majority of the group seem to think that fuel price is of highest priority, followed by one pair who thinks it is of medium priority, and another pair who thinks fuel price is of low priority. In the whole, the stakeholders seem to agree on the relative importance between the economic sub-criteria.

For technical sub-criteria, the individual priorities seem to be quite unified, however, two groups can be distinguished, see figure 4.7b. The majority who think reliable supply of fuel is more important than available infrastructure, and a group of three who think reliable supply of fuel and available infrastructure are of equal importance.

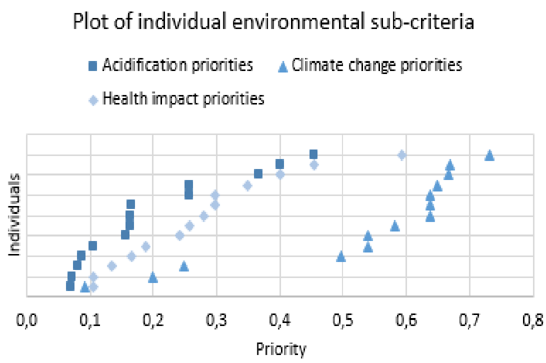
For environmental sub-criteria, the majority seems to think climate change is of higher priority than both acidification and health impact. There are three people, however, who seem to think the opposite, see figure 4.7c.



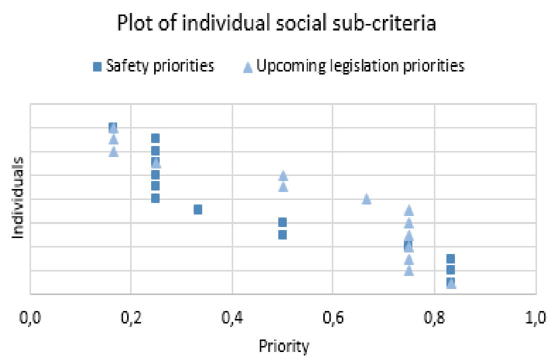
(a) Economic priorities



(b) Technical priorities



(c) Environmental priorities



(d) Social priorities

Figure 4.7: Plot over individual priorities for each group of sub-criteria. Graph 4.7a) - 4.7d) show the individual priorities for respective sub-criteria.

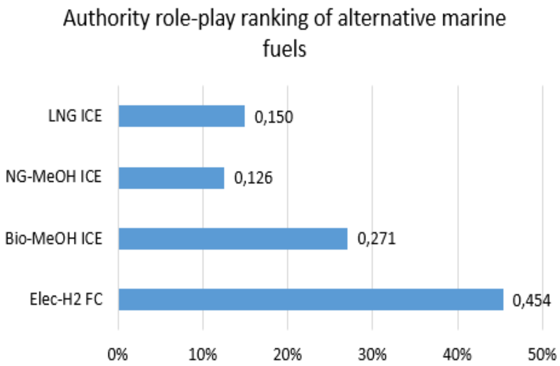
For social sub-criteria two groups with opposite opinions are distinguished, see figure 4.7d. One group who thinks that safety is of higher priority than upcoming legislation, and another group who thinks that upcoming legislation is of higher priority than safety (besides from two persons who think they are of equal importance).

4.4 Role-play

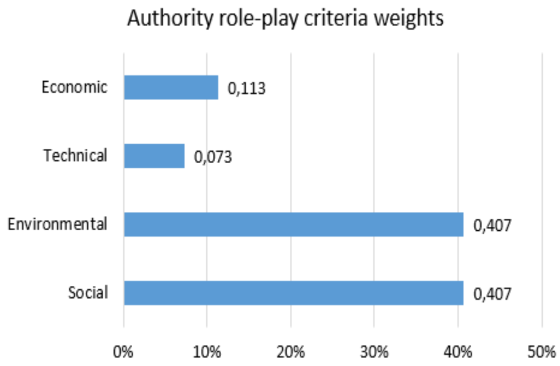
Below are the results from the role play, for which the involved stakeholders were asked to take on different perspectives when comparing the criteria; the role of an authority person, a shipowner, a fuel manufacturer and an engine manufacturer.

4.4.1 Authorities

The final ranking of alternative marine fuels and the criteria priorities from a fictional authority perspective is presented in figure 4.8. The most important criteria are environmental and social criteria, which are much more prioritised than economic and technical criteria. This results in a ranking order that strongly favours Elec-H_2 over the other alternatives.



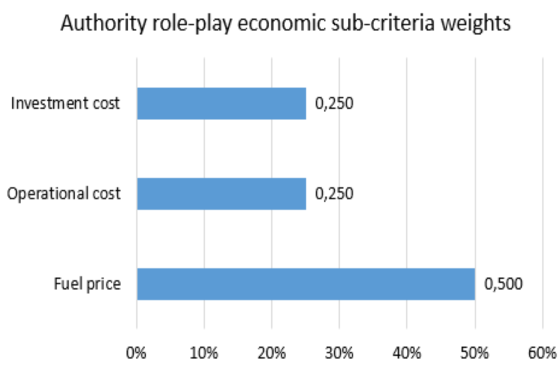
(a) Ranking of marine fuels



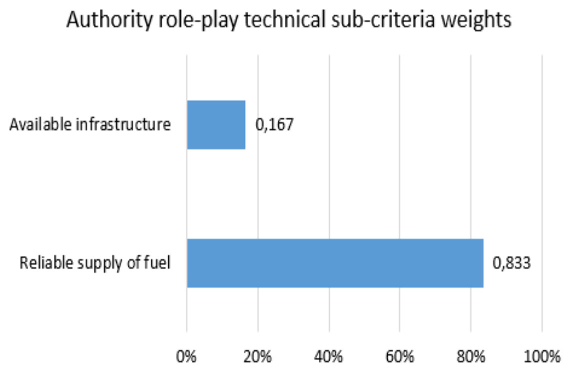
(b) Criteria priorities

Figure 4.8: The results from a fictional authority perspective, figure 4.8a) shows the ranking order of alternative marine fuels and figure 4.8b) the criteria priorities.

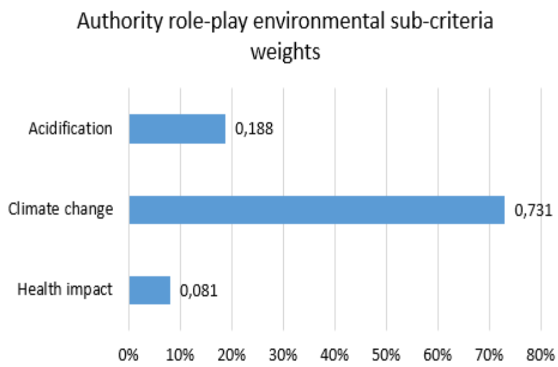
The sub-criteria priorities from a fictional authority perspective are presented in figure 4.9. The fuel price is more prioritised than investment cost and operational cost, see figure 4.9a. Reliable supply of fuel is much more prioritised than available infrastructure, see figure 4.9b. Climate change is the most prioritised environmental sub-criteria, see figure 4.9c, and upcoming legislation is much more prioritised than safety, see figure 4.9d.



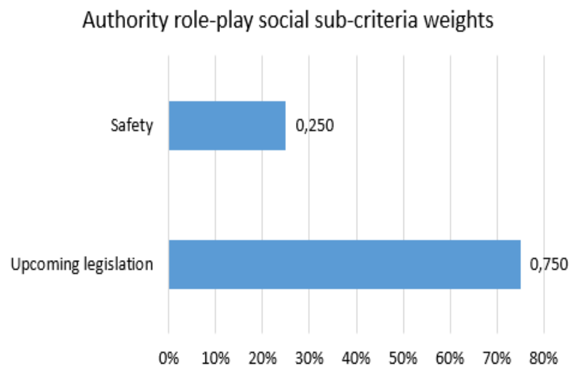
(a) Economic sub-criteria



(b) Technical sub-criteria



(c) Environmental sub-criteria

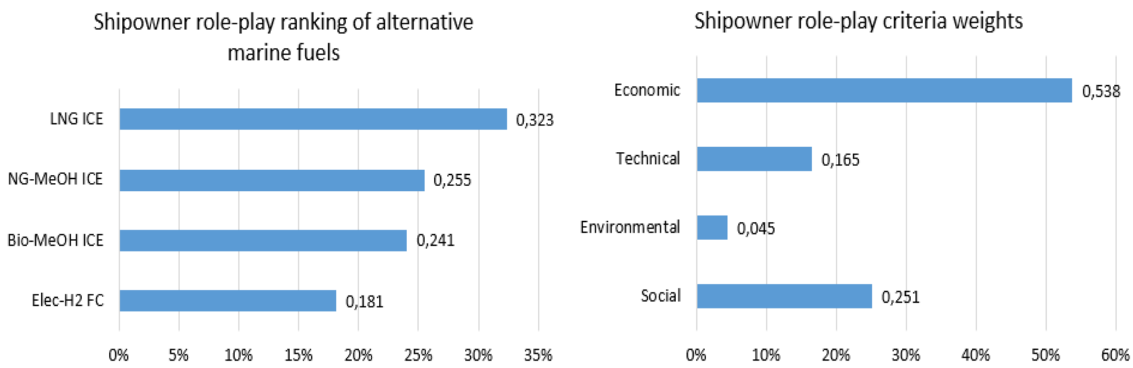


(d) Social sub-criteria

Figure 4.9: Sub-criteria priorities from a fictional authority perspective.

4.4.2 Shipowner

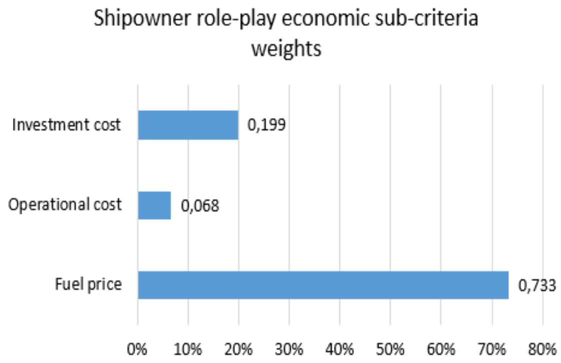
The final ranking of alternative marine fuels and the criteria priorities from a fictional shipowner perspective are presented in figure 4.10. Economic criteria is strongly prioritised when selecting alternative marine fuel, and environmental criteria is almost not prioritised at all. This results in a ranking order of LNG $\succ$ NG-MeOH $\succ$ Bio-MeOH $\succ$ Elec-H_2.



