Master's thesis - Master Energy Science

ASSESSMENT AND COMPARISON OF ALTERNATIVE MARINE FUELS
TOWARDS THE DECARBONISATION OF PORT OF AMSTERDAM

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Abstract

By shipping more than eighty per cent of the world's trade volumes, the global maritime industry is essential for the world economy. However, due to expected continuous increasing shipping volumes, the significant amounts of greenhouse gases produced by the sector are likely to grow in a *business-as-usual* scenario. Therefore, to ensure a sustainable future, the International Maritime Organisation aims at the decarbonisation of the maritime sector. The goal of this decarbonisation strategy is a greenhouse gas emission reduction of at least fifty per cent in 2050, relative to 2008. To meet these goals, a transition to alternative marine fuels and corresponding propulsion systems is considered to be crucial. Port of Amsterdam supports this transition to ensure her societal and future commercial interests.

The main problem that comes with this transition derives from the global uncertainty about future dominant alternative marine fuels. Port of Amsterdam and her stakeholders need clarity to develop alternative fuel supply chains, bunker facilities, and innovative propulsion systems. The objective of the research for this paper was to set up an analytical framework that analyses the commercial and operational aspects of the most promising alternative fuels for the Amsterdam port. A multi-criteria decision analysis framework was found to be most appropriate as it is able to deal with the diverse characteristics and contradictory strengths and weaknesses of alternative fuels.

The scope of the assessment aims at alternative fuels for coastal and inland vessels in the year 2030 and beyond. Selected fuels are biodiesel (HVO), bio LNG, bio methanol, compressed hydrogen, liquid hydrogen, e-methanol, and sodium borohydride. These fuels are assessed according to scalability, together with technological, economic, environmental, and social-political criteria. Weight factors are defined by marine fuel experts to deal with the relative importance of the criteria.

The outcomes of the research show that biodiesel, more specific hydrotreated vegetable oil (HVO), is the most promising alternative fuel for coastal and inland vessels in the Amsterdam port in 2030. It has the lowest fuel and propulsion system costs. In addition, biodiesel (HVO) comes with a high volumetric energy density and fits perfectly in the current infrastructure of Amsterdam, making conventional fuels rather easily replaceable. Methanol turns out to be a good alternative as it could be sustainably produced via biomass and via hydrogen. Also, the long-term potential of sodium borohydride is confirmed by this study. Bio LNG, compressed hydrogen and liquid hydrogen have less potential for coastal and inland shipping purposes. Further research could be done on specific criteria such as the local availability of primary energy and the economic consequences of a changing fuel infrastructure in the port.

Executive summary

The global maritime industry is essential for the world economy by shipping more than eighty per cent of the world's trade volumes. However, the sector produces significant amounts of greenhouse gases that are likely to grow in a *business-as-usual* scenario due to expected increasing shipping volumes. Therefore, the International Maritime Organisation aims at the decarbonisation of the maritime sector to ensure a sustainable future. The goal is a greenhouse gas emission reduction of at least fifty per cent in 2050, relative to 2008. A transition to alternative marine fuels and corresponding propulsion systems is considered to be crucial in meeting the climate goals. Port of Amsterdam supports this transition to ensure her societal and future commercial interests. Namely, sustainable development of port activities is crucial in maintaining and strengthening her international competitive position as one of the largest logistics hubs in the EU for the modalities: rail, inland waterways, road, and sea.

Research design

The main problem that comes with the transition is the global uncertainty about future dominant alternative marine fuels. Port of Amsterdam and her maritime stakeholders need clarity to develop alternative fuel supply chains, including production locations, storage terminals and bunker facilities, and innovative propulsion systems. The objective of the research was to set up an analytical framework that analyses the commercial and operational aspects of the most promising alternative fuels for the Amsterdam port. A multi-criteria decision analysis framework was found to be most appropriate as it is able to deal with the diverse characteristics and contradictory strengths and weaknesses of alternative fuels.

The scope of the assessment aims at alternative fuels for coastal and inland vessels in the year 2030 and beyond. The switch to alternative fuels is expected to be earlier for coastal and inland shipping because their refuelling patterns are better predictable than deep-sea shipping, and they are more affected by strict EU regulations. Selected fuels for analysis are biodiesel (HVO), bio LNG, bio methanol, compressed hydrogen, liquid hydrogen, e-methanol, and sodium borohydride as these could actively contribute to decarbonisation of the maritime and port sector in the short term. These fuels are assessed according to scalability, together with technological, economic, environmental, and social-political criteria. The criteria definitions are given in Table 1. Data is collected from industrial and academic literature, twenty interviews conducted at Port of Amsterdam and her maritime stakeholders, and a survey to define the relative importance of the assessment criteria.

Table 1: Criteria definitions

Criteria	Definitions
Scalability	The potential of the alternative marine fuel to be able to meet the future (growing) demand of the maritime and port sector in Amsterdam.
Technological	The maturity and energy efficiency of fuel production processes and vessel propulsion systems. Also, the energy density of the alternative marine fuel is included in this criterium.
Economics	The cost related to possible new fuel infrastructure, the CAPEX of propulsion systems onboard and the alternative marine fuel cost.
Environmental	The amount of generated GHG emissions and local pollutants related to the production and use of alternative fuels. Safety issues related to flammability, toxicity, and environmental impact are also included in this criterium
Social-political	The social and political acceptability and support related to the alternative marine fuel.

Results

The final scores and scores per criteria are shown per alternative fuel in Figure 1. Hereby, 0 is the least preferred and 100 the most preferred performance.

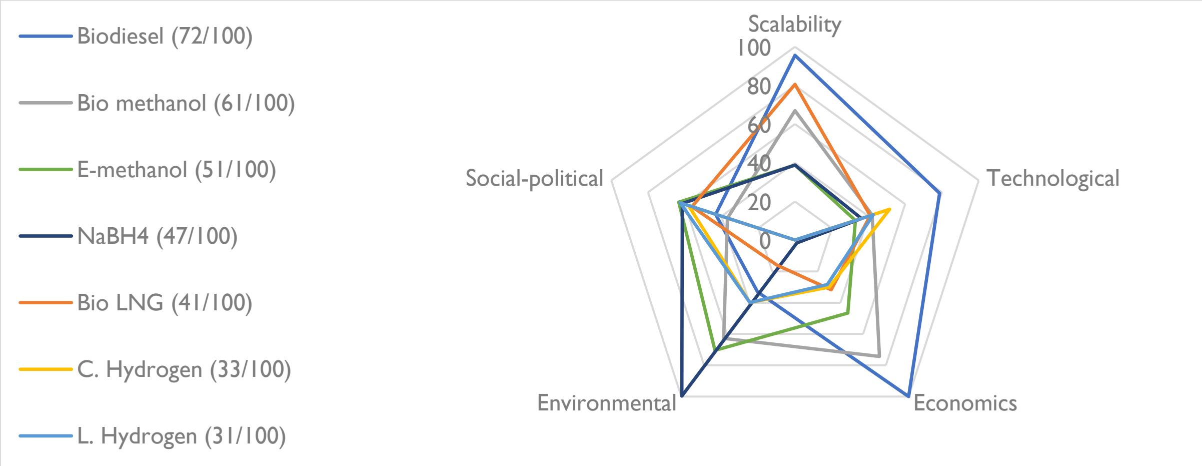

Figure 1: Spider plot with criteria scores per alternative fuel. Final scores are given in the brackets.

The outcomes of the research show that biodiesel, more specifically hydrotreated vegetable oil (HVO), is the most promising alternative fuel for coastal and inland vessels in the Amsterdam port in 2030. Its fuel and propulsion system cost are preferable. Besides, biodiesel (HVO) comes with a high volumetric energy density and fits perfectly in the current infrastructure of Amsterdam. Methanol turns out to be a good alternative as it could be sustainably produced via biomass and via hydrogen. Bio methanol is more preferred than e-methanol towards 2030 due to its better availability, higher maturity, and lower fuel price. However, the long-term scenario of the study showed that e-methanol is likely to become more attractive towards 2040 and beyond as a consequence of growing electrolyser capacity and decreasing green hydrogen production costs. Also, the long-term potential of sodium borohydride is confirmed by this research. Sodium borohydride is preferred from an environmental and social-political perspective since it is safe; it comes with zero emissions and does not contain carbon. Bio LNG could be a successor of fossil LNG but has relatively high production costs, a limited GHG emission reduction potential and flammability hazards. Compressed hydrogen and liquid hydrogen are mainly suitable for short-distance coastal and inland shipping purposes due to their low volumetric energy density.

Recommendations

An alternative fuel outlook is presented in Figure 2. The outlook contains promising fuels for coastal and inland shipping which are plotted against the related opportunities in the Amsterdam port. The dotted areas of the fuels represent the timeframe of pre-market developments, and the full-coloured areas show the timeframe of expected full commercial acceptance. Biobased marine fuels could play a significant role in the maritime industry as it is the most feasible alternative on the short-term, and it could drive the implementation of hydrogen-related fuels on the long-term. Other e-fuels and ammonia are not analysed in this research but have an interest by the maritime industry.

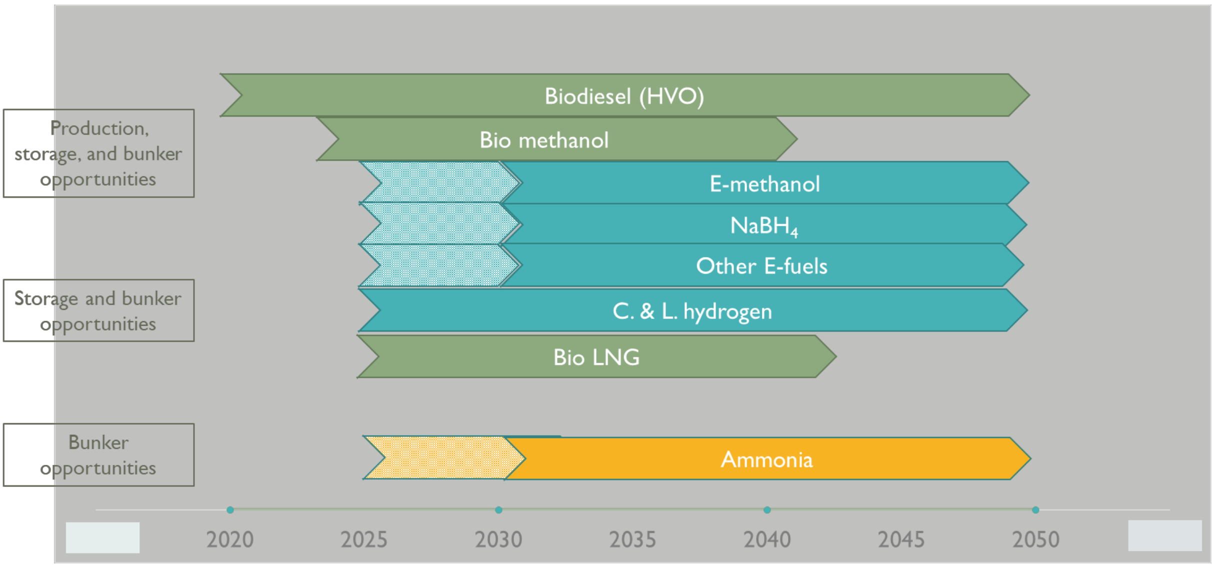

Figure 2: Promising alternative fuels for coastal and inland vessels according to added value Amsterdam port

The most important recommendations for Port of Amsterdam and her maritime stakeholders are:

- Include a holistic approach among maritime stakeholders and other ports to overcome the 'chicken or the egg' dilemma related to the supply and demand side of alternative fuels. Every stakeholder – including fuel supply chain, bunker, and shipping companies – should be given a specific role so that both sides can develop at the same pace.
- Make the port 'alternative fuel ready' by setting the right conditions for alternative fuels. The right conditions include hydrogen production, hydrogen infrastructure, CO_2 infrastructure, and clear environmental and safety requirements. The alternative fuel market is still too uncertain to focus only on a few particular fuels, so concentrate on the most promising mix and regularly research in further market development.
- Focus on developing alternative fuels for the coastal and inland shipping market instead of deep-sea in the Amsterdam port. This market is expected to switch to alternative fuels earlier and fits better to size and available assets in the Amsterdam port. Large-scale fuel 'production' for the deep-sea market is better appropriate in ports like Rotterdam.
- Be critical on the sustainability of biomass feedstocks to deal with societal concerns. Biomass feedstock should not be competitive with the food industry and should not let to a loss of biodiversity. Moreover, upstream emissions during harvest, transportation and pre-treatment are desired to be avoided as much as possible.

More recommendations are in Section 5.3. of the written thesis.

Preface

This master's thesis is the final delivery for the completion of the Energy Science master's program at Utrecht University. Research has been done during a graduation internship at Port of Amsterdam, Amsterdam, the Netherlands. The cooperation with the company, allowed the author to apply his knowledge and skills acquired in the Energy Science program in an industrial, maritime environment. This industrial environment was under the special interest of the author, which resulted in high levels of motivation. Port of Amsterdam provided valuable input for this thesis from her internal knowledge and external network. To serve the interests of Port of Amsterdam, an executive summary of this research is enclosed. Moreover, the thesis is a delivery for the Interreg North-West Europe project H2SHIPS, which increases societal relevance. The H2Ships project aims at the demonstration of the technical and economic feasibility of maritime hydrogen technologies and the identification of required market conditions.

Acknowledgements

Firstly, I want to thank my supervisor at Utrecht University, Prof. dr. Gert Jan Kramer, for supervising me during the process of this master's thesis. He provided me with critical and valuable feedback and suggestions that highly contributed to the quality of the final delivery. Besides, I want to thank him for sharing his knowledge and expertise in the industrial environment and his drive to address the global climate problem.

Secondly, I want to thank Port of Amsterdam for giving me the opportunity to cooperate for the full length of this research. Special thanks are there for my supervisor at Port of Amsterdam, Jan Egbertsen. Jan was very involved, gave useful input and feedback, and showed much appreciation, which helped and motivated me a lot. Even during the changing working conditions as a result of COVID-19, the contact between me, and Jan remained excellent. I also want to thank the internal and external interviewees for sharing their highly valuable knowledge and opinions on alternative marine fuels. The experience of working in the environment of Port of Amsterdam and the meetings with stakeholders contributed to my personal development and made myself ready for a professional career.