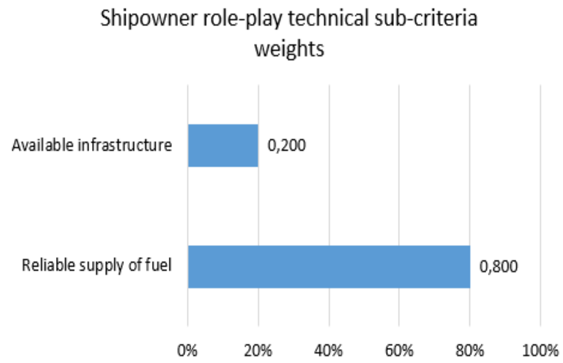
(a) Ranking of marine fuels **(b)** Criteria priorities

Figure 4.10: The results from a fictional shipowner perspective, figure 4.10a) shows the ranking order of alternative marine fuels and figure 4.10b) the criteria priorities.

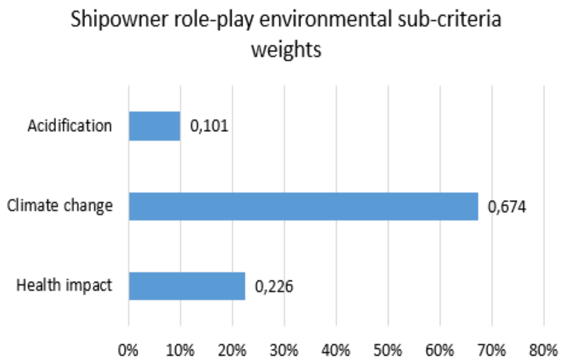
The sub-criteria priorities from a fictional shipowner perspective when selecting alternative marine fuels are presented in figure 4.11. Fuel price, reliable supply of fuel, climate change, and safety have highest priority in respective group of sub-criteria.



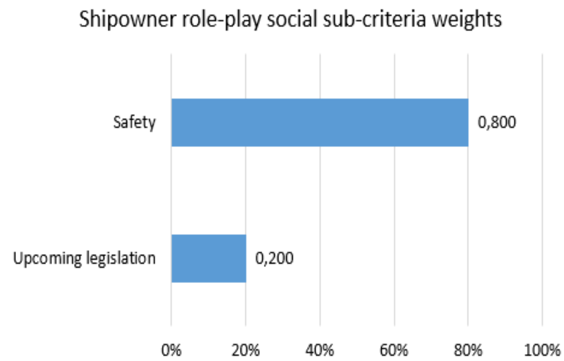
(a) Economic sub-criteria



(b) Technical sub-criteria



(c) Environmental sub-criteria

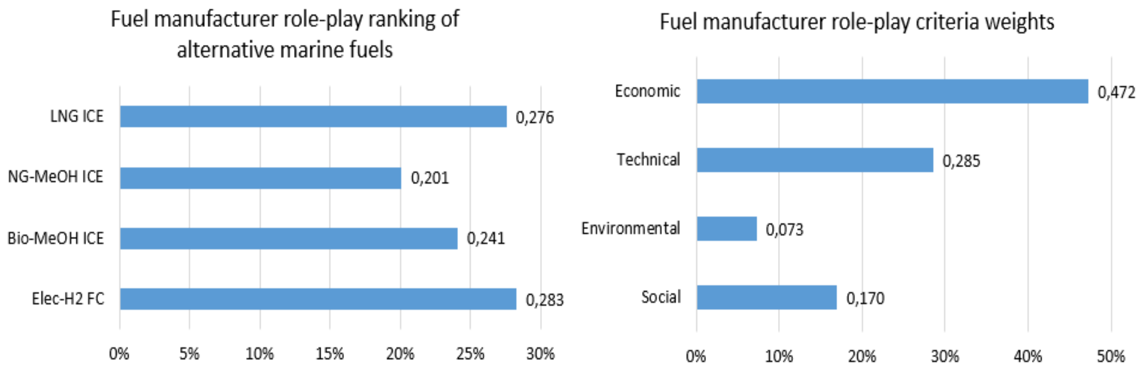


(d) Social sub-criteria

Figure 4.11: Sub-criteria priorities from a fictional shipowner perspective.

4.4.3 Fuel manufacturer

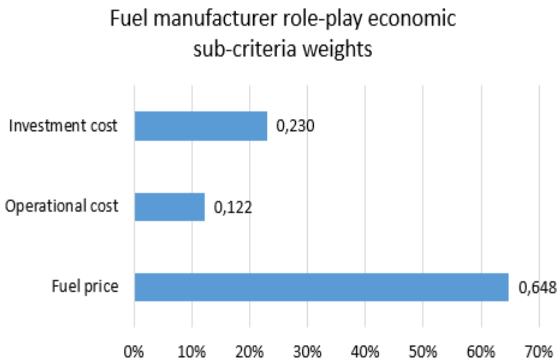
The ranking order of alternative marine fuels and the criteria priorities from a fuel manufacturer perspective are presented in figure 4.12. Economic criteria is prioritised the most when changing marine fuel, followed by technical criteria, social criteria, and last, environmental criteria. The resulting ranking order of alternatives is Elec-H_2 ≻ LNG ≻ Bio-MeOH ≻ NG-MeOH, however, Elec-H_2 and LNG are ranked very close.



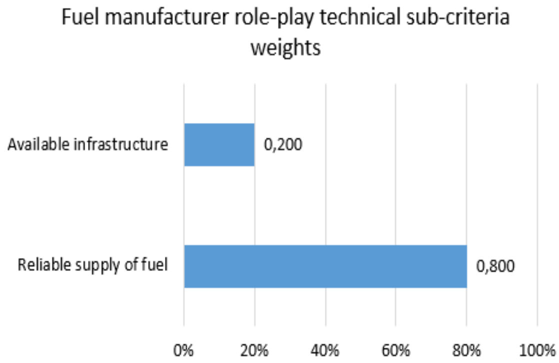
(a) Ranking of marine fuels **(b)** Criteria priorities

Figure 4.12: The results from a fictional fuel manufacturer perspective, figure 4.12a) shows the ranking order of alternative marine fuels and figure 4.12b) shows the criteria priorities.

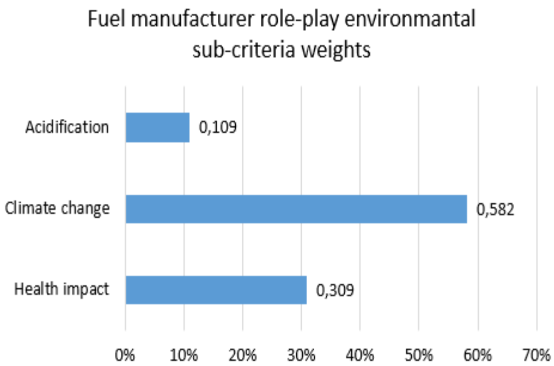
The sub-criteria priorities from a fictional fuel manufacturer are presented in figure 4.13. The most important economic sub-criteria is fuel price, see figure 4.13a. Reliable supply of fuel is the most important technical sub-criteria, see figure 4.13b. Climate change is the most important environmental sub-criteria followed by health impact, see figure 4.13c. For social sub-criteria, upcoming legislation is much more important than safety, see figure 4.13d.



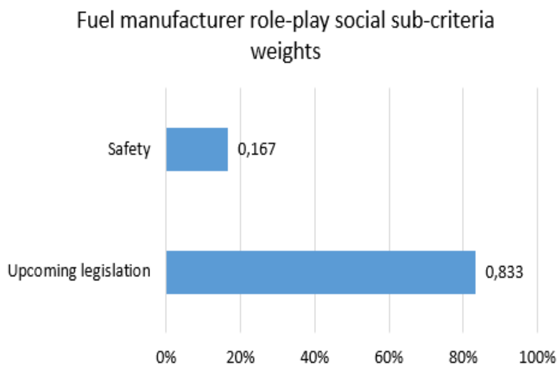
(a) Economic sub-criteria



(b) Technical sub-criteria



(c) Environmental sub-criteria

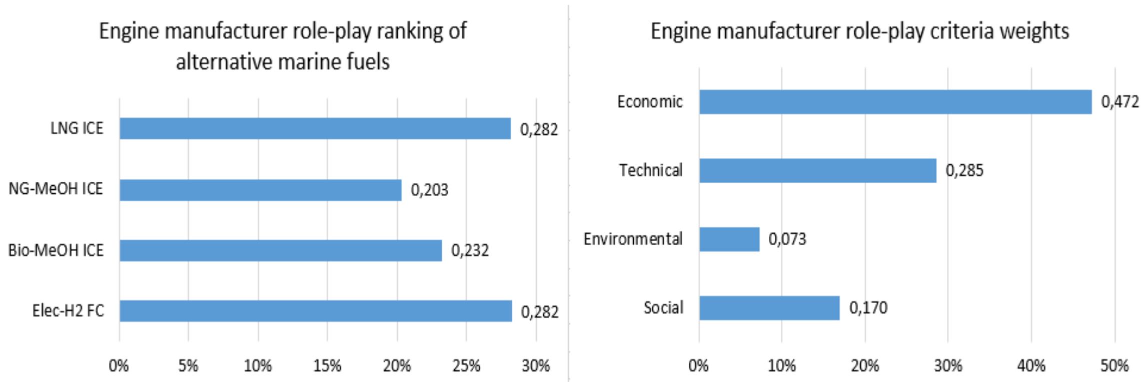


(d) Social sub-criteria

Figure 4.13: Sub-criteria priorities from a fictional fuel manufacturer perspective.

4.4.4 Engine manufacturer

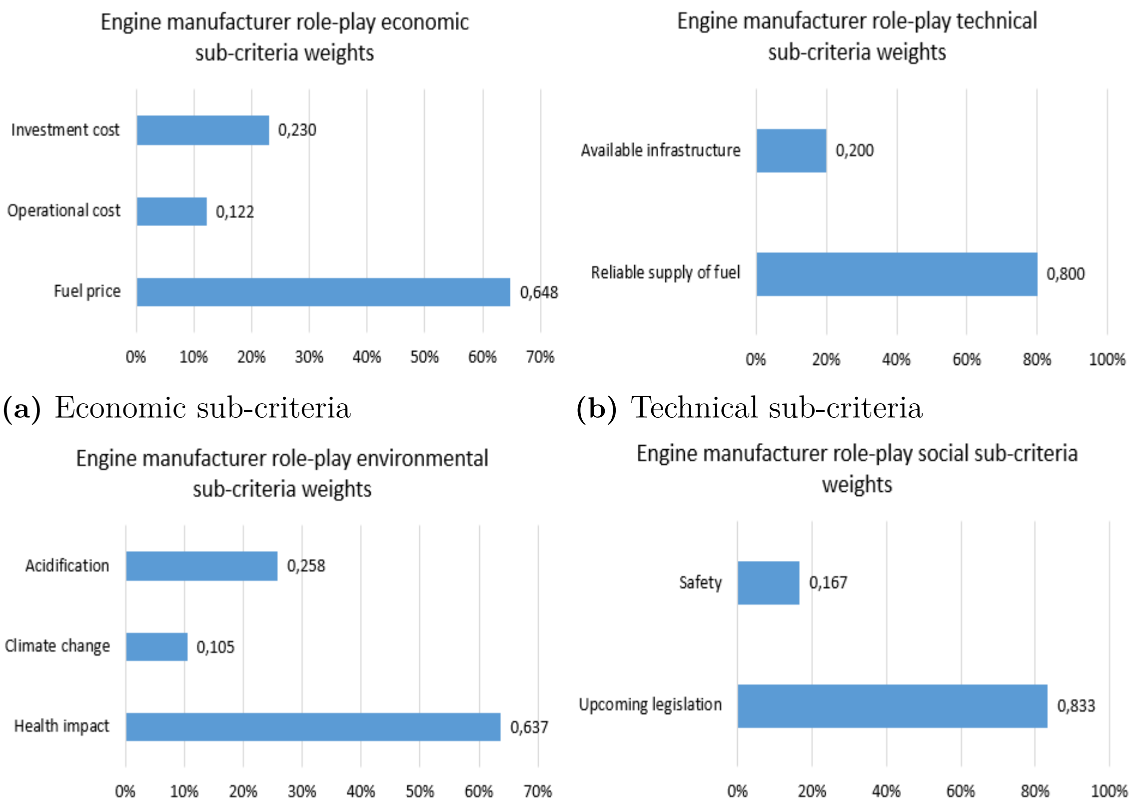
The final ranking of alternative marine fuels and the criteria priorities from a fictional engine manufacturer perspective are presented in figure 4.14. Engine manufacturer has the same criteria priorities as fuel manufacturers, but the final ranking order of alternative marine fuels differs slightly because the sub-criteria are prioritised differently. The ranking order for engine manufacturers is Elec-H_2 $=$ LNG $\succ$ Bio-MeOH $\succ$ NG-MeOH.



(a) Ranking of marine fuels **(b)** Criteria priorities

Figure 4.14: The results from a fictional engine manufacturer perspective, figure 4.14a) shows the ranking order of alternative marine fuels and figure 4.14b) shows the criteria priorities.

The sub-criteria priorities from a engine manufacturer perspective are presented in figure 4.15. The only difference from the fuel manufacturer perspective is that the engine manufacturer strongly favours health impact over climate change, and health impact is thus the most important environmental sub-criteria, see figure 4.15c. The reason for this was that it would be impossible for an engine manufacturers to sell a product that causes harm to people, and the responsibility for mitigating climate change lies with the user of the engine.



(a) Economic sub-criteria **(b)** Technical sub-criteria

(c) Environmental sub-criteria **(d)** Social sub-criteria

Figure 4.15: Sub-criteria priorities from a fictional engine manufacturer perspective.

The original ranking order of the alternative marine fuels and the results from the role-play are shown in figure 4.16, and summarised in table 4.12.

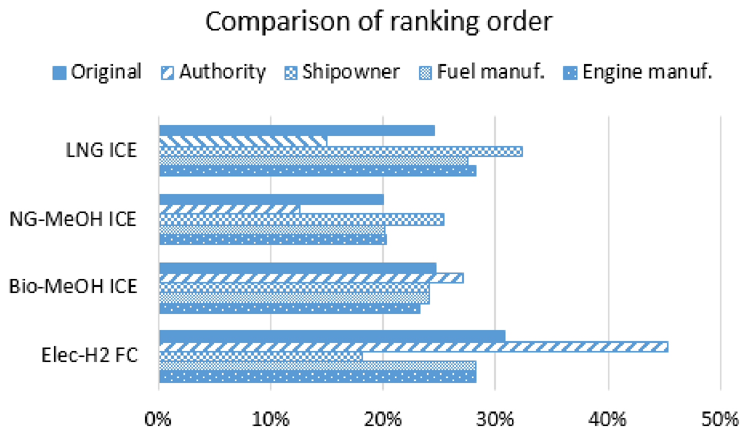


Figure 4.16: Comparison of the original ranking order of alternative marine fuels and the role-play results.

Table 4.12: Summary of the multi-criteria decision analysis and the role-play results

Ranking of alternative marine fuels					
	Original MCDA	Authority	Shipowner	Fuel manuf.	Engine manuf.
LNG	3 (0.245)	3 (0.150)	1 (0.323)	2 (0.276)	1 (0.282)
NG-MeOH	4 (0.200)	4 (0.126)	2 (0.255)	4 (0.201)	3 (0.203)
Bio-MeOH	2 (0.247)	2 (0.271)	3 (0.241)	3 (0.241)	2 (0.232)
Elec-H_2	1 (0.309)	1 (0.454)	4 (0.181)	1 (0.283)	1 (0.282)
Criteria importance					
	Original MCDA	Authority	Shipowner	Fuel manuf.	Engine manuf.
Economic	1 (0.346)	2 (0.113)	1 (0.538)	1 (0.472)	1 (0.472)
Technical	4 (0.166)	3 (0.073)	3 (0.165)	2 (0.285)	2 (0.285)
Environmental	3 (0.228)	1 (0.407)	4 (0.045)	4 (0.073)	4 (0.073)
Social	2 (0.260)	1 (0.407)	2 (0.251)	3 (0.170)	3 (0.170)

5
Discussion

This section includes general reflections on the results and how the execution of the Multi-criteria decision analysis has affected the outcomes.

5.1 General reflections on the results

General reflections on the results from the questionnaire, the impact assessment of the selected alternative marine fuels, the stakeholders' values and priorities of criteria, the final ranking order of the alternative marine fuels, and the role-play results are discussed here.

5.1.1 Questionnaire

All stakeholders agreed that climate change and reliable supply of fuel are important criteria when selecting alternative marine fuel. The reason for this may be that climate change is high up on the world agenda, and reliable supply of fuel is important since changing marine fuel represents a large investment that requires major changes to the ship that has a lifetime of approximately 30 years. It is surprising that none of stakeholders thought that impacts from fuel spills was important, nor public opinion or job creation. The reason for this could be that they became less important in comparison to the other criteria. It could also be, for fuel spills, that the alternative marine fuels are already known to have less impacts than the conventional fuels, and therefore it becomes less important to consider fuel spills when changing marine fuel. Another surprising aspect is that mature propulsion technology was not considered important enough to include in the study. This could be a sign of willingness to try new technology among the stakeholders, or maybe it is a criteria that is only important for shipowners.

5.1.2 Impacts of alternative marine fuels

In the impact assessment, LNG has shown to be the cheapest alternative marine fuel in terms of fuel price. The investment costs for propulsion and the operational costs are expected to be lower for NG-MeOH and Bio-MeOH, and Elec-H_2 is much more expensive in all economic categories. On the other hand, the environmental benefits are highest for Elec-H_2, and it is the fuel that is expected to meet all future regulations. In terms of safety, LNG and methanol (NG-MeOH and Bio-MeOH) are assumed to be more safe because they have been handled more extensively in shipping. Infrastructure is assumed to be available to the largest extent for LNG, and there is no existing infrastructure for Elec-H_2. The reliable supply of fuel is assumed to be highest for local production of Elec-H_2, and lowest for LNG and NG-MeOH, or Bio-MeOH depending on the assumptions made.

Aspects influencing the economic impacts of alternative marine fuels are that the investment costs for propulsion has been estimated for a newly built container ship. It is, however, possible to retrofit existing ships to run on alternative marine fuels. Using retrofits instead of new-builds could affect the economic impacts. Furthermore, fuel prices fluctuates a lot and have been estimated based on historical prices or production costs. There is a chance that these prices will change up to 2030. The fuel prices will also be affected by the selection of alternative marine fuels, as they are likely to have economy of scale and thus become cheaper when production increases.

Aspects influencing the environmental impacts are that the land use change has not been included, which is relevant for Bio-MeOH as it affects the impact on climate change. The amount of methane slip in the supply chain of LNG and NG-MeOH is another uncertainty that affects how well they perform regarding climate change.

Further, the impacts of technical and social criteria are very subjective since it is not possible to put exact numbers on available infrastructure, reliable supply of fuel, safety and upcoming legislation. The judgements are therefore based on an overall view that is obtained from studying the shipping industry and the fuels. It is important to remember that different persons draw different conclusions from the same information, and the ratings of the impacts in this study are based on the author's view. For example, when assessing available infrastructure, larger emphasis was taken to existing and upcoming production capacity, storage capacity in ports, and available bunkering opportunities. This way of reasoning favours LNG more than NG-MeOH and Bio-MeOH. If more emphasis is put on the compatibility, NG-MeOH and Bio-MeOH are rated higher and LNG lower since methanol is argued to be more compatible to existing infrastructure than LNG. The sensitivity analysis showed, however, that this did not change the original ranking order of fuels. The reason for this is probably because available infrastructure has low priority, which means that it does not affect the ranking order as much as other criteria. A possible reason for why available infrastructure has low priority could be because the stakeholders viewed it as easily solved since it is only a matter of cost.