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Acronyms

AHP	Analytical hierarchy process
CO_2	Carbon dioxide
CCS	Carbon capture and storage
CCU	Carbon capture and utilisation
ECA	Emission Control Area
E-fuel	Electro fuel
EU	European Union
FAME	Fatty acid methyl ester
FC	Fuel cell
GHG	Greenhouse gases
H_2	Hydrogen
HFO	Heavy fuel oil
H_2O	Water
HVO	Hydrotreated vegetable oil
ICE	Internal combustion engine
IEA	International Energy Agency
IMO	International Maritime Organization
LNG	Liquefied natural gas
MCDA	Multi-criteria decision analysis
MGO	Marine gas oil
$NaBH_4$	Sodium borohydride
$NaBO_2$	Sodium metaborate
NO_x	Nitrogen oxides
PoA	Port of Amsterdam
PEM	Proton exchange membrane
PM	Particulate matter
RED	Renewable Energy Directive
SOEC	Solid oxide electrolysis fuel cell
SOLAS	Safety of Life at Sea
SO_x	Sulphur oxides
TRL	Technology Readiness Level
UN	United Nations
UNCTD	The United Nations Conference on Trade and Development
UU	Utrecht University
WHO	World Health Organization

1. Introduction

By being responsible for more than 80 per cent of the world's trade volumes, the maritime sector takes in a crucial role for the world economy. Global trade and consequent maritime transport are only likely to grow in the future due to their relatively energy-efficient and low-cost nature of transportation. Despite their high energy energy-efficiency though, most vessels run on highly polluting heavy fuel oil (HFO) or marine gas oil (MGO), which obstruct global climate goals and affect local air quality. Currently, more than two per cent of all global emissions derive from shipping, whereby the volume of emissions could grow between 150 and 250 per cent in the next decades, in a *business-as-usual* scenario (Bouman et al., 2017). The United Nations Conference on Trade and Development (UNCTD) and the International Maritime Organization (IMO) call for action to cut emissions from the maritime industry. A transition to alternative marine fuels is therefore perceived as critical to ensure a sustainable future of the maritime sector (Brynolf et al., 2014; UN, 2019a). Recognising the need for this transition, the research of this paper aims to assess and compare sustainable alternative marine fuels. In the current chapter, the background of this problem is discussed, together with the research design and approach.

1.1. Background

Currently, several targets and regulations are set to stimulate the decarbonisation of the maritime sector. The IMO has set a greenhouse gases (GHG) reduction goal of worldwide shipping by at least 50 per cent in 2050, relative to 2008. This target aligns with the Paris Agreement (Global Maritime Forum, 2019a). More recent, the European Union announced a goal of even higher ambitious nature in their 'Green deal'; namely, to be utterly climate-neutral in 2050. Coinciding with this Green deal, the Dutch maritime and port sector raised the GHG reduction target from 50 to 70 per cent in 2050, relative to 2008 (I&W, 2019). The IMO also put stricter regulations in place regarding local pollutants by increasing the limit in the share of sulphur in marine fuels to protect the health of people and environment in port and coastal areas (IMO, 2019).

Decarbonisation measures for the maritime sector are multifaceted and versatile. Recently, scholars have reviewed 150 studies on possible decarbonisation measures for the maritime industry and estimated their associated CO_2 reduction potentials. The formulated decarbonisation categories include hull design, propulsion system, alternative fuels, alternative energy sources and operation. It was found that in order to obtain the required emission reduction potential, a transition to alternative fuels is the only fulfilling measure (Bouman et al., 2017).

The global maritime industry is highly aware of the need for alternative fuels and acknowledges this through large-scale initiatives like the Getting to Zero Coalition. This alliance aims to accelerate the decarbonisation of maritime shipping by supporting the development of zero-emission propulsion systems. Their goal is to have zero-emission vessels in operation by 2030, which they consider essential to meet the GHG reduction target set by the IMO. One of the coalition members of the Getting to Zero Coalition is Port of Amsterdam (Global Maritime Forum, 2019b).

Port of Amsterdam (PoA) is the authority that facilitates the port region of Amsterdam, the fourth largest harbour of Europe. The company executes a role as a landlord, matchmaker, and co-creator. Port of Amsterdam does not run terminals and ships by themselves but is responsible for smooth, safe, and sustainable operations. A key objective is to maintain and strengthen the international competitive position of Amsterdam's harbour as one of the largest logistics hubs in the EU for the modalities: rail, inland waterways, road, and sea. Traditionally, the vast majority of revenues generated in ports result from the distribution, storage, and processing of fossil fuels. In Amsterdam, oil products and coal accounted for over 70 per cent of the transhipped volumes in the port in 2018. A strong future competitive position requires alignment with the above stated global emission reduction targets. Therefore, a rigid change in the focus of Amsterdam's port region is needed, from conventional fossil fuel-related business activities to renewable, clean, and circular business activities. The consequences of this transition are enormous since ports have a crucial role in fossil fuel systems (Port of Amsterdam, 2019).

In line with their sustainable ambitions, Port of Amsterdam aspires to take in a central role in the transition to alternative marine fuels to yield her societal and future commercial interests. Alternative fuel supply chain activities are a sustainable source of revenues that could replace fossil-fuel related revenues (Maritime manager, personal communication, 20-3-2020). Moreover, the realisation of bunker facilities for alternative fuels allows the Amsterdam port to become a leading infrastructural hub in fuelling ships with innovative propulsion systems. Therefore, the Port of Amsterdam seeks to support the development of innovative propulsion systems by facilitating shipbuilders and shipping companies. Also, the port authority aims to redesign the current fuel supply chains and bunkering facilities (Innovation manager J. Egbertsen, personal communication, 6-2-2020). It has to be taken into consideration that ships and fuel infrastructure have long lifespans and replacement will take decades. Therefore, it is key for ports to include this transition in their business development strategy as soon as possible. Otherwise, emission reduction targets cannot realistically be met (Gilbert et al., 2018).

1.2. Problem definition

The problem that arises with this transition to alternative fuels is the global unclarity about the fuel(s) and corresponding propulsion system(s) that are going to be dominant in the future maritime industry. Recent studies suggest several gaseous and liquid alternative fuels such as liquefied natural gas (LNG), biobased fuels and hydrogen-based fuels (Deniz & Zincir, 2016; Hansson et al., 2019). Besides, there are possibilities for electric and nuclear-based propulsion systems (Eide et al., 2013). Research outcomes have shown some consensus about the prospects of alternative fuels and corresponding propulsion systems but also leave a lot of inconsistencies and uncertainties. Studies are affected by varying research methods, time frames, geographical locations, and stakeholder preferences. Furthermore, several alternatives are still in the pilot or test phase, which makes performance assessment and comparison difficult (Hansson et al., 2019).

Due to current uncertainty on future propulsion trajectories, clarity is necessary for Port of Amsterdam and her stakeholders to determine a focussed business development strategy on alternative marine fuels. Ships and fuel supply systems namely have lifespans of more than thirty years which require substantiated long-term investments.

1.3. Previous studies

As stated earlier, scholars have set out a number of alternative fuels that could potentially replace current propulsion systems. The first alternative marine fuel, LNG, can be used in internal combustion engines to power ships. Beneficial is that natural gas is widely available for a low price. Furthermore, sulphuric, nitrogen and particulate matter emission can be reduced by about 90 per cent relative to HFO, which improves the local air quality (Elgohary et al., 2015). However, the GHG reduction potential of LNG is limited by its leakage rate, which offsets the maximal 10-20 per cent CO_2 reduction (Horvath et al., 2018; Pavlenko et al., 2020). This makes the above stated global climate goals for 2050 unachievable with LNG.

Secondly, biofuels such as biodiesel, bio LNG, bioethanol, and bio methanol can serve as alternative marine fuels. These fuels have the potential to decrease the climate impact of shipping if these are produced from sustainable biomass (Brynolf et al., 2014). Furthermore, the use of biofuels does not require high capital investments since its applicability, conversion technologies and storage requirements are comparable to fossil fuels. A downside of biofuels is their competition with other sectors (SSI, 2019). The price and availability heavily depend on the food industry, the road sector and possibly the air sector in the future. Another disadvantage is the nitrogen oxide footprint of biofuels (Bengtsson et al., 2012; Darda et al., 2019; Hansson et al., 2019).

Electric propulsion is the third alternative to replace polluting HFO and MGO. This type of propulsion is emission-free when electricity originates from renewable sources. One major disadvantage is that electric propulsion requires electricity storage in relatively expensive batteries. Furthermore, these batteries have a low energy density which makes electric propulsion only applicable for short distance sailing. Fully electric propulsion for long-distance deep-sea, coastal, and inland shipping is considered to be unrealistic (Ryste, 2019).

The fourth alternative, nuclear propulsion, is already in a mature state. This technology has mainly been used for military submarines but also has seen usages for freight shipping. Nuclear powered ships can operate with low fuel costs, with small refuelling intervals and without emissions. Nevertheless, interest is poor due to its lack of social acceptance. This is caused by issues in processing radio-active waste and nuclear disasters in the past (Alam, 2018).

Hydrogen is the last considered alternative marine fuel. Usage of this fuel does produce zero GHG emissions if formed via renewable electricity. This carbon-free fuel can be combusted in engines or used in more energy-efficient fuel cells to power ships. Current issues of hydrogen are the lack of bunkering infrastructure, the limited amount of green hydrogen available and the high costs. However, estimations are that green hydrogen production volumes will soar in the next decade (Thornhill, 2019). Acceptable cost levels for the shipping industry are expected to be reached in 2030 (Horvath et al., 2018; Ryste, 2019). Hydrogen is produced, stored, and bunkered in different forms. The first two options are compressing or liquefying the hydrogen in its pure form. Other options involve metal, chemical and liquid organic hydrogen carriers, such as methanol, ammonia, and formic acid.

From these earlier studies, it can be concluded that biobased and hydrogen-based fuels are the most promising alternatives for deep-sea, coastal, and inland shipping to meet climate goals. However, many types of biobased and hydrogen-based fuels could potentially be used as a marine fuel. So far, no proper research has been done on the assessment and comparison of different types of biobased and hydrogen-based marine fuels. Direct comparison is difficult due to the diverse strengths and weaknesses of alternative fuels.

1.4. Aim of the research

The objective of this study is to set up an analytical framework that is able to assess and compare the different bio- and hydrogen alternative marine fuels. This framework is used to find out which fuels are most promising in becoming dominant in the future maritime industry. A case study is performed on Port of Amsterdam. A future dominant marine fuel requires high commercial and operational performance to ensure long-term sustainability. The outcomes may provide Port of Amsterdam and her stakeholders with valuable knowledge to determine business development strategies regarding fuel supply chains, bunkering facilities, and innovative propulsion systems.

1.5. Research questions

The resulting main research question is:

What is the commercial and operational most promising alternative marine fuel for coastal and inland shipping in 2030 and beyond in order to decarbonise the Amsterdam port?

The main research question will be answered according to the following sub-questions:

1. *What bio- or hydrogen-based marine fuels could potentially be used for propulsion of coastal and inland vessels in 2030 and beyond?*
2. *What are suitable fuel production pathways for the Port of Amsterdam?*
3. *What are the relevant stakeholders, and what are their preferences regarding alternative marine fuels?*
4. *What are the criteria for commercial and operational assessment of alternative marine fuels?*
5. *What are the criteria scores of the different alternative marine fuels?*
6. *What are the weight factors of the chosen criteria that are representative of the Amsterdam port?*
7. *What do the outcomes on alternative fuels mean for the business development strategies of Port of Amsterdam and her stakeholders?*

1.6. Scope

The study aims at coastal and inland vessels since these are responsible for the relatively large intra-European share of trade in Amsterdam (Port of Amsterdam, 2015). Furthermore, these vessel types are expected to earlier switch to alternative fuels than deep-sea vessels. This is because refuelling patterns of coastal and inland vessels are better predictable, and they are more affected by strict EU regulations. Moreover, they are not affected by lagging ports outside of Europe (Innovation manager J. Egbertsen, personal communication, 5-3-2020). The lessons learned from developments in coastal and inland shipping can help deep-sea shipping in the future. In addition, the research aims at the year 2030 and beyond, since it is expected that acceptable price levels for hydrogen-based marine fuels are met by then. Also, this period gives the port authority and stakeholders a reasonable amount of time to implement the outcomes of this research in their strategy and activities. Alternative fuels that may not be interesting yet in 2030 are identified, but not further investigated.

1.7. Plan of approach

In order to answer the main research question, a multi-criteria decision analysis (MCDA) is executed. Therefore, proper literature and industry research is conducted to find the most promising bio- and hydrogen-based marine fuels in an initial review. From this, seven alternative fuels are selected for further analysis. Alternative marine fuels can be produced via several primary energy sources and conversion technologies. The most suitable production pathways per fuel are identified according to their applicability, matureness, and economic viability for the Port of Amsterdam. The alternative fuels are assessed and compared based on criteria. The assessment criteria are aimed at long-term sustainability by including scalability, technological, economic, environmental, and social-political dimensions. Marine fuel experts defined weight factors per criterium. In addition to the MCDA, a sensitivity analysis is executed to test the robustness of the results.

The results of this research give the maritime and port sector, including Port of Amsterdam, valuable insights, and recommendations into promising biobased and hydrogen-based marine fuels for ship propulsion. Renewable energy producers, companies in the marine fuel supply chain, bunkering companies, shipbuilders, and shipping companies can use the outcomes in their business development strategies. Furthermore, the analytical framework provides a basis that can be used by the Port of Amsterdam to analyse other marine fuels. Moreover, stakeholders, including other ports, governmental organisations, and policymakers, can use the framework according to local inputs and interests. In this way, this study constructively contributes to a long-term sustainable future of the global maritime and port sector.

The study has been structured as follows. In Chapter 2, the methodology behind the multi-criteria analysis is addressed, including the applied data collection methods. Chapter 3 contains the results whereby the initial review, the selection of pathways, the criteria scores, the final performance matrix, and the sensitivity analysis are discussed. Chapter 4 elaborates on the main conclusions which follow directly from the results. The analytical framework and the results are further interpreted and evaluated in Chapter 5. At last, the recommendations for Port of Amsterdam and her stakeholders are given.