One thing that did alter the ranking order of the alternative marine fuels is how reliable supply of fuel is judged. In this study, three sustainability constraints have been the foundation for how to rate reliable supply of fuel. This has favoured electrolytic hydrogen from wind power over the other fuels. Further, no competitive use of the fuel and raw materials was assumed, which favoured Bio-MeOH over NG-MeOH and LNG, because biomass for Bio-MeOH production is renewable and more accessible to countries than natural gas is. This is a very strong assumption, however, and maybe not applicable in reality since many sectors are planning to switch from fossil based material to bio based. One can therefore argue that the land use constraint is more limiting than limited availability of fossil fuels and the limited assimilation capacity. The sensitivity analysis showed that if this is the case, LNG becomes more preferable than Bio-MeOH, which makes this an important aspect to consider. The reason for why reliable supply of fuel alters the ranking order is probably because it is prioritised higher than available infrastructure. In reality, if Bio-MeOH is to be used as an alternative marine fuel, energy efficient measures and the possibility to run on dual fuel is likely necessary. Also, a high willingness to pay is needed from the shipping industry since many sectors are interested in bio-energy. An alternative way to handle reliable supply of fuel is to use dual fuel engines that can run on two different fuels.

The ranking order of alternative marine fuels is also sensitive to whether LNG or methanol is considered most safe, and how upcoming legislation is expected to affect the alternative marine fuels. The reason for this is probably because they are both highly prioritised, which means that they have a large impact on the final ranking order. It can also be due to the original ranking order, in which Bio-MeOH and LNG are ranked very close, Bio-MeOH only surpasses LNG with 0.2%, and it is therefore not surprising that they change order.

5.1.3 Stakeholders' values and priorities of criteria

The most prioritised criteria when selecting alternative marine fuels is economic criteria, which is not very surprising since the shipping industry is characterised by close to perfect competition. Fuel price is the most important economic sub-criteria which is not very surprising either since the fuel cost make up a large part of the running costs, which directly affects the profits. The second most prioritised criteria is social criteria, and both safety and upcoming legislation are considered important, closely followed by environmental criteria for which climate change is most prioritised. It is surprising, however, that technical criteria is prioritised the least when reliable supply of fuel was very important in the questionnaire for selecting the criteria to include in the study. One reason could be that available infrastructure, which is considered less important, affects the importance of technical criteria in general, resulting in a lower priority. Another reason could be that technical criteria is seen as something that can be influenced, and there is a general belief that is if the economy is good, technology does not pose a problem since technology development is only a matter of cost. In other words, as long as there is enough money to spend on technology, technology in it self is not a problem.

In general, it seems like criteria most crucial for the daily operations are prioritised higher. For example, economic criteria has a direct effect on the operation, as well as social criteria with safety and upcoming legislation. It is somewhat more difficult to understand why environmental criteria is more important than technical criteria, since available infrastructure and reliable supply of fuel affects the daily operations more than pollution does. A possible reason for this could be that technical criteria is seen as something that can be influenced, while environmental criteria cannot be solved as easily.

Another interesting aspect is that acidification is prioritised higher than health impacts in the aggregated environmental sub-criteria. This despite that the emissions causing the two are more or less the same. Instinctively, one would think human lives are more important than acidification is to most people. The result does, however, not necessarily imply that this is the case. It could be that acidification is more connected to emissions from shipping than health damage is, and therefore considered more important. It could also be that some damage to human health is accepted as a trade-off for the benefits shipping provides, while acidification primarily causes damage to nature.

There are some stakeholders who think the opposite to the majority for each criteria. It is difficult to explain why some people think the opposite to the majority, other than it is a usual phenomenon in group decisions. Allowing for people to have different opinions is also one of the main ideas behind Multi-criteria decision analysis. There are, however, some different perspectives that may explain how people think regarding the importance of criteria when selecting alternative marine fuels. For example, one can think differently regarding the purpose of changing marine fuel. If the purpose of changing marine fuel is to mitigate emissions, environmental criteria may become more important. But if the purpose is to comply with regulations, social criteria becomes more important. For environmental sub-criteria, one can either argue that acidification and health impacts are already taken care of by SECA regulations, while climate change is still an unsolved problem that needs to be addressed when changing marine fuel. On the other hand, one can argue that the global share of greenhouse gases from shipping is very small, while it is a large contributor to the global share of emissions causing acidification and health impacts, and therefore, acidification and health impacts become more important to consider when changing marine fuel.

5.1.4 Final ranking of alternative marine fuels

The final ranking order of the alternative marine fuels, according to the stakeholders' joint preference, is Elec-H_2 FC $\succ$ Bio-MeOH ICE $\succ$ LNG ICE $\succ$ NG-MeOH ICE, however, the difference between LNG and Bio-MeOH is very small and they switch order in parts of the sensitivity analysis. This ranking may seem counter-intuitive at first since the most important criteria is economic criteria and Elec-H_2 FC is the most expensive option. The reason for this is probably because the economic benefit of the alternative marine fuels are only found under economic criteria, while the advantage of Elec-H_2 is present in many of the other criteria; acidification potential, climate change, health impact, reliable supply of fuel, and upcoming legislation. It also happens that LNG and NG-MeOH that perform best economically, perform worse in the other criteria. In the whole, the assessed criteria will favour a sustainable alternative, but only if the decision makers in the AHP process value technical, environmental and social criteria high enough. If economic criteria is much more prioritised than the other criteria, the alternatives will be ranked according to their economic performance, or more specifically, according to the fuel price. This is observed in both the sensitivity analysis and in the shipowner role-play.

The ranking order of alternative marine fuels is sensitive to whether LNG or methanol is considered most safe, how upcoming legislation is expected to affect the alternative marine fuels, and how one reasons regarding reliable supply of fuel. In the whole, Elec-H_2 scores the highest throughout the sensitivity analysis and NG-MeOH scores the lowest. The reason for why the ranking order changes could be that the initial difference between LNG and Bio-MeOH is only 0.002.

5.1.5 Role-play

The four perspectives in the role-play did not differ very much in how they prioritised sub-criteria, except for safety and upcoming legislation. From a shipowner perspective, safety was much more prioritised than upcoming legislation, in contrast to the other three perspectives, for which upcoming legislation was much more prioritised than safety. The reason for this is probably because accidents have a direct effect on the shipowner as it leads to material damage, bad publicity and damage to reputation. This in turn leads to economic damage and so on. The safety of personnel is probably an important factor as well. In contrast to authorities for which safety is not within their area of responsibility, other than regulation-wise in terms of safety standards. One reason given for why upcoming legislation is valued high from an authority perspective, is that it is their best tool for influencing the maritime sector. For fuel and engine manufacturers, upcoming legislation is probably more important because it influences their business while safety is not their primary responsibility.

The major difference between the four perspectives are in how the criteria are valued. From an authority perspective, social and environmental criteria are valued the most, probably because authorities are responsible for seeing to the best interests of society. From a shipowner perspective, economic criteria is most important, which is not surprising since it affects their business the most. From a fuel manufacturer perspective, it was believed that technical criteria would be prioritised the highest, however, economic criteria was prioritised higher and technical criteria came in second place. The explanation for this was that it is economy that decides. Even for authorities, economy is important because it affects the amount of subsidies needed for introducing the alternative marine fuel. Another reason could be that economy and technology are believed to go hand in hand. If the economy is good, technology does not pose a problem.

The difference in criteria priority between the four roles affected the ranking order of alternative marine fuels, and different alternative marine fuels are preferred depending on the role. The largest difference is between the authority perspective and the shipowner perspective. From an authority perspective, renewable electrolytic hydrogen stands out as the best alternative, but from a shipowner perspective, the alternatives are ordered according to the fuel price and electrolytic hydrogen is therefore least preferred because of the high costs. From a fuel and engine manufacturer perspective, the alternatives are ranked very close, and it is probably likely that they will produce the fuels and engines the market demands, as long as the market is sizeable.

Some interesting view points can be drawn from the role-play. First of all, there seems to be a conflict in interest between society and the shipping industry in terms of what alternative marine fuel is the best option. This implies possible difficulties in agreeing on what alternative marine fuel to select for the future. The shipping industry seems to be prone to market based policies as economic criteria is most important, however, if renewable electrolytic hydrogen is to be realised, technology specific policies are probably needed to improve the fuel cell technology and to provide the production and infrastructure that are missing.

5.2 General reflections on the method

General reflections on the methods includes reflections on data collection, methodological choices and future studies.

5.2.1 Data collection

A lot of the information regarding available infrastructure and the current use of the alternative marine fuels are collected from business associations, interest organisations and companies. There is therefore a risk that some of the information is biased since business associations, interest organisations, and companies tend to have underlying agendas. This has been considered, however, and a mix of different sources have been used and carefulness has been taken to strong statements.

For economic and environmental impacts scientific papers have been available. It should be noted, however, that the scientific paper for comparing the operational cost between LNG and methanol are published some years before the first methanol ship was in use, which means there is a risk that the estimated operational cost differs slightly from the real operational cost.

Further, it takes time to obtain a comprehensive view of the shipping industry. It is a very complex industry with an optimised network of actors. The time limit has affected the amount of reading that could be done, and the judgements in scoring the alternatives.

It has also been challenging to find information. For example, there is much less information available on Bio-methanol and hydrogen, than there is for LNG. This is probably because LNG has been used more both as a marine fuel and as an energy source in general. The production volumes and trade of LNG is also much more transparent than for the other fuels. It was surprisingly hard to find information on production volumes and trade for methanol. Neither the global trade association, nor the international methanol producers and consumers association provided accessible information on volumes, trade and future trends on methanol. Development projects for methanol production are therefore not included in the study.

5.2.2 Methodological choices

It is important to remember that even though Multi-criteria decision analysis is a tool for aiding decision making by including and structuring more aspects of the real problem than one person can do, it is not possible for a MCDA to include all aspects of the real problem. One cannot assume that the whole problem is addressed. In this MCDA, it is also very clear that many important aspects are excluded since only 10 criteria are included in the study. This means that the ranking order may change if more criteria are added. Infrastructure cost and mature propulsion technology are two criteria that would be disadvantageous for electrolytic hydrogen. Including these may therefore change the ranking order.

The evaluation of criteria affect the result as well, and in this study environmental impact categories have been used instead of emissions. The advantage of this is in the weighting of criteria, as it is easier to judge the relative importance of acidification, health impact and climate change, than it is to judge the relative importance of various emissions such as SO_x and NO_x. The draw-back, however, is that one type of pollutant usually affects more than one impact category, meaning that high SO_x emissions for example results in worse scoring for both acidification and health impact. On the other hand, one can argue that if a fuel causes damage to both nature and humans, it should score worse.

It is more questionable whether CO_2 emissions and climate change should be considered to affect the limited assimilation capacity when assessing the reliable supply of fuel, since it has already been considered in the environmental impacts. This means that LNG and NG-MeOH are punished twice because of their greenhouse gas emissions. This was not considered in the beginning and therefore tested in the sensitivity analysis. In future studies, it is probably better to only include one of the two for a more balanced result, and to avoid double counting.

The sensitivity analysis that was done to analyse how much different perspective in technical and social criteria affect the ranking order of alternatives marine fuels was done one perspective at a time, meaning that it is still uncertain how a combination of different perspectives may affect the final ranking order. This is something that could have been explored more. Further, in the sensitivity analysis, only the strongest assumptions were tested. Another way to test the scoring could be to change the scoring more systematically, as in the sensitivity analysis of criteria weights. It is also possible to aggregate scores, and one way to improve the result could therefore be to let a panel of experts conduct the scores.

In this study, the stakeholders conducting the weighting of criteria were given the same say, it is however possible to give stakeholders different weights and let their judgements affect the aggregated priorities more or less depending on the organisation they represent. Since this Multi-criteria decision analysis included more stakeholders from research institutes than from other organisations, it would be interesting to see how much the aggregated priorities would change if their judgements were balanced, to represent an equal participation of different organisations.

The choice of which alternative marine fuels to include in the study was made without addressing the stakeholders. The outcome of the MCDA is therefore limited to the alternative marine fuels assessed in this study, and the results could have been different if more alternative marine fuels were assessed. It would therefore be interesting to include more alternative marine fuels in future studies, for example, liquefied biogas that is the renewable alternative to LNG and electrofuels.

It would also be interesting to see how much the selected MCDA-model affects the outcome, and therefore test what happens to the final ranking order if the Multi-Attribute Utility Theory is used instead of the Analytic Hierarchy Process.

In future studies, it would be interesting to include more alternative marine fuels, and follow up the stakeholders' weighting with individual interviews to get a better reasoning behind the priorities. It would also be interesting to include a cargo owner in the role-play, to see if the costumers are willing to pay a higher price for a more sustainable shipping industry.

6

Conclusion

This master's thesis has investigated the prospects for renewable marine fuels from a stakeholder perspective using a multi-criteria decision analysis. A synthesis of knowledge on impacts showed that locally produced electrolytic hydrogen from wind power has the largest environmental benefits, but is far more expensive than the other alternative marine fuels. The technical and social impacts of the alternative marine fuels are more subjective and depend on which assumptions that are made. The panel of stakeholders judging the importance of criteria valued economic criteria the most, followed by social criteria, environmental criteria and technical criteria. The relative importance between the criteria are not that large however, and the most preferred alternative marine fuel is electrolytic hydrogen, which is positive in terms of the prospects for renewable marine fuels. If electrolytic hydrogen is to be a future marine fuel, however, international collaboration and technology specific policies and subsidies are most likely needed and new infrastructure must be built.

Bibliography

Andersson, K. & Salazar, C. M. (2015). *Methanol as a marine fuel report.* Accessed 2017-03-12. FCBI Energy. Retrieved from http://www.g2xenergy.com/images/downloads/0815_MethanolMarineFuel_Report-EN-lowres.pdf

Baumann, H. & Tillman, A. (2004). The hitch hiker's guide to LCA. An orientation in life cycle assessment methodology and application.

Bengtsson, S., Andersson, K., Ellis, J., Haraldsson, L., Ramne, B., & Stefenson, P. (2012). Criteria for future marine fuels. The IAME 2012 Conference September 2012.

Brunelli, M. (2015). *Introduction to the analytic hierarchy process.* SpringerBriefs in Operations Research. Springer International Publishing.

Brynolf, S. (2014). *Environmental assessment of present and future marine fuels.* Thesis for the degree of Doctor of Philosophy, Department of Shipping and Marine Technology, Chalmers University of Tehcnology, Gothenburg, Sweden.

Brynolf, S., Fridell, E., & Andersson, K. (2014). Environmental assessment of marine fuels: Liquefied natural gas, liquefied biogas, methanol and bio-methanol. *Journal of Cleaner Production*, (74), 86–95.

Burman, Å. (2016). Vad händer inom svensk sjöfart på klimat- och miljöfronten? Presentation, 3 Feb 2016, Ekocentrum.

Calderón, M., Illing, D., & Veiga, J. (2016). Facilities for bunkering of liquefied natural gas in ports. *Transportation Research Procedia*, (14), 2431–2440.

DNV GL. (2016). Global sulphur cap 2020 know the different choices and challenges for on-time compliance. DNV GL - Maritime.

Ellis, J. & Tanneberger, K. (2015). Study on the use of ethyl and methyl alcohol as alternative fuels in shipping. European Maritime Safety Agency.

Encyclopaedia Britannica. (2017). *Flash point.* Accessed 2017-04-04. Retrieved from http://academic.eb.com/levels/collegiate/article/flash-point/34494#

Erhorn, T., Schnack, P., Krüger, M., Wuersig, G.-M., Chiotopoulos, A., & Adams, S. (2014). LNG as ship fuel. DNV GL Maritime Communication.

European Commission. (2011). *White paper: Roadmap to a single european transport area – towards a competitive and resource efficient transport system.* Accessed 2017-02-20. European Commission. Retrieved from https://ec.europa.eu/transport/sites/transport/files/themes/strategies/doc/2011_white_paper/white-paper-illustrated-brochure_en.pdf

European Commission. (2016). Communication from the commission to the european parliament, the council, the european economic and social committee and the committee of the regions on an eu strategy for liquefied natural gas and gas storage. European Commission.

European Environment Agency. (2017). *Particulate matter*. Accessed 2017-04-06. Retrieved from http://www.eea.europa.eu/themes/air/air-quality/resources/glossary/particulate-matter

European Maritime Safety Agency. (2017). *Air emissions: General background*. Accessed 2017-04-07. Retrieved from http://www.emsa.europa.eu/implementation-tasks/environment/149-air-pollution/532-air-emissions-general-background.html

Gamper, C. D., Thöni, M., & Week-Hannemann, H. (2006). A conceptual approach for the use of cost benefit and multi criteria analysis in natural hazard management. *NaturalHazards and Earth System Sciences*, (6), 293–302.

Geckoicapital. (2017). *Global LNG prices*. Accessed 2017-03-30. Retrieved from http://www.geckoicapital.com/global-lng-prices

Global Carbon Project. (2016). *Carbon budget and trends 2016*. Accessed 2017-05-19. Published on 14 November 2016. Retrieved from www.globalcarbonproject.org/carbonbudget

Grahn, M. (2016). Renewable fuels focusing on biofuels. Presentation, 31 August 2016, Department of Energy and Environment, Chalmers University of Technology.

Heyne, S., Grahn, M., & Sprei, F. (2015). Systems perspecties on alternative future transportation fuels. a litterature review of systems studies and scenarios, challenges and possibilities for bioenergy, production of biofuels and use of alternative transportation fuels. The Swedish Knowledge Centre for Renewable Transportation Fuels.

Holladay, J., Hu, J., King, D., & Wang, Y. (2009). An overview of hydrogen production technologies. *Catalysis Today*, (139), 244–260.

Holz, F., Richter, P. M., & Eggingy, R. (2015). A Global Perspective on the Future of Natural Gas: Resources, Trade, and Climate Constraints. *Review of Environmental Economics and Policy*, (9), 85–106.

Hosseini, S. E. & Wahid, M. A. (2016). Hydrogen production from renewable and sustainable energy resources: Promising green energy carrier for clean development. *Renewable and Sustainable Energy Reviews*, (57), 850–866.

ICS. (2014). *Shpping, World Trade and the Reduction of CO2 Emissions*. Accessed 2017-04-06. International Chamber of Shipping. Retrieved from http://www.ics-shipping.org/docs/default-source/resources/environmental-protection/shipping-world-trade-and-the-reduction-of-co2-emissions.pdf?sfvrsn=6

ICS. (2015a). *Shipping and world trade*. Accessed 2017-02-20. International Chamber of Shipping. Retrieved from http://www.ics-shipping.org/shipping-facts/shipping-and-world-trade

ICS. (2015b). *World seaborne trade*. Accessed 2017-02-20. International Chamber of Shipping. Retrieved from http://www.ics-shipping.org/shipping-facts/shipping-and-world-trade/world-seaborne-trade

IEA. (2007). Hydrogen production & distribution. International Energy Agency.

IEA. (2016). Gas Security Review 2016 How Flexible are LNG Markets in Practice? International Energy Agency.

IGU. (2016). IGU World Gas LNG Report — 2016 Edition. IGU International Gas Union.

IMO. (2015). Third IMO Greenhouse Gas Study 2014 Executive Summary and Final Report. International Maritime Organisation, London, UK.

IMO. (2016). *IMO regulations to reduce air pollution from ships and the review of fuel oil availability*. Accessed 2017-03-13. International Maritime Organization. Retrieved from http://www.imo.org/en/MediaCentre/HotTopics/GHG/Documents/sulphur%20limits%20FAQ_20-09-2016.pdf

IMO. (2017a). *Greenhouse Gas Emissions*. Accessed 2017-05-06. International Maritime Organization. Retrieved from http://www.imo.org/en/OurWork/Environment/PollutionPrevention/AirPollution/Pages/GHG-Emissions.aspx

IMO. (2017b). *Nitrogen Oxides (NOx) – Regulation 13*. Accessed 2017-05-06. International Maritime Organization. Retrieved from http://www.imo.org/en/OurWork/Environment/PollutionPrevention/AirPollution/Pages/Nitrogen-oxides-(NOx)-%E2%80%93-Regulation-13.aspx

IMO. (2017c). *Prevention of Air Pollution from Ships*. Accessed 2017-03-17. International Maritime Organization. Retrieved from http://www.imo.org/en/OurWork/Environment/PollutionPrevention/AirPollution/Pages/Air-Pollution.aspx

IRENA. (2013). Production of Bio-methanol Technology Brief. International Renewable Energy Agency.

Karen Law and Jeffrey Rosenfeld and Michael Jackson. (2013). Methanol as a renewable energy resource. Methanol Institute.

Karlsson, S., Azar, C., Berndes, G., Holmberg, J., & Lindgren, K. (1997). Man and Materials flows - Towards sustainable materials management. *A Sustainable Baltic Region*, (3).

Keeney, R. L. (1982). Decision analysis: An overview. *Operations Research*, (30), 803–838.