2. Methodology

In this chapter, the steps of the analysis and the data collection approaches are described.

Multi-criteria decision analysis is defined as the most appropriate method for this research. This method is widely used to deal with sustainable energy development problems, whereby scenarios with factors that have contradictory effects frequently occur (Siksnelyte et al., 2018). This also is the case for alternative marine fuels, which makes it challenging for decision-makers to assess and compare them directly. The MCDA ranks the alternative marine fuels from most promising to least promising based on quantitative and qualitative data and the preferences and interests of stakeholders.

The analysis contains eight steps. The first two steps are the selection of alternative marine fuels and the selection of corresponding production pathways. The next steps are the selection of stakeholders and criteria, followed by the determination of scores and weight factors. The seventh step is the execution of the model to define the ranking in a performance matrix. The last step contains a sensitivity analysis to check the robustness of the outcomes. A visual overview of the steps is presented in Figure 3.

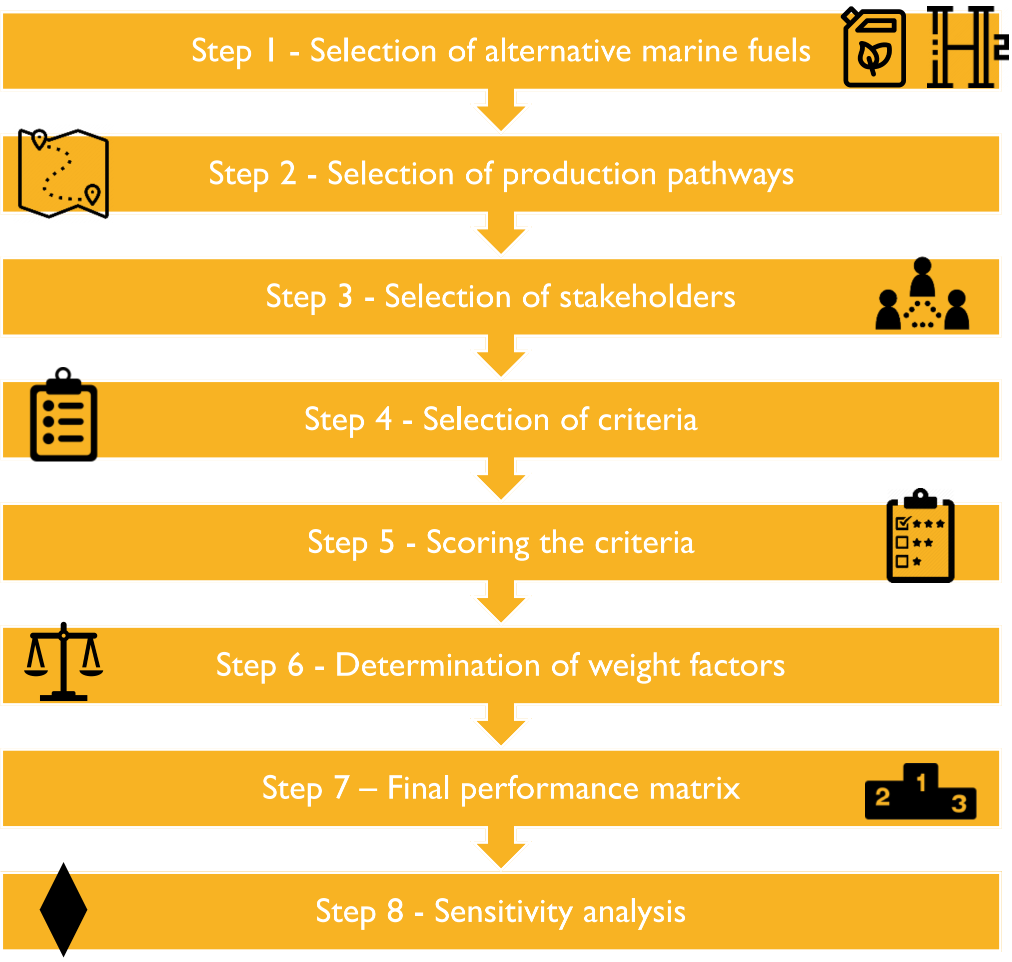

Figure 3: Overview of the analysis steps

2.1. Selection of alternative marine fuels

The first step of this research is an initial review of biobased, and hydrogen-based fuels that could potentially be used as a marine fuel in 2030 and beyond and are in line with the emission targets. These alternative fuels are briefly explained in Appendix I. Seven of the most applicable, mature, and economically viable alternative fuels are selected for this research. The other fuels are not further analysed but might be interesting for the maritime and port sector in the long-term future (2040-2050). The results section contains an overview of the initial review wherein the applicability, maturity and economic viability of the alternative fuels are broadly assessed. Colours are given with green as most preferred until red as least preferred.

Applicability is assessed based on the general opinion of researchers and interviewees about the utilisation of the fuel for propulsion of coastal and inland vessels. Also, the suitability of the fuel supply chain in the Amsterdam port is included. Namely, a fuel is commercially and operationally more interesting if production, storage, and bunkering activities fit in current assets and regulations of the Amsterdam port region. Moreover, this can accelerate the implementation process. Colour definitions are presented in Table 2.

Table 2: Assessment of applicability for initial review

The fuel is very well applicable to ships, and its supply chain fits very well in the Amsterdam port.	(dark green)
The fuel is well applicable to ships, and its supply chain fits well in the Amsterdam port.	(light green)
The fuel is applicable to ships, and its supply chain fits in the Amsterdam port.	(yellow)
The fuel is moderately applicable to ships, and its supply chain fits moderately in the Amsterdam port.	(orange)
The fuel is badly applicable to ships, and its supply chain fits badly in the Amsterdam port.	(red)

Maturity is assessed based on the current Technology Readiness Level (TRL) of the fuel production and propulsion technologies. The TRL scale is developed by NASA and widely used to measure maturity levels of technologies. Higher mature fuels have a higher probability of successfully entering the market (Mai, 2015). Colour definitions are presented in Table 3.

Table 3: Assessment of maturity for initial review

The fuel technologies are proven by successful implementation in the maritime and port sector (TRL 9).	(dark green)
The fuel technologies are starting to be implemented in the maritime and port sector (TRL 8).	(light green)
The fuel technologies are demonstrated by prototypes in the maritime and port sector (TRL 7).	(yellow)
The fuel technologies are partly demonstrated in the maritime and port sector (TRL 6).	(orange)
The fuel technologies are not demonstrated the maritime and port sector (TRL ≤5).	(red)

Economic viability is assessed based on the propulsion system investment cost and fuel prices. Investment cost and fuel prices are broadly estimated based on studies aimed at the West and North European maritime sector. Propulsion system cost and alternative fuel prices cost are compared with fossil LNG since LNG prices are less volatile than oil prices. Furthermore, biobased, and hydrogen-based marine fuels are often considered together with fossil LNG by shipping companies (Innovation manager J. Egbertsen, personal communication, 20-3-2020). Colour definitions are presented in Table 4.

Table 4: Assessment of economic viability for initial review

The alternative fuel price and propulsion system cost are comparable to or lower than fossil LNG.	(dark green)
The alternative fuel price and propulsion system cost are nearly comparable to fossil LNG.	(light green)
The alternative fuel price and propulsion system cost could be comparable to fossil LNG in 2030.	(yellow)
The alternative fuel price and propulsion system cost could be challenging to be comparable in the long term.	(orange)
The alternative fuel price and propulsion system cost are not feasible.	(red)

2.2. Selection of production pathways

The second step is the identification and selection of suitable pathways to produce and process the selected alternative marine fuels. The pathway determines the design of the fuel supply chain and vessel propulsion system. The first stage of the pathway is the primary energy source. This must be a renewable source such as biomass, solar, wind or hydro energy, in order to make sure it is in line with the previously mentioned emission reduction targets. The second stage of the pathway is the energy conversion process to produce the alternative marine fuel. The last stage is the type of propulsion system that is used on the vessel, which could be an internal combustion engine (ICE) or a fuel cell.

Most marine fuels do have several possible production pathways or can be used in both combustion engines and fuel cells. One pathway per fuel is selected for the multi-criteria analysis based on applicability, maturity, and economic viability for the Port of Amsterdam. However, this study does not exclude the other pathways, since market-based processes highly influence the way production pathways develop over time. Different pathways that could have a significant impact on the outcomes of the fuel assessment are discussed in the sensitivity analysis. See Figure 4 for a simple illustration of possible pathways.

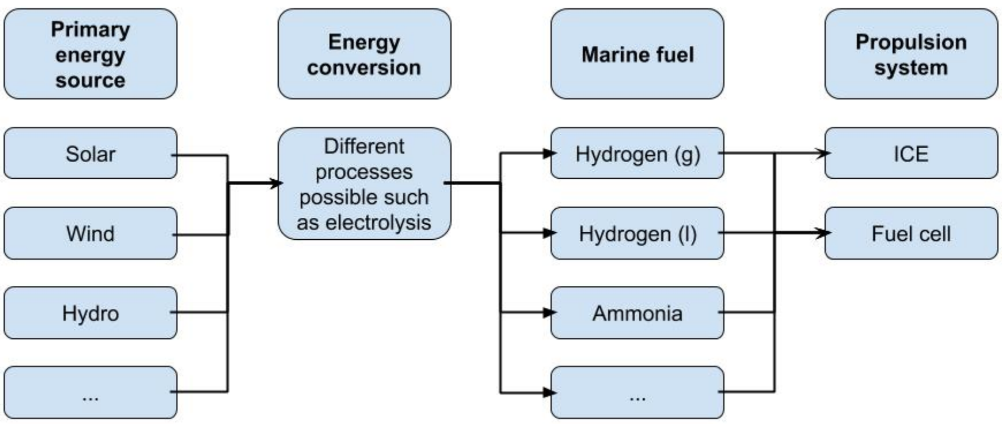

Figure 4: Illustration of possible pathways

2.3. Selection of stakeholders

The third step is the selection of stakeholders. A stakeholder is defined as ‘any group or individual who can affect or is affected by the achievement of the organisation’s objective’ (Mitchell et al., 1997). Relevant stakeholders are identified and organised according to the Triple Helix model. This model describes the main institutions – academia, the private sector and government – that are necessary for industrial development. The Triple Helix aims at a knowledge-based economy wherein a network is created between the institutions to stimulate innovation (Leydesdorff, 2006). A good mixture of stakeholders is required for reliable outcomes of the research that involve the whole maritime sector. Therefore, the institutions of the Triple Helix and interconnecting organisations are included as stakeholders in this study. Research institutes connect academia and the private sector. The port authority (Port of Amsterdam) connects the government and the private sector. The private sector includes fuel supply chain companies, shipbuilders and shipping companies. Suppliers consist of fuel production, storage, and bunker companies. The government consists of local, national, continental, and global levels. The knowledge, interests and judgements of stakeholders are necessary for the criteria selection, criteria assessment, and definition of weight factors for the multi-criteria decision analysis. Figure 5 shows a schematic representation of the Triple Helix model, including relevant maritime stakeholders. Relevant stakeholders were identified during nine internal interviews conducted with employees of Port of Amsterdam. The stakeholders visualised in bold in the figure were interviewed for this research as well. See Section 2.9. for elaboration on the interviews.

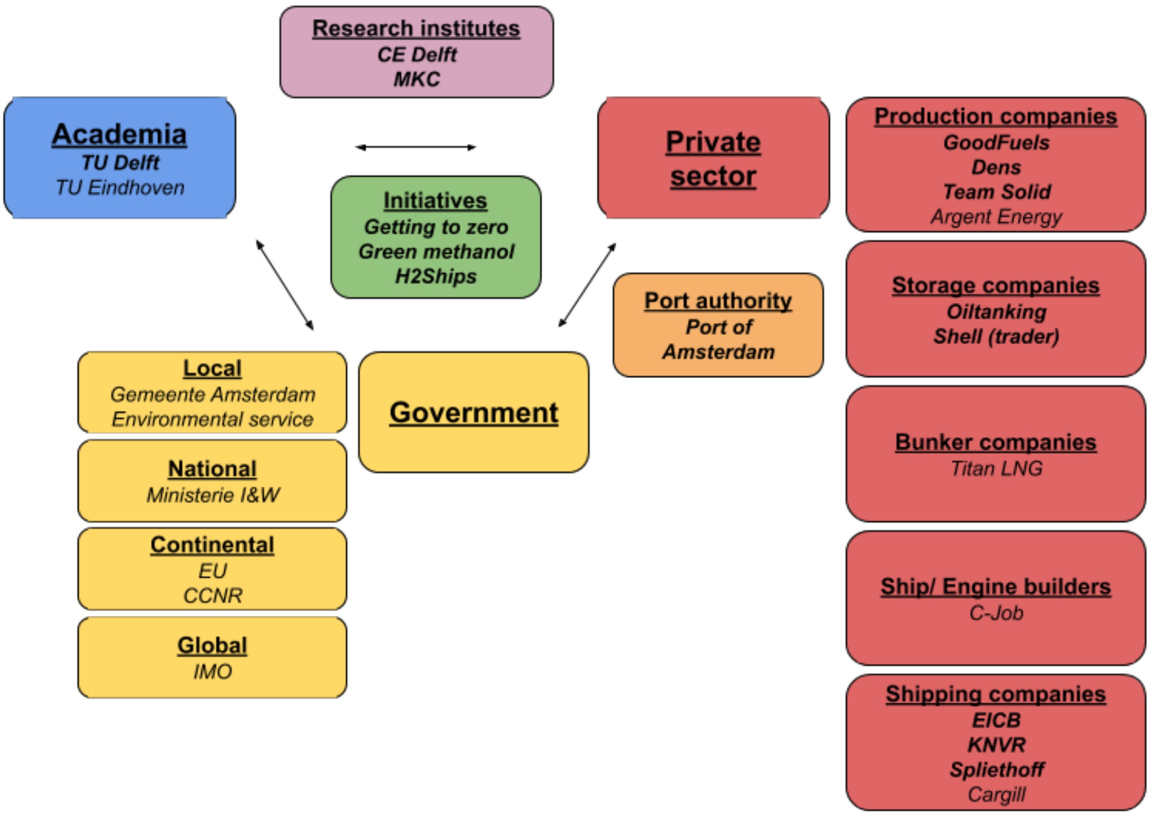

Figure 5: Triple Helix model with relevant maritime stakeholders (bold stakeholders have been interviewed)

The role and relevance of the different stakeholders are defined as:

Academia

- TU Delft: The technical university where research is conducted on sodium borohydride and biobased marine fuels.
- TU Eindhoven: The technical university where DENS and Team Solid are originating.

Research institutes

- CE Delft: Conducts general research on alternative marine fuels.
- Maritiem Kennis Centrum (MKC): Conducts general research on alternative marine fuels.

Government (Local)

- Gemeente Amsterdam: Is the 100% shareholder of Port of Amsterdam which has to approve large investments.
- Environmental service: Grants permits for fuel bunkering activities.

Government (National)

- Ministry of Infrastructure and Water Management (I&W): Supports the emission reduction targets for the maritime sector and includes the Human Environment and Transport Inspectorate.

Government (Continental)

- European Union (EU): Sets European regulations for the maritime and port sector.
- Central Commission for the Navigation of the Rhine (CCNR): Sets regulations for inland vessels and aims at 'ultimately nearly' zero emissions in 2050.

Government (Global)

- International Maritime Organisation (IMO): Sets global (emission) regulations for the maritime and port sector and aims at 50% GHG reduction in 2050.

Port authority

- Port of Amsterdam: Supports the energy transition by facilitating the companies in the Amsterdam port area in a role as a landlord, matchmaker, and co-creator.

Private sector (Production companies)

- GoodFuels: Sells a bio HFO and a bio MGO and researches other biobased marine fuels.
- DENS: Develops formic acid fuel and formic acid fuel cell systems.
- Team Solid: Develops iron powder as a marine fuel.
- Argent Energy: Produces biodiesel and is interested in synthetic fuels. It is a part of the John Swire group, which has a lot of investment power in different sectors.

Private sector (Storage companies)

- Oiltanking: Owns large fuel storage terminals in Amsterdam, including a pipeline to Schiphol. Is interested in bio and synthetic fuels as well.
- Shell: Trades oil and sells different fossil bunker fuels. Is interested in alternative fuels.

Private sector (Bunker companies)

- Titan LNG: Bunkers LNG and researches other alternative marine fuels.

Private sector (Ship/ Engine builders)

- C-Job: Designs ships and propulsion systems and focussed on alternative marine fuels.

Private sector (Shipping companies)

- EICB: Branch organisation for inland shipping.
- KNVR: Branch organisation for sea shipping.
- Spliethoff: Shipping company that aims at dry cargo and located in Amsterdam.
- Cargill: Shipping company that aims at agricultural bulk and located in Amsterdam.

Initiatives

- Getting to zero coalition: Alliance that aims to accelerate the decarbonisation of maritime shipping with supporting the development of zero-emission propulsion systems for ships.

- Green methanol project: Consortium that investigates the feasibility of methanol as a sustainable alternative marine fuel.
- H2Ships: Project that investigates the technical and economic feasibility of hydrogen bunkering and propulsion for shipping.

2.4. Selection of criteria

The next step is the selection of assessment criteria that are used in the analysis. Several conditions apply for the criteria. Firstly, the criteria need to be heterogeneous, which means that they do not depend on each other to prevent double counting. The independency will be checked in the sensitivity analysis (Section 2.8.) Secondly, the criteria need to reflect the performance in meeting the research objective (Dodgson et al., 2009). The objective of this research is to find the commercial and operational most promising alternative marine fuel. Therefore, sustainability is taken into account by including economic, environmental and social criteria, ensuring long-term commercial and operational solution with respect to people, planet and profits (Slaper & Hall, 2011). Further, several MCDA studies focussing on the maritime sector agree on the incorporation of technological and political criteria (Hansson et al., 2019; Ren & Lützen, 2017). Namely, technological performance usually has a significant impact on the economic and environmental performance of marine fuels. In addition, political attitudes can influence the advancement of certain technologies by creating social opinion, setting regulations and other measures.

A list of (sub)-criteria is obtained from literature and a workshop of the Getting to Zero coalition (GtZ, 2020). A stakeholder group discussed evaluation criteria for marine fuels in this workshop. The most relevant criteria for this research are identified according to conducted internal and external interviews. There is explicitly asked for assessment criteria in the interviews. Criteria that were not mentioned in the interviews are assumed to be not relevant enough for the assessment of alternative marine fuels in the Amsterdam port. Comparable criteria are integrated to ensure heterogeneity among criteria. See Appendix II for the list of the selected and unselected criteria. The selected criteria are presented in Table 5.

Table 5: Criteria for multi-criteria decision analysis

Criteria	Sub-criteria
Scalability	Availability of primary inputs
	Added value Amsterdam port
Technological	Maturity
	Energy efficiency
	Energy density
Economic	Infrastructure
	Propulsion system cost
	Marine fuel cost
Environmental	GHG emissions
	Local pollution
	Safety
Social-political	Social acceptability
	Governmental support
	Regulations and classifications

2.5. Scoring the criteria

The alternative marine fuels will be assessed per criterium so that a performance matrix can be created, which gives an overview of the strengths and weaknesses. Initially, the criteria have different scales on which they are assessed. Some criteria are scored on a quantitative numerical scale, and some are scored on a qualitative ordinal basis. The scores will be specific for the port region of Amsterdam if possible.

The scores are standardised for multi-criteria analysis purposes. Standardisation means translating all scores to the same scale. The range of the standardised scale is from 0 until 100, where 0 represents the least preferred performance and 100 the most preferred performance. The chosen method for this research is interval standardisation. The scores are linear interpolations between the least preferred score and the most preferred score per criterium according to this method. Consequently, relative differences in scores become clear. Furthermore, the overall appliance of this conventional standardisation method ensures consistency among criteria (Dodgson et al., 2009).

In this section, the definition, initial measurement scale and standardisation method are discussed per criterium.

2.5.1. Scalability – Availability of primary inputs

This criterium covers the primary inputs that are required for alternative fuel production. It involves the global amount of available sustainable biomass, hydrogen, and CO_2 in 2030. Biomass feedstocks that cause environmentally and socially harmful impact are not included. Harmful conditions could be competition with the food industry and the loss of biodiversity. Moreover, the objective of this study is to find alternative fuels that have a substantial GHG reduction potential which means that the availability of grey hydrogen is excluded in this criterium. The availability of primary inputs may be subject to competition with other industrial or transport sectors. However, it does not fit in the scope of this study to investigate such competition. The criterium is measured in EJ per year.

Standardisation

The scores of this criterium are linearly converted to an interval scale from 0 until 100 according to Equation 1.

$$Standardised\ score = \frac{Score - Lowest\ score}{Highest\ score - Lowest\ score} * 100 \qquad (1)$$

2.5.2. Scalability – Added value Amsterdam port

Port of Amsterdam prefers a fuel supply chain that is located in the Amsterdam port area as this yields practical and economic benefits. Production and storage facilities in the port result in fewer external dependency, avoidance of transportation of the fuel and the generation of additional local revenues. Furthermore, supply chain collaboration increases overall firm performances due to synergies in the use of resources and processes (Cao & Zhang, 2011). Possibilities for a local supply chain depend on the physical area, environmental requirements and safety contours of the fuel production and storage facilities. The integration of a local supply chain comes with added value for the Amsterdam port. The criterium is measured on an ordinal scale which is presented in Table 6.

Table 6: Ordinal scale for assessing the sub-criterium Added value Amsterdam port

Definition	Score
The supply chain of the alternative fuel could lead to no added value for the Amsterdam port	1
The supply chain of the alternative fuel could lead to poor added value for the Amsterdam port	2

The supply chain of the alternative fuel could lead to moderate added value for the Amsterdam port	3
The supply chain of the alternative fuel could lead to fairly high added value for the Amsterdam port	4
The supply chain of the alternative fuel could lead to high added value for the Amsterdam port	5

Standardisation
The scores of this criterium are linearly converted to an interval scale from 0 until 100. See Equation 1.

2.5.3. Technological – Maturity

This criterium assesses the maturity of the production route and the propulsion system related to the alternative fuels. Mature technologies are proven in operational environments and more reliable. The criterium is measured in technological readiness level (TRL). This scale is developed by NASA and is widely used to measure maturity levels of particular technologies. The TRL's of both the production route and the propulsion system are defined. The lowest TRL of the two is the value for the analysis since both the production route and the propulsion system are required to be mature.

Standardisation
The scores of this criterium are linearly converted to an interval scale from 0 until 100. See Equation 1.

2.5.4. Technological – Energy efficiency

The energy efficiency takes the whole supply chain into account. This means energy losses, from renewable electricity or biomass feedstock until marine propulsion power, are included. The lower the losses, the more promising the technology is since less primary energy is required. Transportation and storage losses are assumed to be negligible. See Equation 2 for the calculation of energy efficiency.

$$Energy\ efficiency\ [\%] = \eta_{Production} * \eta_{Propulsion} \tag{2}$$

Standardisation
The scores of this criterium are linearly converted to an interval scale from 0 until 100. See Equation 1.

2.5.5. Technological – Energy density

The energy density of the marine fuel is of high relevance as it determines the size of the storage tanks on board and the required buoyancy of a ship. The criterium is measured as a combination of volumetric [kWh/m^3] and gravimetric [kWh/tonne] contained energy density. The contained density includes the volume and mass of storage tanks since certain types result in significant additional volume or weight. The volumetric density is used as input for the multi-criteria analysis since it affects cargo losses or the bunker frequency. Changes in gravimetric energy density are considered to be less relevant since these can be offset by the ship design (Innovation manager J. Egbertsen, personal communication, 15-5-2020).

Standardisation
The scores of this criterium are linearly converted to an interval scale from 0 until 100. See Equation 1.

2.5.6. Economic – Infrastructure

Marine fuels that use the current infrastructure are beneficial, as this avoids costs of disruption of current infrastructure and large investments for new infrastructure. A fuel infrastructure includes fuel transportation systems, storage tanks, and bunker facilities, both in the port and on board. Marine fuels that have comparable characteristics as HFO and MGO are desired. The criterium is measured on an ordinal scale which is presented in Table 7.

Table 7: Ordinal scale for assessing the sub-criterium Infrastructure

Definition	**Score**
The alternative fuel does not fit in current infrastructure at all	1
The alternative fuel fits poorly in current infrastructure	2
The alternative fuel fits moderately in current infrastructure	3
The alternative fuel fits fairly well in current infrastructure	4
The alternative fuel fits well in current infrastructure	5

Standardisation

The scores of this criterium are linearly converted to an interval scale from 0 until 100. See Equation 1.

2.5.7. Economic – Propulsion system cost

The capital expenditures of the propulsion system on board of a vessel are essential to shipping companies. High capital expenditures are barriers for the adoption of new technologies, even if the pay-back period is relatively short. The propulsion system cost is estimated for inland and coastal shipping in 2030. The criterium is measured in euro per kW.

Standardisation

The scores of this criterium are inversely linearly converted to an interval scale from 0 until 100. See Equation 3.

$$Standardised\ score = \frac{Highest\ score - Score}{Highest\ score - Lowest\ score} * 100 \quad (3)$$

2.5.8. Economic – Marine fuel cost

This criterium involves the marine fuel cost for shipping companies estimated for 2030. Adjustments in other operational costs such as crew salaries, port charges and maintenance cost are considered to be negligible or independent of propulsion type and thus not included in the analytical framework. The criterium is measured in euro per MWh shaft output.

Standardisation

The scores of this criterium are inversely linearly converted to an interval scale from 0 until 100. See Equation 3.

2.5.9. Environmental – GHG emissions

The production and use (well-to-wake) of marine fuels could emit GHG emissions such as carbon dioxide, methane, and nitrous oxide. These emissions cause global warming and must be as low as possible to achieve climate goals that are set by the EU and the IMO. Emissions that occur during transport and storage are excluded as these are assumed to be negligible or independent of the fuel type. In addition, there is not accounted for operational carbon emissions that are offset by carbon uptake during production. The criterium is measured in CO_2 equivalent per kWh of shaft output.

Standardisation
The scores of this criterium are inversely linearly converted to an interval scale from 0 until 100. See Equation 3.

2.5.10. Environmental – Local pollutants

The production and use (well-to-wake) of marine fuels could also emit local pollutants which are sulphur oxides, nitrogen oxides, and particulate matter. These emissions affect the local air quality and must be avoided as much as possible. Emissions that occur during transport and storage are excluded as these are assumed to be negligible or independent of the fuel type. The criterium is measured in grams of emission per kWh of shaft output.

Standardisation
The scores of the local pollutants are inversely linearly converted to an interval scale from 0 until 100. See Equation 2. A combined standardised score for local pollution is obtained by weighting the different local pollutants according to the WHO Guidelines for Air Quality (Gurjar et al., 2008). See Equation 4.

$$Local\ pollutants = \frac{2}{7} * Standardized\ score\ (SO_x) + \frac{1}{7} * Standardized\ score\ (NO_x) + \frac{4}{7} * Standardized\ score\ (PM) \quad (4)$$

2.5.11. Environmental – Safety

Safety is important to prevent hazards to the planet, people, and assets. The main identified hazards for fuels are flammability, toxicity, and environmental impact. These hazards are assessed on their severity and likelihood (Sii et al., 2001). The associated levels of risk define the safety considerations that play a role in the port regarding transportation and bunkering of the marine fuel. Also, they play a role on board of the vessel. The higher the safety risks, the higher the required safety measures. The criterium is measured based on the Globally Harmonized System of Classification and Labelling of Chemicals which is presented in Table 8 (UN, 2019b).

Table 8: Ordinal scale for assessing the sub-criterium Safety

Definition	**Flammability**	**Toxicity**	**Environmental impact**	**Score**
The alternative fuel is	Extremely flammable	Highly acute toxic	Very toxic to aquatic life	Cat. 1 (Severe hazard)
The alternative fuel is	Highly flammable	Moderately acute toxic	Toxic to aquatic life	Cat. 2 (Serious hazard)
The alternative fuel is	Flammable	Low acute toxic	Harmful to aquatic life	Cat. 3 (Moderate hazard)
The alternative fuel is	Combustible	Practically non-toxic	Might be harmful to aquatic life	Cat. 4 (Slight hazard)
The alternative fuel is	Not flammable	Not toxic	Not harmful for aquatic life	No hazard

Standardisation
The score of the most severe hazard of this criterium is linearly converted to an interval scale from 0 until 100. See Equation 1.