Krčum, M., Gudelj, A., & Žižić, L. (2010). Marine applications for fuel cell technology. Conference Paper.

LindeGroup. (2005). Safety data sheet. compressed hydrogen. Linde Gas North America LLC.

Linkov, I. & Moberg, E. (2012). *Multi-criteria decision analysis - environmental applications and case studies*. Boca Ranton, CRC Press Taylor & Francis Group.

Lundqvist, U. (2016). Sustainability constraints. Presentation, 13 April 2016, Department of Energy and Environment, Chalmers University of Technology.

Medina, E. & Roberts, R. R. (2013). Methanol Safe Handling Manual. The Methanol Institute.

Methanex. (2015). *Methanex is the methanol industry leader and is well-positioned to create value for shareholders*. Accessed 2017-03-18. Methanex Corporation. Retrieved from https://www.methanex.com/investor-relations/why-invest

Methanex. (2016). *Methanol Safety Data Sheet according to Regulation (EC) No. 1907/2006 (REACH) as amended*. Accessed 2017-03-09. Methanex Corporation. Retrieved from https://www.methanex.com/about-methanol/methanol-safety-data-sheets

Methanex. (2017). *Methanex posts regional contract methanol prices for North America, Europe and Asia. Current Posted Prices*. Accessed 2017-03-30. Retrieved from https://www.methanex.com/our-business/pricing

Methanol Institute. (2017). *The methanol industry.* Accessed 2017-03-18. Methanol Institute. Retrieved from http://www.methanol.org/the-methanol-industry/

Ott, J., Gronemann, V., Pontzen, F., Fiedler, E., Grossmann, G., Kersebohm, D. B., ... Witte, C. (2012). Methanol. Ullmann's Encyclopedia of Industrial Chemistry. Wiley-VCH Verlag GmbH & Co. KGaA, Weinheim.

PGW. (2015). *Safety Data Sheet: Liquified Natural gas (LNG).* Accessed 2017-03-09. Philadelphia Gas Works. Retrieved from http://www.pgworks.com/uploads/pdfs/LNGSafetyData.pdf

Royal Academy of Engineering. (2013). Future ship powering options exploring alternative methods of ship propulsion. Royal Academy of Engineering, ISBN: 978-1-909327-01-6.

Saaty, T. L. (1980). The Analytic Hierarchy Process: Planning, Priority Setting, Resource Allocation. McGraw-Hill, New York.

Saaty, T. L. (2008). Decision making with the analytic hierarchy process. *Int. J. Services Sciences*, (1), 83–98.

Sames, P. C., Clausen, N. B., & Andersen, M. L. (2011). Costs and benefits of LNG as ship fuel for container vessels. Accessed 2017-03-05. GL and MAN Diesel & Turbo. Retrieved from http://marine.man.eu/docs/librariesprovider6/technical-papers/costs-and-benefits-of-lng.pdf?sfvrsn=18

Scott, J. (2016). Methanol production from natural gas. *Chemical Engineering*, (123), 37.

Shell. (2017). *Liquefied natural gas (LNG).* Accessed 2017-05-18. Shell Global. Retrieved from http://www.shell.com/energy-and-innovation/natural-gas/liquefied-natural-gas-lng.html

Sims, R., Schaeffer, R., Creutzig, F., Cruz-Núñez, X., D'Agosto, M., Dimitriu, D., ... Tiwari, G. (2014). Transportation, In: Climate Change 2014: Mitigation of Climate Change. *Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, 599–670.

Sterman, J. D. (2008). Risk communication on climate: Mental models and mass balance. *Science*, (33), 532–533.

Taljegård, M., Brynolf, S., Grahn, M., Andersson, K., & Johnson, H. (2014a). Cost-Effective Choices of Marine Fuels in a Carbon-Constrained World: Results from a Global Energy Model. *Environmental Science & Technology*, (48), 12986–12993.

Taljegård, M., Brynolf, S., Grahn, M., Andersson, K., & Johnson, H. (2014b). Supporting information for cost-effective choices of marine fuels in a carbon constrained world: Results from a global energy model.

Teknomo, K. (2015). *Finding Eigen Value of Symmetric matrix Using Microsoft Excel.* Accessed 2017-04-02. Retrieved from http://people.revoledu.com/kardi/tutorial/Excel/EigenValue.html

Transport & Environment. (2017). *Air pollution from ships.* Accessed 2017-02-20. European Federation for Transport and Environment. Retrieved from https://www.transportenvironment.org/what-we-do/shipping/air-pollution-ships

Tronstad, T., Åstrand, H. H., Haugom, G. P., & Langfeldt, L. (2017). Study on the use of fuel cells in shipping. European Maritime Safety Agency.

Tsita, K. G. & Pilavachi, P. A. (2013). Evaluation of next generation biomass derived fuels for the transport sector. *Energy Policy*, (62), 443–455.

UNCTAD. (2016). *Review of maritime transport 2016*. Accessed 2017-04-06. United Nations Conference On Trade and Development. Retrieved from http://unctad.org/en/PublicationsLibrary/rmt2016_en.pdf

World Bank. (2016). *GDP growth (annual %)*. Accessed 2017-02-20. The World Bank Group. Retrieved from http://data.worldbank.org/indicator/NY.GDP.MKTP.KD.ZG?end=2015&start=1961&view=chart

World Health Organisation. (2013). *Health effects of particulate matter*. Accessed 2017-04-07. Retrieved from http://www.euro.who.int/___data/assets/pdf_file/0006/189051/Health-effects-of-particulate-matter-final-Eng.pdf

WPCI. (2017). *LNG fuelled vessels*. Accessed 2017-03-18. World Ports Climate Initiative. Retrieved from http://www.lngbunkering.org/lng/map/node

Wu, W.-H., Chiang, C.-t., & Lin, C.-t. (2008). Comparing the aggregation methods in the analytic hierarchy process when uniform distribution. *WSEAS TRANSACTIONS on BUSINESS and ECONOMICS*, (5), 82–87.

Zelma, R., Huijbregts, M. A., Hollander, H. A., Jaarsveld, H. A., Sauter, F. J., Struijs, J., … van de Meent, D. (2008). European characterization factors for human health damage of PM10 and ozone in life cycle impact assessment. *Atmospheric Environment*, (42), 441–453.

A

Appendix

This appendix includes the weights given to the criteria and the respective sub-criteria by the stakeholders at the workshop. Tables A.1-A.13 display the pairwise comparison matrices from the individual weights. Tables A.14-A.17 display the pairwise comparison matrices from the role-play. Please note that investment cost for propulsion is referred to as investment cost, available infrastructure has been shortened to infrastructure, reliable supply of fuel is referred to as reliable supply, and upcoming legislation is referred to as legislation.

Table A.1: Stakeholder's pairwise comparison matrices.

			Criteria weights		
	Economic	Technical	Environmental	Social	Priorities
Economic	1	3	1/3	1/3	0.163
Technical	1/3	1	1/3	1/3	0.094
Environmental	3	3	1	1	0.371
Social	3	3	1	1	0.371
					$\lambda_{max} = 4.155$
					CR = 0.058
			Criteria weights		
	Economic	Technical	Environmental	Social	Priorities
Economic	1	1/6	1/7	1/4	0.051
Technical	6	1	1/3	3	0.286
Environmental	7	3	1	3	0.514
Social	4	1/3	1/3	1	0.149
					$\lambda_{max} = 4.183$
					CR = 0.069
			Criteria weights		
	Economic	Technical	Environmental	Social	Priorities
Economic	1	3	5	7	0.564
Technical	1/3	1	3	5	0.263
Environmental	1/5	1/3	1	3	0.118
Social	1/7	1/5	1/3	1	0.055
					$\lambda_{max} = 4.117$
					CR = 0.044

Table A.2: Stakeholder's pairwise comparison matrices.

Criteria weights					
	Economic	Technical	Environmental	Social	Priorities
Economic	1	3	1/3	1/5	0.118
Technical	1/3	1	1/5	1/7	0.055
Environmental	3	5	1	1/3	0.263
Social	5	7	3	1	0.564
					$\lambda_{max} = 4.117$
					CR = 0.044
Criteria weights					
	Economic	Technical	Environmental	Social	Priorities
Economic	1	5	7	3	0.564
Technical	1/5	1	3	1/3	0.118
Environmental	1/7	1/3	1	1/5	0.055
Social	1/3	3	5	1	0.263
					$\lambda_{max} = 4.117$
					CR = 0.044
Criteria weights					
	Economic	Technical	Environmental	Social	Priorities
Economic	1	5	7	5	0.613
Technical	1/5	1	3	1/3	0.113
Environmental	1/7	1/3	1	1/5	0.053
Social	1/5	3	5	1	0.222
					$\lambda_{max} = 4.240$
					CR = 0.091
Criteria weights					
	Economic	Technical	Environmental	Social	Priorities
Economic	1	3	2	2	0.420
Technical	1/3	1	2	3	0.269
Environmental	1/2	1/2	1	2	0.190
Social	1/2	1/3	1/2	1	0.121
					$\lambda_{max} = 4.261$
					CR = 0.099
Criteria weights					
	Economic	Technical	Environmental	Social	Priorities
Economic	1	7	3	3	0.542
Technical	1/7	1	1/3	1/3	0.068
Environmental	1/3	3	1	2	0.229
Social	1/3	3	1/2	1	0.162
					$\lambda_{max} = 4.069$
					CR = 0.026
Criteria weights					
	Economic	Technical	Environmental	Social	Priorities
Economic	1	5	7	5	0.632
Technical	1/5	1	3	1	0.153
Environmental	1/7	1/3	1	1/3	0.062
Social	1/5	1	3	1	0.153
					$\lambda_{max} = 4.073$
					CR = 0.028

Table A.3: Stakeholder's pairwise comparison matrices.

			Criteria weights		
	Economic	Technical	Environmental	Social	Priorities
Economic	1	1/3	1/5	1/5	0.063
Technical	3	1	1/5	1/5	0.109
Environmental	5	5	1	1	0.414
Social	5	5	1	1	0.414
					λ_{max} = 4.155
					CR = 0.058
			Criteria weights		
	Economic	Technical	Environmental	Social	Priorities
Economic	1	1/5	1/8	1/7	0.040
Technical	5	1	1/6	1/5	0.105
Environmental	8	6	1	2	0.517
Social	7	5	2	1	0.338
					λ_{max} = 4.254
					CR = 0.096
			Criteria weights		
	Economic	Technical	Environmental	Social	Priorities
Economic	1	3	7	1	0.397
Technical	1/3	1	5	1/3	0.160
Environmental	1/7	1/5	1	1/7	0.047
Social	1	3	7	1	0.397
					λ_{max} = 4.073
					CR = 0.028
			Criteria weights		
	Economic	Technical	Environmental	Social	Priorities
Economic	1	5	3	7	0.564
Technical	1/5	1	1/3	3	0.118
Environmental	1/3	3	1	5	0.263
Social	1/7	1/3	1/5	1	0.055
					λ_{max} = 4.117
					CR = 0.044
			Criteria weights		
	Economic	Technical	Environmental	Social	Priorities
Economic	1	5	3	3	0.526
Technical	1/5	1	1/3	1/2	0.087
Environmental	1/3	3	1	1	0.203
Social	1/3	3	1	1	0.203
					λ_{max} = 4.034
					CR = 0.013

Table A.4: Stakeholder's pairwise comparison matrices.

Economic sub-criteria weights				
	Investment cost	Operational cost	Fuel price	Priorities
Investment cost	1	1/3	1/5	0.105
Operational cost	3	1	1/3	0.258
Fuel price	5	3	1	0.637
				λ_{max} = 3.039
				CR = 0.037
Economic sub-criteria weights				
	Investment cost	Operational cost	Fuel price	Priorities
Investment cost	1	1/2	1/5	0.122
Operational cost	2	1	1/3	0.230
Fuel price	5	3	1	0.648
				λ_{max} = 3.004
				CR = 0.004
Economic sub-criteria weights				
	Investment cost	Operational cost	Fuel price	Priorities
Investment cost	1	3	3	0.600
Operational cost	1/3	1	1	0.200
Fuel price	1/3	1	1	0.200
				λ_{max} = 3.000
				CR = 0.000
Economic sub-criteria weights				
	Investment cost	Operational cost	Fuel price	Priorities
Investment cost	1	5	3	0.637
Operational cost	1/5	1	1/3	0.105
Fuel price	1/3	3	1	0.258
				λ_{max} = 3.039
				CR = 0.037
Economic sub-criteria weights				
	Investment cost	Operational cost	Fuel price	Priorities
Investment cost	1	2	1/4	0.193
Operational cost	1/2	1	1/6	0.106
Fuel price	4	6	1	0.701
				λ_{max} = 3.009
				CR = 0.009
Economic sub-criteria weights				
	Investment cost	Operational cost	Fuel price	Priorities
Investment cost	1	3	1/3	0.258
Operational cost	1/3	1	1/5	0.105
Fuel price	3	5	1	0.637
				λ_{max} = 3.039
				CR = 0.037

Table A.5: Stakeholder's pairwise comparison matrices.

Economic sub-criteria weights				
	Investment cost	Operational cost	Fuel price	Priorities
Investment cost	1	3	1/5	0.188
Operational cost	1/3	1	1/7	0.081
Fuel price	5	7	1	0.731
				$\lambda_{max} = 3.065$
				CR = 0.062
Economic sub-criteria weights				
	Investment cost	Operational cost	Fuel price	Priorities
Investment cost	1	3	1/3	0.243
Operational cost	1/3	1	1/7	0.088
Fuel price	3	7	1	0.669
				$\lambda_{max} = 3.007$
				CR = 0.007
Economic sub-criteria weights				
	Investment cost	Operational cost	Fuel price	Priorities
Investment cost	1	1/5	1/3	0.114
Operational cost	5	1	1	0.481
Fuel price	3	1	1	4.05
				$\lambda_{max} = 3.029$
				CR = 0.028
Economic sub-criteria weights				
	Investment cost	Operational cost	Fuel price	Priorities
Investment cost	1	1/3	1/3	0.258
Operational cost	1/3	1	1/5	0.105
Fuel price	3	5	1	0.637
				$\lambda_{max} = 3.039$
				CR = 0.037
Economic sub-criteria weights				
	Investment cost	Operational cost	Fuel price	Priorities
Investment cost	1	5	1/3	0.279
Operational cost	1/5	1	1/7	0.072
Fuel price	3	7	1	0.649
				$\lambda_{max} = 3.065$
				CR = 0.062

Table A.6: Stakeholder's pairwise comparison matrices.

Economic sub-criteria weights				
	Investment cost	Operational cost	Fuel price	Priorities
Investment cost	1	1	1/3	0.200
Operational cost	1	1	1/3	0.200
Fuel price	3	3	1	0.600
				λ_{max} = 3.000
				CR = 0.000
Economic sub-criteria weights				
	Investment cost	Operational cost	Fuel price	Priorities
Investment cost	1	3	1/3	0.258
Operational cost	1/3	1	1/5	0.105
Fuel price	3	5	1	0.637
				λ_{max} = 3.039
				CR = 0.037
Economic sub-criteria weights				
	Investment cost	Operational cost	Fuel price	Priorities
Investment cost	1	5	1	0.455
Operational cost	1/5	1	1/5	0.091
Fuel price	1	5	1	0.455
				λ_{max} = 3.000
				CR = 0.000

Table A.7: Stakeholder's pairwise comparison matrices.

Environmental sub-criteria weights				
	Acidification	Climate change	Health impact	Priorities
Acidification	1	1/2	1/3	0.157
Climate change	2	1	1/3	0.249
Health impact	3	3	1	0.594
				λ_{max} = 3.054
				CR = 0.051
Environmental sub-criteria weights				
	Acidification	Climate change	Health impact	Priorities
Acidification	1	1/7	1/6	0.069
Climate change	7	1	2	0.582
Health impact	6	1/2	1	0.348
				λ_{max} = 3.032
				CR = 0.031

Table A.8: Stakeholder's pairwise comparison matrices.

	Environmental sub-criteria weights			
	Acidification	Climate change	Health impact	Priorities
Acidification	1	1/3	3	0.258
Climate change	3	1	5	0.637
Health impact	1/3	1/5	1	0.105
				$\lambda_{max} = 3.039$
				CR = 0.037
	Environmental sub-criteria weights			
	Acidification	Climate change	Health impact	Priorities
Acidification	1	1/3	3	0.258
Climate change	3	1	5	0.637
Health impact	1/3	1/5	1	0.105
				$\lambda_{max} = 3.039$
				CR = 0.037
	Environmental sub-criteria weights			
	Acidification	Climate change	Health impact	Priorities
Acidification	1	1/5	1/3	0.105
Climate change	5	1	3	0.637
Health impact	3	1/3	1	0.258
				$\lambda_{max} = 3.039$
				CR = 0.037
	Environmental sub-criteria weights			
	Acidification	Climate change	Health impact	Priorities
Acidification	1	1/7	1/5	0.072
Climate change	7	1	3	0.649
Health impact	5	1/3	1	0.279
				$\lambda_{max} = 3.065$
				CR = 0.062
	Environmental sub-criteria weights			
	Acidification	Climate change	Health impact	Priorities
Acidification	1	1/4	1	0.167
Climate change	4	1	4	0.667
Health impact	1	1/4	1	0.167
				$\lambda_{max} = 3.000$
				CR = 0.000
	Environmental sub-criteria weights			
	Acidification	Climate change	Health impact	Priorities
Acidification	1	1/7	1/3	0.081
Climate change	7	1	5	0.731
Health impact	3	1/5	1	0.188
				$\lambda_{max} = 3.065$
				CR = 0.062

Table A.9: Stakeholder's pairwise comparison matrices.

Environmental sub-criteria weights				
	Acidification	Climate change	Health impact	Priorities
Acidification	1	1/7	1/3	0.088
Climate change	7	1	3	0.669
Health impact	3	1/3	1	0.246
				$\lambda_{max} = 3.007$
				CR = 0.007
Environmental sub-criteria weights				
	Acidification	Climate change	Health impact	Priorities
Acidification	1	1	2	0.367
Climate change	1	1	5	0.498
Health impact	1/2	1/5	1	0.135
				$\lambda_{max} = 3.094$
				CR = 0.090
Environmental sub-criteria weights				
	Acidification	Climate change	Health impact	Priorities
Acidification	1	1/3	1/2	0.163
Climate change	3	1	2	0.540
Health impact	2	1/2	1	0.297
				$\lambda_{max} = 3.009$
				CR = 0.009
Environmental sub-criteria weights				
	Acidification	Climate change	Health impact	Priorities
Acidification	1	1/3	1/2	0.163
Climate change	3	1	2	0.540
Health impact	2	1/2	1	0.297
				$\lambda_{max} = 3.009$
				CR = 0.009
Environmental sub-criteria weights				
	Acidification	Climate change	Health impact	Priorities
Acidification	1	5	1	0.455
Climate change	1/5	1	1/5	0.091
Health impact	1	5	1	0.455
				$\lambda_{max} = 3.000$
				CR = 0.000
Environmental sub-criteria weights				
	Acidification	Climate change	Health impact	Priorities
Acidification	1	2	1	0.400
Climate change	1/2	1	1/2	0.200
Health impact	1	2	1	0.400
				$\lambda_{max} = 3.000$
				CR = 0.000

Table A.10: Stakeholder's pairwise comparison matrices.

Technical sub-criteria weights			
	Infrastructure	Reliable supply	Priorities
Infrastructure	1	1/5	0.167
Reliable supply	5	1	0.833
			λ_{max} = 2.000
			CR = 0.000
Technical sub-criteria weights			
	Infrastructure	Reliable supply	Priorities
Infrastructure	1	1/5	0.167
Reliable supply	5	1	0.833
			λ_{max} = 2.000
			CR = 0.000
Technical sub-criteria weights			
	Infrastructure	Reliable supply	Priorities
Infrastructure	1	1/5	0.167
Reliable supply	5	1	0.833
			λ_{max} = 2.000
			CR = 0.000
Technical sub-criteria weights			
	Infrastructure	Reliable supply	Priorities
Infrastructure	1	1/3	0.250
Reliable supply	3	1	0.750
			λ_{max} = 2.000
			CR = 0.000
Technical sub-criteria weights			
	Infrastructure	Reliable supply	Priorities
Infrastructure	1	1/7	0.125
Reliable supply	7	1	0.875
			λ_{max} = 2.000
			CR = 0.000
Technical sub-criteria weights			
	Infrastructure	Reliable supply	Priorities
Infrastructure	1	1	0.500
Reliable supply	1	1	0.500
			λ_{max} = 2.000
			CR = 0.000
Technical sub-criteria weights			
	Infrastructure	Reliable supply	Priorities
Infrastructure	1	1/5	0.167
Reliable supply	5	1	0.833
			λ_{max} = 2.000
			CR = 0.000

Table A.11: Stakeholder's pairwise comparison matrices.