2.5.12. Social-political – Social acceptability

Social acceptance is the first social-political criterium and can be defined as the positive or negative public attitude towards technologies. The social acceptability of energy technologies is based on knowledge, perception, and fear (Assefa & Frostell, 2007). This is of high relevance for the Amsterdam port because of its proximity to the city of Amsterdam. The public acceptability could drive or put back the development of alternative fuels and innovative propulsion systems. The criterium is measured on an ordinal scale which is presented in Table 9.

Table 9: Ordinal scale for assessing the sub-criterium Social acceptance

Definition	**Score**
The alternative fuel does come with social aversion	1
The alternative fuel does come with poor social acceptance	2
The alternative fuel does come with moderate social acceptance	3
The alternative fuel does come with fairly high social acceptance	4
The alternative fuel does come with high social acceptance	5

Standardisation

The scores of this criterium are linearly converted to an interval scale from 0 until 100. See Equation 1.

2.5.13. Social-political – Governmental support

Governmental support is important to drive the transition to alternative marine fuels. Namely, conventional marine fuels such as HFO and MGO are very low-cost. Therefore, governmental incentives are required to make alternative fuels competitive. Governmental incentives could be taxes, regulations, and subsidies. Support for certain alternative fuels could be on a global, European, national, and regional level. The criterium is measured on an ordinal scale which is presented in Table 10.

Table 10: Ordinal scale for assessing the sub-criterium Governmental support

Definition	**Score**
The alternative fuel does come with governmental aversion	1
The alternative fuel does come with poor governmental support	2
The alternative fuel does come with moderate governmental support	3
The alternative fuel does come with fairly high governmental support	4
The alternative fuel does come with high governmental support	5

Standardisation

The scores of this criterium are linearly converted to an interval scale from 0 until 100. See Equation 1.

2.5.14. Social-political – Regulations and classifications

International maritime operations have to meet global safety and environmental standards which are set by the IMO. The most common one is the Safety of Life at Sea (SOLAS) code which describes all safety requirements on board. Also, vessels need to be certified by classifications societies such as Bureau Veritas and DNV GL in order to enable insurance of vessels and their cargo (Tveitan, 2017). The non-existence of regulations or classification on alternative fuels can slow down the development process. Namely, it usually takes years to develop regulations frameworks and classification schemes. The criterium is measured on an ordinal scale which is presented in Table 11.

Table 11: Ordinal scale for assessing the sub-criterium Regulations and classifications

Definition	Score
Regulatory frameworks and classifications schemes for the alternative fuel do not exist	1
Regulatory frameworks and classifications schemes for the alternative fuel are under development	2
Regulatory frameworks and classifications schemes for the alternative fuel exist without regulatory gaps	3

Standardisation

The scores of this criterium are linearly converted to an interval scale from 0 until 100. See Equation 1.

2.6. Weight factors

It can be assumed that the selected criteria are not equally important in the decision-making process. Therefore, all criteria are linked to a specific weight factor which is in line with their relative importance. This relative importance is based on the judgements of the decision-maker and stakeholders. However, absolute judgements wherein a criterium has to be reflected on a specific scale is always subjective according to cognitive psychologist Blumenthal (Blumenthal, 1977). Comparative judgements wherein the relation of two criteria relative to each other are measured, is proven to be a more objective manner. This principle is the basis of the analytical hierarchy process (AHP) which is a theory that is widely used for the determination of weight factors for a multi-criteria decision analysis (Saaty, 2008; Siksnelyte et al., 2018). The AHP theory will be used in this research to enhance the reliability and objectivity of the results.

AHP uses a pairwise comparison of the criteria, such as criterium A is *moderately more important* than criterium B. A scale indicates how many more times important or dominant one criterium is in relation to another criterium. The scale starts with 1, *equally important*, and ends with 5, *strongly more important* (see Table 12). Seven marine fuel experts of Port of Amsterdam and stakeholders are approached for their judgements regarding pairwise comparison in the form of a survey. The judgements resulting from the surveys are put into matrices. The geometric mean of each row in the matrix is calculated according to Equation 5. Then, the geometric means are normalised by dividing the mean per criteria by the total sum of means to derive the weight factor per criteria. The weight factors of the experts are averaged and included in the multi-criteria analysis (Dodgson et al., 2009; Saaty, 2008).

$$Geometric\ mean = (Score_1 * Score_2 * \ldots * Score_n)^{1/n} \tag{5}$$

Table 12: Scale of the intensity of importance for pairwise comparison (Saaty, 2008)

Intensity of importance	Definition	Explanation
1	Equal importance	Two criteria contribute equally to the objective
2	Slight “	Judgements slightly favour one criterium over another
3	Moderate ‘’	Judgements moderately favour one criterium over another
4	Moderate plus ‘’	Judgements moderately plus favour one criterium over another
5	Strong ‘’	Judgements strongly favour one criterium over another

At last, the AHP method judgements are checked on consistency. For example, if Criteria A is two times as important as Criteria B and Criteria B is two times as important as Criteria C, then Criteria A has to be four times as important as Criteria C in a perfect rational judgement. The consistency ratio is calculated according to Equation 6. This consistency ratio has to be no more than 0.1 to approve judgements for this research. A consistency ratio of 0.1 means that 10% of the judgements are inconsistent or could have been given randomly (Brunelli, 2015).

$$Consistency\ ratio\ (CR) = \frac{(\lambda_{max} - n) * RI_n}{n-1} \tag{6}$$

Whereby,

λ_{max} = Maximum eigenvalue

n = Order of matrix

RI = Random Index

2.7. Final performance matrix

The final step of the multi-criteria decision analysis is calculating the final scores per alternative fuel. This is done by multiplying the scores per criterium with their corresponding weight factor. See Table 13 for the form of the final performance matrix. Summing all the weighted criteria scores per alternative fuel give the final score (Dodgson et al., 2009). These final scores rank the alternative marine fuels on overall performance. The top-ranked fuel is defined as the commercially and operational most promising marine fuel for decarbonisation of the Port of Amsterdam in 2030. In this way, the objective of this research is met. Moreover, the strengths and weaknesses of the alternative fuels are clear, which could help the Port of Amsterdam and other stakeholders in the development process of the supply chain and vessel propulsion systems.

Table 13: Form final performance matrix

	Alternative 1	Alternative 2	…	Alternative i	**Weights**
Criteria 1 (C_1)	Score (S_{11})	Score (S_{21})	…		**… % (W_1)**
Criteria 2 (C_2)	Score (S_{12})	…			**… % (W_2)**
…	…				**…**
Criteria n (C_n)				Score (S_{in})	**…% (W_n)**
Final scores	$\sum_{j=1}^{n} W_j S_{ij}$	**…**	**…**	**…**	

2.8. Sensitivity analysis

A sensitivity analysis is conducted to give extra insights and to test the robustness of the outcomes of the MCDA. First, three scenarios, other than the base case, are tested to provide additional insights. The scenarios are defined according to literature and in cooperation with Port of Amsterdam. Then the robustness of the MCDA outcomes is checked by incorporating uncertainties in criteria scores and weight factors. The next robustness check consists of testing different applicable standardisation methods. The final check consists of examining the independency among the criteria. Hereby, it is assumed: the lower the correlation, the higher the independence. The DEFINITE Bosda 3.1 software is used to incorporate uncertainties factors, to test different standardisation methods and to define the correlation coefficients between different criteria. The independence check is not part of recent MCDA studies (Ren & Lützen, 2017). Successful incorporation of this check on independency justifies the selected criteria. This improves the AHP method that can be used for future work.

2.9. Data collection overview

The data collection for this research is a mix of qualitative and quantitative data because the analytical framework consists of tangible and intangible aspects. Different primary and secondary data sources are combined to increase the level of research validity and reliability. Academic and industrial literature are the main sources of information because previous studies about alternative marine fuels contain a lot of useful information. However, location-specific information for Amsterdam is required to meet the objective of this research. Therefore, nine semi-structured interviews are conducted in various departments (strategy, commerce, and operations) of the Port of Amsterdam. Also, eleven interviews have been conducted among stakeholders to gather data that is not publicly available. The internal and external interview templates are in Appendix III. Quantitative criteria scores are averaged over several academic and industrial values that are considered to be reliable and applicable for the scope of this research. At last, surveys are executed among seven marine fuel experts to define the weight factors via pairwise comparison. The data of step 2, 5 and 6 is used for the final performance matrix and sensitivity analysis. The data collection method per step of the methodology is presented in Table 14.

Table 14: Data collection methods and sources

Step	**Collection method**	**Source**
Step 1: Selection of alternative marine fuels	- Literature research - Semi-structured interviews	Literature Port of Amsterdam Fuel production companies
Step 2: Selection of pathways	- Literature research - Semi-structured interviews	Literature Port of Amsterdam Stakeholders
Step 3: Selection of stakeholders	- Semi-structured interviews	Port of Amsterdam
Step 4: Selection of criteria	- Literature research - Semi-structured interviews	Literature Port of Amsterdam
Step 5: Criteria scores	- Literature research - Semi-structured interviews	Literature Port of Amsterdam Stakeholders
Step 6: Weight factors	- Surveys	Port of Amsterdam Stakeholders
Step 7: Final performance matrix	N.A.	N.A.
Step 8: Sensitivity analysis	N.A.	N.A.

3. Results

This chapter contains the results of the initial review, the selection of pathways, the criteria scores, the final performance matrix, and the sensitivity analysis.

3.1. Selection of alternative marine fuels

An overview of the alternative fuels of the initial review is presented in Table 15. Further descriptions of the fuels are in Appendix I. Biobased fuels, selected for further analysis, are biodiesel, bio LNG and bio methanol. These are most applicable, mature, and economic viable of all alternative fuels. Bioethanol has a lack of interest in the maritime sector due to its heavy competition with road transport and is not selected.

Hydrogen is the building block of the other alternative fuels. Hydrogen could also purely be used as a marine fuel in a compressed or liquefied form. These pure forms are both further analysed since these are scoring relatively well in the initial review, and there is much attention for hydrogen by governmental institutes. The trade-off for hydrogen is whether the energy losses and extra cost of liquefying are worth the increased volumetric energy density.

The hydrogen-based alternative fuels are categorised according to the presence of carbon. Formic acid, one of the carbon-containing fuels, is not mature enough to play a role in the maritime sector in 2030. At the moment, e-diesel and e-LNG are considered too costly for 2030, but they have long-term potential. E-methanol is already commercially produced for and is well applicable to the maritime sector. Therefore, e-methanol is further analysed in this study. The toxicity hazards of zero-carbon fuel ammonia are excessive, which is a barrier for its development in the Amsterdam port. Therefore, ammonia is not selected for further research. Liquid organic hydrogen carriers and iron powder are too immature for further analysis but could play a role in the long-term. Sodium borohydride is included in further analysis since it has a particular interest by Port of Amsterdam. Their new port authority vessel will be powered by sodium borohydride.

Table 15: Overview of the alternative fuels in the initial review

Fuel	Applicability	Matureness	Economic viability	Critical notes	Action
Biobased:					
Biodiesel					Further analysis
Bioethanol				Heavy competition with road transport	-
Bio LNG				Issues around methane slip	Further analysis
Bio methanol					Further analysis
Hydrogen:					
Compressed hydrogen				Highly explosive	Further analysis
Liquid hydrogen				Use of cryogenic tanks	Further analysis
Carbon hydrogen-based:					
Formic acid					Long-term potential
E-diesel					Long-term potential
E-LNG				Issues around methane slip	Long-term potential
E-methanol					Further analysis
Zero-carbon hydrogen-based:					
Ammonia				Highly toxic	-
Liquid organic hydrogen carriers					Long-term potential
Iron powder				Low gravimetric energy density	Long-term potential
Sodium borohydride				Particular interest by Port of Amsterdam	Further analysis

3.2. Selection of pathways

The production pathways are discussed per alternative fuel. First, the primary energy source and other primary inputs are elaborated. Then, the energy conversion routes and propulsion systems on board are explained per fuel.

3.2.1. Biodiesel

Primary energy source

Biodiesel can be produced from different types of biomass feedstocks. Selection of feedstock has significant consequences since it is responsible for 75% of the total cost of biodiesel. First-generation edible oils such as soybean, rapeseed, and palm oil could be the primary energy source for biodiesel but are non-desirable due to their competition with the food industry. Therefore, second-generation non-edible vegetable oils, waste oil and animal fats are more suitable as the primary energy source to produce biodiesel. Furthermore, second-generation feedstocks mitigate land-use change issues and offer lower lifecycle GHG emissions than first-generation feedstocks (IEA, 2019c; Mohd Noor et al., 2018). Lignocelluloses is also a possible feedstock for biodiesel with potential on the long-term since it is widely available. However, lignocelluloses feedstock is not expected to have a significant market share for transportation fuels in 2030 due to the immatureness of conversion routes (Yousuf, 2012).

Energy conversion

Currently, hydrotreated vegetable oil (HVO) and fatty acid methyl ester (FAME) are the most promising biodiesels for the marine sector. Both are produced in a transesterification process, wherein oils react with alcohol to form biodiesel and glycerol. The process does not require high pressures or temperatures, which results in high conversion efficiency and low processing costs. The difference is that HVO is catalysed by hydrogen and FAME by methanol (Mohd Noor et al., 2018). HVO is beneficial in terms of NO_x emissions, stability, and heating value since it does not contain oxygen. Moreover, HVO contains fewer impurities than FAME which makes it better compatible with marine diesel engines (Ryste, 2019). Therefore, the properties of HVO are used in the multi-criteria analysis.

Propulsion system

The HVO type biodiesel can be blended with heavy fuel oil and marine gas oil or purely be used in conventional marine diesel engines. Blending could be done in any desired ratio. Lower quality biodiesels often have limited blending ratios and are thus not suitable in achieving GHG reduction targets. This research assumes the use of pure biodiesel in marine diesel engines for a fair comparison with other alternative fuels and a maximum GHG emission reduction. The pathways are visualised in Figure 6.

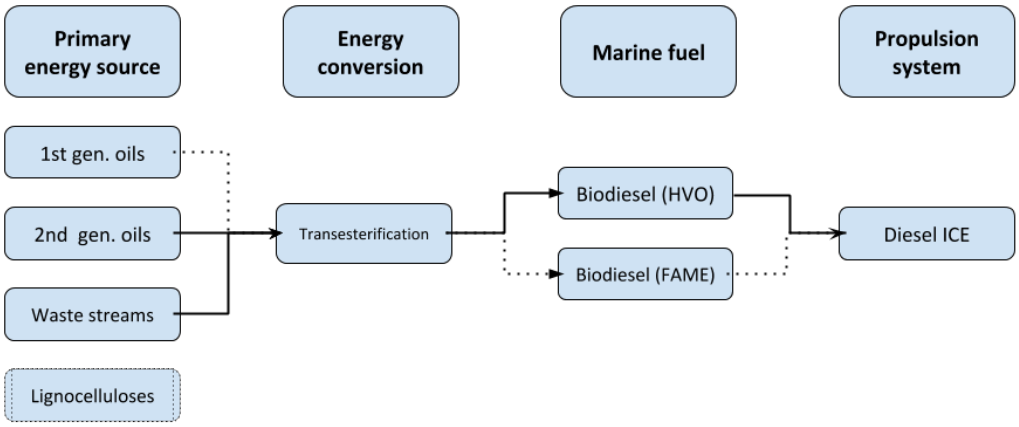

Figure 6: Production pathways biodiesel (dotted pathways are not preferred)

3.2.2. Bio LNG

Primary energy source

Primary energy sources for bio LNG could be agricultural and municipal waste streams and second-generation lignocelluloses biomass. Agricultural waste streams consist of crop residues from the harvest of, for example, maize and sugar beet. It could also be harvested crops that are grown for purposes like avoidance of erosion or preservation of fertility of the soil. These waste streams do not affect the food supply. Manure from livestock is another agricultural waste stream to produce bio LNG. Organic fractions of municipal waste or wastewater sludge could also be used. Lignocelluloses or woody biomass another feedstock option for bio LNG but requires a different conversion route (IEA, 2020).

Energy conversion

The conversion from the primary energy source to bio LNG involves anaerobic digestion or gasification. The agricultural and municipal waste streams are put into anaerobic digesters. Herein, microorganisms break down the organic matter in the absence of oxygen. A mixture is formed that consist of roughly

50-70% methane, 30-50% CO_2 and other gasses. The methane is separated from this mixture by water scrubbing and membrane separation. The last step involves liquefaction of the methane, so bio LNG is obtained.

Gasification of lignocelluloses is a second option to produce bio LNG. Woody biomass is broken down in a high-temperature reactor (>700°C) under high pressure and a limited amount of oxygen. Syngas if formed that mainly consists of hydrogen and carbon monoxide. This gas is cleaned from contaminations and undergoes a methanation process to form methane. The resulting methane is also liquefied to obtain bio LNG.

The properties of the gasification conversion route are chosen as input for the multi-criteria analysis since it is assumed as more cost-effective on the long-term and does not rely on decentral livestock farming (IEA, 2020; Nelissen et al., 2020).

Propulsion system
Bio LNG has the same properties as fossil LNG and can thus directly be used in marine LNG engines. The pathways are visualised in Figure 7.

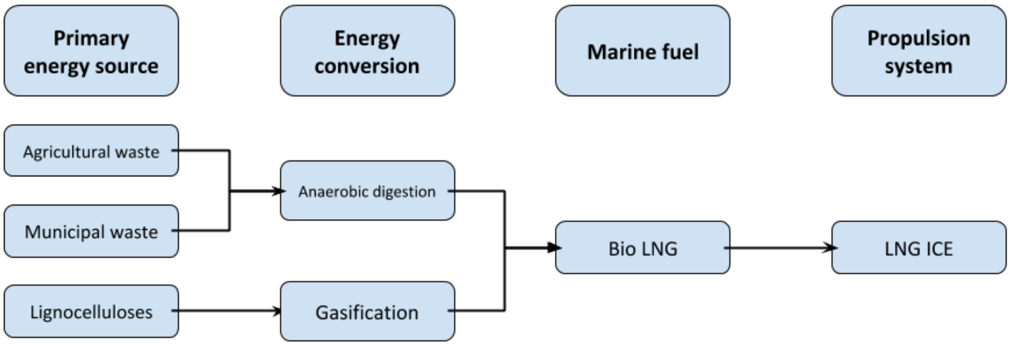

Figure 7: Production pathways bio LNG (dotted pathways are not preferred)

3.2.3. Bio methanol

Primary energy source
Sustainable biomass feedstocks to produce bio methanol are lignocellulosic biomass and glycerol. The lignocellulosic biomass consists of wood, willow or forest residues which are second-generation feedstocks. These raw materials are also used to produce bio LNG via gasification (Brynolf et al., 2014). Glycerol is a by-product from biodiesel production and could also be used to form bio methanol. Glycerol is produced in the transesterification process at about one-tenth of the mass biodiesel. The utilisation of the crude glycerol improves the overall economics of biodiesel production (Haider et al., 2015).

Energy conversion
The first conversion pathway to bio methanol is based on syngas which is formed in a gasification process from lignocellulosic biomass. This syngas production process is also used in the formation of bio LNG and is explained in Section 3.2.2. The syngas must be put into a reactor to be pressurised and catalysed to form methanol (Hobson & Márquez, 2018). The second conversion pathway with glycerol as a primary energy source is a simple low-pressure process. Glycerol is reacted with water in the presence of basic or redox oxide catalysts in order to produce methanol. Also, some other useful chemicals are produced (Haider et al., 2015). A third option to produce bio methanol is via biomethane through steam reforming and partial oxidation.

The second and third pathways have considerable drawbacks. The glycerol availability is dependent on biodiesel production, which makes the supply uncertain. Further, the direct use of biomethane is more effective than converting it into bio methanol. Therefore, the gasification pathway is used in further analysis.

Propulsion system
Bio methanol can either be used in a combustion engine as in a fuel cell. A regular marine diesel engine requires some adjustments to be compatible with methanol. This 'methanol' engine is currently commercially available and, therefore, chosen as input for further analysis. The use of methanol fuel cell systems in vessels is too immature to play a significant role in 2030 but offers opportunities for the long-term (Ryste, 2019). The pathways are visualised in Figure 8.

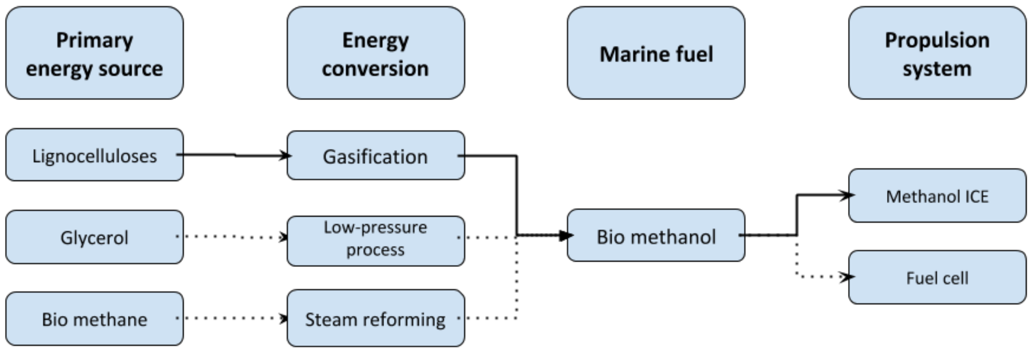

Figure 8: Production pathways bio methanol (dotted pathways are not preferred)

3.2.4. Compressed hydrogen

Primary energy source
Hydrogen can be produced from different primary energy sources. Clean sources are renewable electricity or natural gas with carbon capture and storage (CCS). Renewable electricity can be obtained from wind turbines and solar panels. Surplus electricity that cannot directly be used on the grid would be most suitable to produce hydrogen. Today, hydrogen is mostly produced from natural gas. The installation of CCS technology could reduce GHG emissions from natural gas up to 90%. Freshwater supply is required for conversion processes as well. Seawater could be used in coastal areas if desalinated. This desalination process has only a little impact on the total cost of hydrogen (USD 0.01–0.02/kgH_2) (IEA, 2019b).

Energy conversion
The first conversion pathway involves an electrolysis process where water molecules are split into hydrogen and oxygen through renewable electricity. See Equation 7. There are different technologies available for this process: alkaline electrolysers, proton exchange membrane (PEM) electrolysers and solid oxide electrolysis fuel cells (SOECs). Alkaline electrolysers are globally most widely used and, nowadays, the most cost-effective technology. PEM electrolysers are developed in the 1960s to overcome operational shortcomings of the alkaline technology. PEM systems have a simpler design but are generally more expensive due to the required precious materials. SOECs are not yet available on the commercial market, and its CAPEX is estimated to be higher than the other technologies for 2030 (IEA, 2019b). Hydrogen formed via renewable electricity is known as 'green' hydrogen.

$$2H_2O \rightarrow 2H_2 + O_2 \tag{7}$$

Steam methane reforming is the most widely deployed process for hydrogen production via natural gas. High-temperature steam (700-1000°C) reacts with natural gas to form carbon mono oxide and hydrogen in this process. After that, the carbon mono oxide reacts with steam to form more hydrogen in a so-called ‘water-gas shift reaction’. Simultaneously, there is CO_2 produced that needs to be captured to achieve nearly zero-emission hydrogen (IEA, 2019b). Hydrogen produced via natural gas and CCS is known as ‘blue’ hydrogen.

The hydrogen production pathway based on the alkaline electrolysis process is used for this study since it is completely CO_2 neutral and relatively cost-effective. After the formation, hydrogen is compressed and put into storage tanks under 700 bar.

Propulsion system

There are two hydrogen propulsion systems possible on board of a vessel. Hydrogen can be burned in an internal combustion engine or used in a fuel cell. A fuel cell eliminates operational emissions. Different fuel cell technologies are available, but the Proton Exchange Membrane Fuel Cell (PEMFC) is most promising for maritime applications (Tronstad et al., 2017). This fuel cell has a higher energy efficiency (50-60%) than ICE (40-50%). Fuel cell properties are, therefore, used in further analysis (Ryste, 2019). The pathways are visualised in Figure 9.

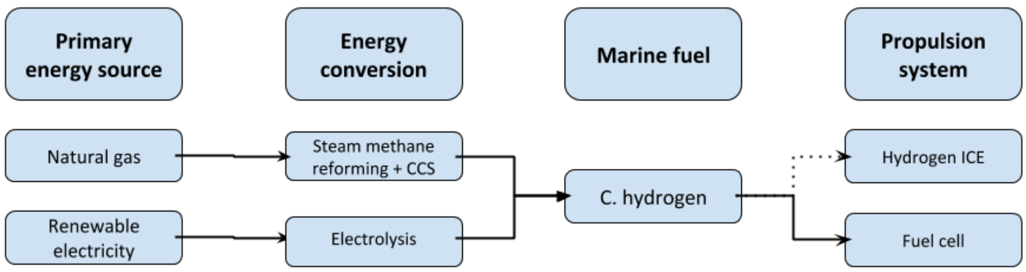

Figure 9: Production pathways compressed hydrogen (dotted pathways are not preferred)

3.2.5. Liquefied hydrogen

Primary energy source

The primary energy sources for liquid hydrogen are the same as for compressed hydrogen. These are renewable electricity and natural gas with CCS. See Section 3.2.4. for a further explanation.

Energy conversion

The pathways to obtain hydrogen from primary energy sources are similar to compressed hydrogen. See Section 3.2.4. for further explanation on alkaline electrolysis and other conversion technologies.

The liquefaction process of hydrogen increases the volumetric energy density. Hydrogen has a condensation point of minus 253 degrees Celsius. Cooling down the hydrogen requires substantial amounts of energy and is done with refrigerants such as liquid nitrogen or helium. After cooling down, the liquid hydrogen is stored in cryogenic tanks to maintain its phase. Cryogenic tanks are well insulated and must prevent hydrogen molecules from diffusing. Today’s liquefaction process is not very energy efficient. The expectation is that the efficiency will rise in the next decades due to technological improvements (IEA, 2019b; Krasae-In et al., 2010).

Propulsion system

Liquid hydrogen needs to be evaporated onboard so that it can be used in internal combustion engines or fuel cells. See Section 3.2.4. for further explanation on these propulsion systems. The evaporation process involves a heat exchanger that recovers gaseous hydrogen with high energy efficiency. The pathways are visualised in Figure 10.

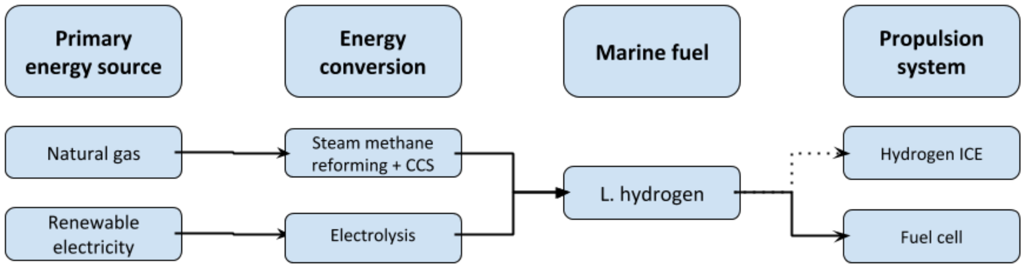

Figure 10: Production pathways liquid hydrogen (dotted pathways are not preferred)

3.2.6. E-methanol

Primary energy source

The primary energy source for renewable methanol is electricity originating from renewable sources such as solar, wind or tidal energy. Another possible energy source is natural gas with CCS. The resulting green or blue hydrogen together with CO_2 are the building blocks for methanol. Additional information about obtaining hydrogen is in Section 3.2.4.

Carbon dioxide can be obtained from different sources. It can be captured from fossil energy and industrial sources, such as coal-fired power plants or steel manufacturers. This carbon capture and utilisation (CCU) system offers lots of opportunities on the short term but is not sustainable on the long-term as it still emits CO_2 from fossil fuels. Another option would be CO_2 capture from biomass combustion or processing, which is sustainable on the long-term. A third option is capturing the carbon dioxide directly from the air (IEA, 2019a).