Technical sub-criteria weights			
	Infrastructure	Reliable supply	Priorities
Infrastructure	1	2	0.667
Reliable supply	1/2	1	0.333
			$\lambda_{max} = 2.000$
			CR = 0.000
Technical sub-criteria weights			
	Infrastructure	Reliable supply	Priorities
Infrastructure	1	1/5	0.167
Reliable supply	5	1	0.833
			$\lambda_{max} = 2.000$
			CR = 0.000
Technical sub-criteria weights			
	Infrastructure	Reliable supply	Priorities
Infrastructure	1	1/3	0.250
Reliable supply	3	1	0.750
			$\lambda_{max} = 2.000$
			CR = 0.000
Technical sub-criteria weights			
	Infrastructure	Reliable supply	Priorities
Infrastructure	1	1	0.500
Reliable supply	1	1	0.500
			$\lambda_{max} = 2.000$
			CR = 0.000
Technical sub-criteria weights			
	Infrastructure	Reliable supply	Priorities
Infrastructure	1	1	0.500
Reliable supply	1	1	0.500
			$\lambda_{max} = 2.000$
			CR = 0.000
Technical sub-criteria weights			
	Infrastructure	Reliable supply	Priorities
Infrastructure	1	3	0.750
Reliable supply	1/3	1	0.250
			$\lambda_{max} = 2.000$
			CR = 0.000
Technical sub-criteria weights			
	Infrastructure	Reliable supply	Priorities
Infrastructure	1	1/3	0.250
Reliable supply	3	1	0.750
			$\lambda_{max} = 2.000$
			CR = 0.000

Table A.12: Stakeholder's pairwise comparison matrices.

Social sub-criteria weights			
	Safety	Legislation	Priorities
Infrastructure	1	1/5	0.167
Reliable supply	5	1	0.833
			λ_{max} = 2.000
			CR = 0.000
Social sub-criteria weights			
	Safety	Legislation	Priorities
Safety	1	5	0.833
Legislation	1/5	1	0.167
			λ_{max} = 2.000
			CR = 0.000
Social sub-criteria weights			
	Safety	Legislation	Priorities
Safety	1	5	0.833
Legislation	1/5	1	0.167
			λ_{max} = 2.000
			CR = 0.000
Social sub-criteria weights			
	Safety	Legislation	Priorities
Safety	1	1	0.500
Legislation	1	1	0.500
			λ_{max} = 2.000
			CR = 0.000
Social sub-criteria weights			
	Safety	Legislation	Priorities
Safety	1	1/3	0.250
Legislation	3	1	0.750
			λ_{max} = 2.000
			CR = 0.000
Social sub-criteria weights			
	Safety	Legislation	Priorities
Safety	1	1/3	0.250
Legislation	3	1	0.750
			λ_{max} = 2.000
			CR = 0.000
Social sub-criteria weights			
	Safety	Legislation	Priorities
Safety	1	1/3	0.250
Legislation	3	1	0.750
			λ_{max} = 2.000
			CR = 0.000

Table A.13: Stakeholder's pairwise comparison matrices.

Social sub-criteria weights			
	Safety	Legislation	Priorities
Safety	1	3	0.750
Legislation	1/3	1	0.250
			λ_{max} = 2.000
			CR = 0.000
Social sub-criteria weights			
	Safety	Legislation	Priorities
Safety	1	1/3	0.250
Legislation	3	1	0.750
			λ_{max} = 2.000
			CR = 0.000
Social sub-criteria weights			
	Safety	Legislation	Priorities
Safety	1	1/2	0.333
Legislation	2	1	0.667
			λ_{max} = 2.000
			CR = 0.000
Social sub-criteria weights			
	Safety	Legislation	Priorities
Safety	1	1/3	0.250
Legislation	3	1	0.750
			λ_{max} = 2.000
			CR = 0.000
Social sub-criteria weights			
	Safety	Legislation	Priorities
Safety	1	1/3	0.250
Legislation	3	1	0.750
			λ_{max} = 2.000
			CR = 0.000
Social sub-criteria weights			
	Safety	Legislation	Priorities
Safety	1	5	0.833
Legislation	1/5	1	0.167
			λ_{max} = 2.000
			CR = 0.000
Social sub-criteria weights			
	Safety	Legislation	Priorities
Safety	1	1	0.500
Legislation	1	1	0.500
			λ_{max} = 2.000
			CR = 0.000

Table A.14: Pairwise comparison matrices from the authority role-play.

Criteria weights					
	Economic	Technical	Environmental	Social	Priorities
Economic	1	3	1/5	1/5	0.113
Technical	1/3	1	1/4	1/4	0.073
Environmental	5	4	1	1	0.407
Social	5	4	1	1	0.407
					$\lambda_{max} = 4.226$
					CR = 0.085
Economic sub-criteria weights					
	Investment cost	Operational cost	Fuel price		Priorities
Investment cost	1	1	1/2		0.250
Operational cost	1	1	1/2		0.250
Fuel price	2	2	1		0.500
					$\lambda_{max} = 3.000$
					CR = 0.000
Environmental sub-criteria weights					
	Acidification	Climate change	Health impact		Priorities
Acidification	1	1/5	3		0.188
Climate change	5	1	7		0.731
Health impact	1/3	1/7	1		0.081
					$\lambda_{max} = 3.065$
					CR = 0.062
Technical sub-criteria weights					
	Infrastructure	Reliable supply			Priorities
Infrastructure	1	1/5			0.167
Reliable supply	5	1			0.833
					$\lambda_{max} = 2.000$
					CR = 0.000
Social sub-criteria weights					
	Safety	Legislation			Priorities
Safety	1	1/3			0.250
Legislation	3	1			0.750
					$\lambda_{max} = 2.000$
					CR = 0.000

Table A.15: Pairwise comparison matrices from the shipowner role-play.

Criteria weights					
	Economic	Technical	Environmental	Social	Priorities
Economic	1	4	7	3	0.538
Technical	1/4	1	6	1/2	0.165
Environmental	1/7	1/6	1	1/6	0.045
Social	1/3	2	6	1	0.251
					$\lambda_{max} = 4.195$
					CR = 0.074
Economic sub-criteria weights					
	Investment cost	Operational cost	Fuel price		Priorities
Investment cost	1	4	1/5		0.199
Operational cost	1/4	1	1/8		0.068
Fuel price	5	8	1		0.733
					$\lambda_{max} = 3.094$
					CR = 0.090
Environmental sub-criteria weights					
	Acidification	Climate change	Health impact		Priorities
Acidification	1	1/5	1/3		0.101
Climate change	5	1	4		0.674
Health impact	3	1/4	1		0.226
					$\lambda_{max} = 3.086$
					CR = 0.082
Technical sub-criteria weights					
	Infrastructure	Reliable supply			Priorities
Infrastructure	1	1/4			0.200
Reliable supply	4	1			0.800
					$\lambda_{max} = 2.000$
					CR = 0.000
Social sub-criteria weights					
	Safety	Legislation			Priorities
Safety	1	4			0.800
Legislation	1/4	1			0.200
					$\lambda_{max} = 2.000$
					CR = 0.000

Table A.16: Pairwise comparison matrices from the fuel manufacturer role-play.

Criteria weights					
	Economic	Technical	Environmental	Social	Priorities
Economic	1	2	5	3	0.472
Technical	1/2	1	4	2	0.285
Environmental	1/5	1/4	1	1/3	0.073
Social	1/3	1/2	3	1	0.170
					$\lambda_{max} = 4.051$
					CR = 0.019
Economic sub-criteria weights					
	Investment cost	Operational cost	Fuel price		Priorities
Investment cost	1	2	1/3		0.230
Operational cost	1/2	1	1/5		0.122
Fuel price	3	5	1		0.648
					$\lambda_{max} = 3.004$
					CR = 0.004
Environmental sub-criteria weights					
	Acidification	Climate change	Health impact		Priorities
Acidification	1	1/5	1/3		0.109
Climate change	5	1	2		0.582
Health impact	3	1/2	1		0.309
					$\lambda_{max} = 3.004$
					CR = 0.004
Technical sub-criteria weights					
	Infrastructure	Reliable supply			Priorities
Infrastructure	1	1/4			0.200
Reliable supply	4	1			0.800
					$\lambda_{max} = 2.000$
					CR = 0.000
Social sub-criteria weights					
	Safety	Legislation			Priorities
Safety	1	1/5			0.167
Legislation	5	1			0.833
					$\lambda_{max} = 2.000$
					CR = 0.000

Table A.17: Pairwise comparison matrices from the engine manufacturer role-play.

Criteria weights					
	Economic	Technical	Environmental	Social	Priorities
Economic	1	2	5	3	0.472
Technical	1/2	1	4	2	0.285
Environmental	1/5	1/4	1	1/3	0.073
Social	1/3	1/2	3	1	0.170
					$\lambda_{max} = 4.051$
					CR = 0.019
Economic sub-criteria weights					
	Investment cost	Operational cost	Fuel price		Priorities
Investment cost	1	2	1/3		0.230
Operational cost	1/2	1	1/5		0.122
Fuel price	3	5	1		0.648
					$\lambda_{max} = 3.004$
					CR = 0.004
Environmental sub-criteria weights					
	Acidification	Climate change	Health impact		Priorities
Acidification	1	3	1/3		0.258
Climate change	1/3	1	1/5		0.105
Health impact	3	5	1		0.637
					$\lambda_{max} = 3.039$
					CR = 0.037
Technical sub-criteria weights					
	Infrastructure	Reliable supply			Priorities
Infrastructure	1	1/4			0.200
Reliable supply	4	1			0.800
					$\lambda_{max} = 2.000$
					CR = 0.000
Social sub-criteria weights					
	Safety	Legislation			Priorities
Safety	1	1/5			0.167
Legislation	5	1			0.833
					$\lambda_{max} = 2.000$
					CR = 0.000