Energy conversion

Renewable methanol can directly be formed out of CO_2 and hydrogen in a hydrogenation reaction which is mostly catalysed by copper- or lead-based compounds. See Equation 8. This is a mature conversion pathway. Another possible mature conversion pathway is the indirect conversion of methanol. In this process, carbon dioxide is transformed into carbon monoxide and mixed with hydrogen to form syngas. Methanol is synthesised in a reactor where the syngas is pressurised and catalysed (IEA, 2019a; Jadhav et al., 2014).

$$CO_2 + 3H_2 \rightarrow CH_3OH + H_2O \tag{8}$$

Propulsion system

Methanol could be combusted in conventional marine engines with a few adjustments. These engines fuelled with methanol are commercially available. It is also technically feasible to use methanol in fuel cells to produce electricity for vessel propulsion. However, these fuel cell systems are not considered viable on the short and long term and thus excluded from the rest of this research (Ryste, 2019). The pathways are visualised in Figure 11.

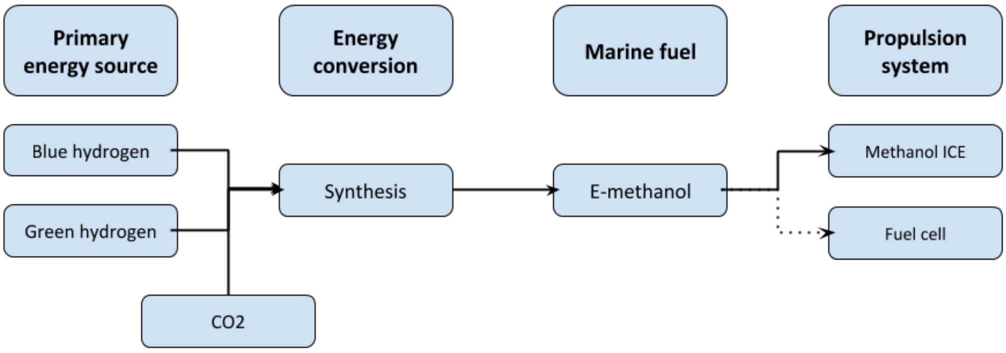

Figure 11: Production pathways e-methanol (dotted pathways are not preferred)

3.2.7. Sodium borohydride

Primary energy source

Associate Professor Marine Engineering K. Visser (Personal communication, 1-7-2020) describes the primary energy source for the formation of sodium borohydride as renewable electricity, water, and magnesium. Further, an initial amount of sodium metaborate compounds are required for the process. These compounds are circularly used after a one-time extraction. Sodium metaborate is a white coloured mineral.

Energy conversion

The sodium metaborate compounds and water are put together in a high-temperature reactor to regenerate sodium borohydride without the use of electrolysers. The oxygen molecules are replaced by hydrogen molecules in this reaction and are released to the air. See Equation 9. The sodium metaborate is obtained from residual flows of ships. This means infrastructure needs to be in place to bunker ships with the sodium borohydride fuel and to return sodium metaborate residues from ships (H2Fuel-Systems, 2020).

$$NaBO_2 + 4H_2 \rightarrow NaBH_4 + 2H_2O \quad (9)$$

Propulsion system

First, the hydrogen in sodium borohydride needs to be released on board of a ship. Ultra-pure water is added to solve the sodium borohydride, and the solution is put in a reactor. Also, an acid or catalyst is added to accelerate the hydrolysis process wherein hydrogen is released from the sodium borohydride. See Equation 10. This process is easy to control (H2Fuel-Systems, 2020; Muir & Yao, 2011). The produced hydrogen can either be used in a fuel cell or an internal combustion engine. See Section 3.2.4. for further explanation on these propulsion systems. The residual sodium metaborate needs to be stored onboard. The pathways are visualised in Figure 12.

$$NaBH_4 + 2H_2O \rightarrow NaBO_2 + 4H_2 \quad (10)$$

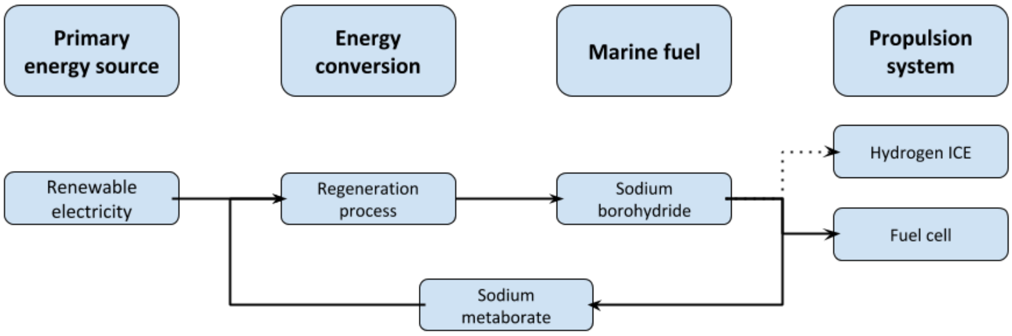

Figure 12: Production pathways sodium borohydride (dotted pathways are not preferred)

3.3. Criteria scores

The alternative fuels are scored per sub-criteria. Each section concludes with the performance matrix that contains the scores in their initial measurement scales.

3.3.1. Scalability – Availability of primary inputs

The energy consumption of the global maritime sector has been estimated to be between 12.1 and 14.2 EJ in 2030 (EEA, 2019). The required primary energy is three or four times as high due to energy losses during production and propulsion (See Section 3.3.4.). The global sustainable potential of 2nd generation energy crops is estimated as 25-40 EJ per year in 2030, which is most suitable for biodiesel production. Global agricultural residues that could be used for the production of bio LNG are estimated to have a sustainable potential of 10-65 EJ in 2030. The potential of forestry products and residues is expected to be between 25 and 60 EJ per year in 2030 and could be used for the production of all biofuels. Beneficial for Amsterdam is that Europe is an interesting supply region for biofuels with a global share of biomass production between 19 until 25 per cent. Aquatic biomass grown in seas and oceans could increase the total potential substantially. The biomass competition with other sectors is not taken into account (Bengtsson et al., 2012; Hansson et al., 2019; Hobson & Márquez, 2018; Nelissen et al., 2020).

The estimated electrolysis capacity is between 7 and 40 GW in Europe and 700 GW worldwide for 2030 (Gielen et al., 2019; Hydrogen Europe, 2018; ICIS, 2020). This capacity results in 11 EJ of annual green hydrogen supply based on a load factor of 48%. Only a small share of the hydrogen supply is expected to be generated in Europe, which could be compensated by hydrogen import from other continents. The production of e-methanol also requires carbon dioxide. The IEA estimates a CCU capacity of 750 Mt CO_2 per year from power and industry facilities in her sustainable development scenario for 2030 (IEA, 2019a). This is abundant to convert 11 EJ of hydrogen into e-methanol. Competition for hydrogen demand of other sectors is not taken into account. See Table 16 for the performance matrix of the sub-criterium Availability of primary inputs.

Table 16: Performance matrix Availability of primary inputs

Sub-criteria	Unit	Biodiesel	Bio LNG	Bio methanol	C. Hydrogen (700 bar)	L. Hydrogen	E-methanol	$NaBH_4$
Availability of primary inputs	EJ/year	50-100	35-125	25-60	11	11	11	11

(Bengtsson et al., 2012; Gielen et al., 2019; Hansson et al., 2019; Hobson & Márquez, 2018; Hydrogen Europe, 2018; ICIS, 2020; Nelissen et al., 2020)

3.3.2. Scalability – Added value Amsterdam port

Biodiesel is already produced and stored in the Amsterdam port. Also, blending facilities and waste collectors are available, which could be beneficial for the development of biodiesels and could lead to high local added value. Biogas production via anaerobic digestion is done locally at farms and via gasification could be done in the Amsterdam port. Large scale LNG storage does currently not exist in the Amsterdam port but could be an opportunity for the future according to a storage company. There are decent production and storage opportunities for bio methanol since safety, and environmental requirements are manageable. Hydrogen production and storage require large safety zones which could affect large-scale production and storage facilities. Port of Amsterdam is planning a hydrogen infrastructure with connections to the Groningen Seaports and Port of Rotterdam. Thereby, hydrogen import could be necessary to meet future demand. The limited local production in Amsterdam leads to moderate added value. Further, there is a project under development for CO_2 infrastructure, including CCU systems in the Amsterdam port. These planned facilities offer opportunities for the production of e-methanol and sodium borohydride which comes with high added value for the Amsterdam port. See Table 17 for the performance matrix of the sub-criterium Added value Amsterdam port.

Table 17: Performance matrix Added value Amsterdam port

Sub-criteria	Unit	Biodiesel	Bio LNG	Bio methanol	C. Hydrogen (700 bar)	L. Hydrogen	E-methanol	$NaBH_4$
Added value Amsterdam port	Ordinal	5	4	5	3	3	5	5

(Internal and external interviews, 2020)

3.3.3. Technological – Maturity

Nowadays, biodiesel is already produced and used in conventional diesel engines, so the highest TRL is achieved. The production process of bio LNG and bio methanol; gasification, is at an early commercial stage at the moment and is expected to be almost fully mature in 2030. E-methanol produced via renewable electricity is less developed. CRI in Iceland is a frontrunner with the only known commercial production facility of renewable methanol. Further, demonstration projects are establishing (Bergsma et al., 2020; Platform Duurzame Biobrandstoffen, 2018). Bio LNG can be combusted in regular marine LNG engines which are already fully mature. Methanol marine engines are positively tested in several research projects (Andersson & Salazar, 2015). Moreover, first commercial use is occurring at the moment with engines developed by MAN and Wärtsilä (SWZ Maritime, 2020). Hydrogen electrolysis volumes are expected to grow significantly in the next decade, as well as the use of fuel cell propulsion systems, which make their 2030 prospect fully mature. At last, the development of a first pilot vessel with a sodium borohydride propulsion system is currently in progress. A proof of concept is currently executed regarding the regeneration process of this fuel. The $NaBH_4$ technologies are expected to be implemented in a commercial environment in Amsterdam in 2030 if current pilots are going well. See Table 18 for the performance matrix of the sub-criterium Maturity.

Table 18: Performance matrix Maturity

Sub-criteria	Indicator	Biodiesel	Bio LNG	Bio methanol	C. Hydrogen (700 bar)	L. Hydrogen	E-methanol	$NaBH_4$
Maturity	$TRL_{Production}$	9	8.5	8.5	9	9	7	8
	$TRL_{Propulsion}$	9	9	8	9	9	8	8

(Bergsma et al., 2020; Marin, 2020a; Nelissen et al., 2020; Platform Duurzame Biobrandstoffen, 2018; SWZ Maritime, 2020; Tronstad et al., 2017)

3.3.4. Technological – Energy efficiency

The energetic efficiency of the production of biodiesel and bio methanol from raw biomass is around 50%. The efficiency of the production of bio LNG is higher (64%) but is offset due to the energy losses of the liquefaction process. The hydrogen electrolysis efficiency is assumed to be 70% in 2030, which is the first step for the production of the hydrogen-related alternative fuels. Subsequent compression of hydrogen up to 700 bar comes with extra small energy losses and liquefaction with more substantial losses. Also, the carbon capture and synthesis processes for the production of methanol do consume significant amounts of energy. The regeneration process of sodium borohydride off board has a maximum energy efficiency of 69%, according to Eom et al. (2013).

State of the art marine diesel and gas engines today have an efficiency of 49-50% which is assumed to be the fleet average in 2030. The efficiency of methanol engines is comparable according to several research projects and pilots. The expected efficiencies of fuel cells and electric propulsion systems are 57% and 91%. An electric engine is more efficient than combustion engines due to fewer heat losses. Energy losses of the expansion and evaporation of hydrogen are negligible. The hydrogen extraction out of sodium borohydride does result in energy losses. See Table 19 for the performance matrix of the sub-criterium Energy efficiency.

Table 19: Performance matrix Energy efficiency

Sub-criteria	Indicator	Biodiesel	Bio LNG	Bio methanol	C. Hydrogen (700 bar)	L. Hydrogen	E-methanol	$NaBH_4$
Energy efficiency	η_{Total}	24%	22%	24%	34%	28%	25%	20%
	$\eta_{Production}$	49%	45%	51%	66%	54%	53%	48%
	$\eta_{Propulsion}$	49%	50%	48%	52%	52%	48%	41%

(Bengtsson et al., 2012; Dupczak et al., 2012; Eom et al., 2013; Galindo Cifre & Badr, 2007; Götz et al., 2016; Horvath et al., 2018; IMO, 2016; Lloyd's Register & UMAS, 2019; Nelissen et al., 2020; Ryste, 2019; Tronstad et al., 2017; van Nievelt, 2019; Wärtsilä, 2020)

3.3.5. Technological – Energy density

Biodiesel (HVO) is the only alternative fuel that has comparable energy densities with marine gas oil (MGO). Bio LNG and liquid hydrogen have to be stored in cryogenic tanks to maintain their low temperatures, respectively minus 163 and minus 253 degrees Celsius. These cryogenic storage tanks result in significant lower contained energy densities. Bio methanol and e-methanol have about half the volumetric energy density of MGO. However, there are possibilities to store methanol on board in ballast tanks, whereby additional storage tank volumes can be limited (Platform Duurzame Biobrandstoffen, 2018). Compressed hydrogen has the lowest energy densities. The uncontained volumetric energy density of sodium borohydride is relatively good in comparison with the other alternative fuels. However, sodium borohydride requires a reactor to extract hydrogen out of the white powder, water supply and a tank for the residues onboard. A compact configuration will probably lead to a volumetric energy density that is just over methanol. See Table 20 for the performance matrix of the sub-criterium Energy density.

Table 20: Performance matric Energy density

Sub-criteria	Indicator	Unit	Biodiesel	Bio LNG	Bio methanol	C. Hydrogen (700 bar)	L. Hydrogen	E-methanol	$NaBH_4$
Energy density	Volumetric	MJ/L	27	13	14	3.5	5.5	14	16
	Gravimetric	MJ/kg	31	29	17	6	9	17	11

(Marin, 2020a; Ryste, 2019; van Nievelt, 2019)

3.3.6. Economic – Infrastructure

Biodiesel has comparable characteristics with marine gas oil, which has a widely developed infrastructure. Hence, biodiesel can use existing infrastructure, including blending facilities that are available in the Amsterdam port. Bio LNG can use the infrastructure of fossil LNG as it has comparable characteristics. This infrastructure has been developed to a certain extent in Amsterdam in the last decade. However, extensive use of bio LNG will disrupt current diesel infrastructure, which is the reason that this fuel moderately fits in the current infrastructure. Bio and e-methanol are corrosive liquids and have relatively low viscosity which requires small adaptions to the current infrastructure. Moreover, there is much experience with handling methanol in the chemical industry, which could be beneficial to the maritime sector (Platform Duurzame Biobrandstoffen, 2018). The volatility and broad ignition range of hydrogen make that this alternative fuel is poorly compatible with current infrastructure. Available gas pipelines could be used to a certain extend for hydrogen. Sodium borohydride is a solid fuel which requires an entirely new infrastructure. Besides, a system needs to be built to return residual sodium metaborate from a vessel to the regeneration facility (van Nievelt, 2019). Nevertheless, the $NaBH_4$ infrastructure has analogies with the grain infrastructure and is relatively simple to realise, according to K. Visser (Personal communication, 1-7-2020). See Table 21 for the performance matrix of the sub-criterium Infrastructure.

Table 21: Performance matric Infrastructure

Sub-criteria	Unit	Biodiesel	Bio LNG	Bio methanol	C. Hydrogen (700 bar)	L. Hydrogen	E-methanol	$NaBH_4$
Infrastructure	Ordinal	5	3	4	2	2	4	2

(Bengtsson et al., 2012; Hansson et al., 2019; Platform Duurzame Biobrandstoffen, 2018; van Nievelt, 2019)

3.3.7. Economic – Propulsion system cost

Biodiesel (HVO) is combusted in conventional marine diesel engines which require the lowest investment cost. The methanol engine is mostly similar to conventional diesel engines. However, there are a few adjustments required which increase the capital cost. Bio LNG is combusted in marine LNG engines which are more expensive than diesel engines. A hydrogen fuel cell propulsion system has substantially higher cost since the fuel cell stacks have to be replaced a couple of times during their lifetime (Taljegard et al., 2014). The cost of a sodium borohydride propulsion system is uncertain due to its immatureness. Marin estimated that the cost of this system is about twice the price of a hydrogen fuel cell system. This is due to extra components for the water supply system, hydrogen extraction system and residue system (Marin, 2020a). See Table 22 for the performance matrix of the sub-criterium Propulsion system cost.

Table 22: Performance matric Propulsion system cost

Sub-criteria	Indicator	Unit	Biodiesel	Bio LNG	Bio methanol	C. Hydrogen (700 bar)	L. Hydrogen	E-methanol	$NaBH_4$
Propulsion system cost	CAPEX	€/kW	600	870	617	2632	2632	617	5263

(Bergsma et al., 2020; Horvath et al., 2018; Marin, 2020a; Taljegard et al., 2014)

3.3.8. Economic – Marine fuel cost

The marine fuel costs of the alternative fuels are comparable to each other. Biodiesel and bio methanol are estimated to have the lowest fuel costs in 2030. Also, the price of green hydrogen is expected to sharply decrease in the next decade due to economies of scale, which is beneficial for hydrogen-based fuels. Still, e-methanol is estimated to be more expensive than bio methanol in 2030. The fuel price of sodium borohydride is 160 euro per MWh at the moment, according to Marin (2020). It is assumed that this amount will drop similar to the other fuels since it benefits from lower hydrogen costs as well. Furthermore, the metal carrier, sodium metaborate, is used in a circular manner which only requires initial cost. See Table 23 for the performance matrix of the sub-criterium Marine fuel cost.

Table 23: Performance matric Marine fuel cost

Sub-criteria	Indicator	Unit	Biodiesel	Bio LNG	Bio methanol	C. Hydrogen (700 bar)	L. Hydrogen	E-methanol	$NaBH_4$
Marine fuel cost	OPEX	€/MWh	64	82	70	75	75	82	82

(Bergsma et al., 2020; CE Delft, 2018; Hansson et al., 2019; Horvath et al., 2018; IEA, 2019b, 2020; Lloyd's Register & UMAS, 2019; Marin, 2020a; Nelissen et al., 2020; Platform Duurzame Biobrandstoffen, 2018; Ryste, 2019)

3.3.9. Environmental – GHG emissions

The GHG emissions of biobased fuels are estimated to be higher than hydrogen-based fuels. This is mainly due to the upstream emissions regarding harvest, transportation, pre-treatment, and land-use change. Bio LNG comes with the most GHG emissions since methane slip could occur. Hydrogen, e-methanol, and sodium borohydride have the potential to become completely carbon-neutral by eliminating all upstream GHG emissions. However, upstream emissions are not estimated to be fully avoided yet in 2030. See Table 24 for the performance matrix of the sub-criterium GHG emissions.

Table 24: Performance matric GHG emissions

Sub-criteria	Unit	Biodiesel	Bio LNG	Bio methanol	C. Hydrogen (700 bar)	L. Hydrogen	E-methanol	$NaBH_4$
GHG emissions	g CO_2-e/kWh	167	204	83	53	53	24	27

(Bengtsson et al., 2012; Gilbert et al., 2018; Hansson et al., 2019; Marin, 2020a; Platform Duurzame Biobrandstoffen, 2018; Ryste, 2019)

3.3.10. Environmental – Local pollutants

The biobased fuels and e-methanol are combusted in internal combustion engines which result in local pollutants. Biodiesel has to highest sulphur oxides, nitrogen oxides, and particulate matter emissions and is thus the worse scoring alternative fuel regarding local air quality. Also, bio LNG propulsion causes some local pollution, but fewer in total than methanol propulsion. Vessel propulsion trough electric engines that receive energy from fuel cells is the cleanest technology. As a result, no pollution is involved with the use of compressed hydrogen, liquefied hydrogen, and sodium borohydride. See Table 25 for the performance matrix of the sub-criterium Local pollutants.

Table 25: Performance matrix Local pollutants

Sub-criteria	Indicator	Unit	Biodiesel	Bio LNG	Bio methanol	C. Hydrogen (700 bar)	L. Hydrogen	E-methanol	$NaBH_4$
Local pollutants	SO_x	g SO_x/kWh	0.40	0.18	0.02	0	0	0.02	0
	NO_x	g NO_x/kWh	12	2	3	0	0	3	0
	PM	g PM/kWh	0.44	0.05	0.02	0	0	0.02	0

(Bengtsson et al., 2012; Ellis & Tanneberger, 2016; Gilbert et al., 2018; Lloyd's Register & UMAS, 2019; Ryste, 2019)

3.3.11. Environmental – Safety

The alternative fuels have different safety concerns. Biodiesel is a flammable liquid that is not toxic to humans. Spillage in the environment is the most considerable hazard of biodiesel since it is toxic for aquatic life with long-lasting effects. Vaporized bio LNG is an extremely flammable gas that causes severe risks. Bio LNG does not create an environmental hazard and is not toxic. However, formed methane gas can act as an asphyxiant by replacing oxygen in enclosed areas (Hansson et al., 2019; Ryste, 2019). Methanol is highly flammable and has low acute toxicity. Onboard methanol fuel systems have to be completely closed, so human contact with methanol is extremely unlikely. Further, methanol spillage in an aquatic environment is not marked as a hazard since it dissolves and is biodegraded by micro-organisms (Andersson & Salazar, 2015). Compressed and liquid hydrogen are extremely flammable and explosive, which require substantial safety contours. Hydrogen does not come with toxicity hazards or environmental impact. Sodium borohydride and the residual sodium metaborate are not flammable and have no significant environmental impact. $NaBH_4$ is a strong base which results in low acute toxicity risks. Also, sodium borohydride could decompose in contact with water, acids, and certain metals whereby hydrogen is formed with associated hazards (Marin, 2020a; van Nievelt, 2019). See Table 26 for the performance matrix of the sub-criterium Safety.

Table 26: Performance matrix Safety

Sub-criteria	**Indicator**	**Unit**	**Biodiesel**	**Bio LNG**	**Bio methanol**	**C. Hydrogen (700 bar)**	**L. Hydrogen**	**E-methanol**	**$NaBH_4$**
Safety	Flammability	Ordinal	Cat. 3	Cat. 1	Cat. 2	Cat. 1	Cat. 1	Cat. 1	No hazards
	Toxicity	Ordinal	No hazards	No hazards	Cat. 3	No hazards	No hazards	Cat. 3	Cat. 3
	Environmental impact	Ordinal	Cat. 2	No hazards	No hazards	No hazards	No hazards	No hazards	No hazards

(Andersson & Salazar, 2015; Hansson et al., 2019; Marin, 2020a; Ryste, 2019; van Nievelt, 2019)

3.3.12. Social-political – Social acceptability

The use of biobased alternative fuels does raise concerns among the society: The food versus fuel debate keeps going on, questions around the loss of biodiversity are raised, and the use of chemicals and fertilizers for biomass production are under discussion. Also, the controversial upstream carbon emissions due to (indirect) land-use change, harvest, and transportation of biomass, affect the social acceptability (Darda et al., 2019). Therefore, biobased alternative fuels come with moderate social acceptance. Hydrogen comes with public safety concerns related to the volatility, flammability, and explosive potential. However, there is a public expectation that hydrogen technologies are designed safely, which make that hydrogen comes with moderate social acceptability (Ricci et al., 2008). Research shows that people have a positive perception of CO_2-derived fuels, such as e-methanol (Jones et al., 2017). Marin (2020) estimates that the use of sodium borohydride comes with high social acceptance. Reasons could be its carbon-free nature and low-risk assessment. See Table 27 for the performance matrix of the sub-criterium Social acceptability.

Table 27: Performance matrix Social acceptability

Sub-criteria	**Unit**	**Biodiesel**	**Bio LNG**	**Bio methanol**	**C. Hydrogen (700 bar)**	**L. Hydrogen**	**E-methanol**	**$NaBH_4$**
Social acceptability	Ordinal	3	3	3	2.5	3	4.5	5

(Darda et al., 2019; Jones et al., 2017; Marin, 2020a; Ricci et al., 2008)

3.3.13. Social-political – Governmental support

The IMO is responsible for international policy and regulations that affect short-sea and deep-sea shipping. The European Union and Dutch government define policies and regulations for coastal areas and inland waterways. Regulations and policies of the IMO, EU and Dutch government related to GHG emission reduction do, so far, not support specific alternative fuels. New governmental mechanisms that aim at better competitiveness of alternative fuels in relation to conventional fossil fuels are expected shortly (Maritime advisor, personal communications, 19-3-2020).

Additionally, the IMO has set a 0.5% SO_x fuel content limitation globally and the EU a 0.1% SO_x limitation for Emission Control Area's (ECA's) such as the North Sea and Baltic Sea. All alternative fuels in this research comply with those sulphur regulations. Biodiesel would be affected most if those regulations got stricter in the future. NO_x emissions are regulated according to Tier I, II, and III limits. Tier III regulations apply for vessels build from 2016 that are active in ECA's. Biodiesel engines could require exhaust gas cleaning and methanol engines require engine development to comply with Tier III. Further, the European Union has set sustainability criteria for biofuels in their Renewable Energy Directive (RED), which could affect biodiesel, bio LNG and bio methanol (Hansson et al., 2019; Platform Duurzame Biobrandstoffen, 2018). Therefore, biobased alternative fuels come with moderate to fairly high governmental support. Compressed hydrogen, liquid hydrogen, and sodium borohydride do not produce any local pollutants and thus come with high governmental support. See Table 28 for the performance matrix of the sub-criterium Governmental support.

Table 28: Performance matrix Governmental support

Sub-criteria	Unit	Biodiesel	Bio LNG	Bio methanol	C. Hydrogen (700 bar)	L. Hydrogen	E-methanol	$NaBH_4$
Governmental support	Ordinal	3.5	4	4	5	5	4.5	5

(Hansson et al., 2019; Platform Duurzame Biobrandstoffen, 2018)

3.3.14. Social-political – Regulations and classifications

Biodiesel (HVO) meets the ISO 8217 specifications which are defined for marine gas oil. Therefore, biodiesel fits in existing regulations and classifications in a blend or without a blend. Bio LNG is subject to the same regulations and classifications as fossil LNG. A new Safety of Life at Seas (SOLAS) regulatory framework for LNG, The International Code for Ships using Gases and other Low Flashpoint Fuels, was published in 2017 by the IMO (Platform Duurzame Biobrandstoffen, 2018). Also, classification schemes for LNG powered vessels are in place for new-built ships and retrofits (Ryste, 2019). Methanol is, similar to LNG, a low-flashpoint fuel. However, regulations for methanol are not yet included in the SOLAS framework and are still under development. Lloyd's Register was the first classification society that published an official classification scheme for methanol powered vessels in July 2019 (Lloyd's Register, 2019). Propulsion by hydrogen fuel cells is also not yet regulated in the SOLAS framework. Hydrogen regulations are currently under development and are expected to be published in the next SOLAR revision. Class rules are partly described by DNV GL but are subject to regulatory gaps (Tronstad et al., 2017). Regulations and classification for the use of sodium borohydride on a vessel do not exist yet but are relatively easy to realise due to the low safety risks, according to K. Visser (Personal communication, 1-7-2020). The port authority vessel of Port of Amsterdam could be a first step in the development process to official $NaBH_4$ classification schemes. See Table 29 for the performance matrix of the sub-criterium Regulations and classifications.

Table 29: Performance matrix Regulations and classifications

Sub-criteria	Unit	Biodiesel	Bio LNG	Bio methanol	C. Hydrogen (700 bar)	L. Hydrogen	E-methanol	$NaBH_4$
Regulations and classifications	Ordinal	3	3	2	2	2	2	1

(Lloyd's Register, 2019; Platform Duurzame Biobrandstoffen, 2018; Ryste, 2019; Tronstad et al., 2017)

3.4. Final performance matrix

The criteria scores of the previous section are standardised and combined with weight factors in the final performance matrix. The weight factors are based on the surveys which are filled in by seven experts. The pairwise comparison matrices per respondent are given in Appendix IV. The relative importance of the main criteria is visualised in Figure 13, according to the judgements of the marine fuel experts. Variation in judgements is observed among the experts. Scalability is essential, according to the strategists. The opinion of the external industrial researchers strongly varies on the technological, economic, and environmental criteria. The commercialists of Port of Amsterdam have a clear focus on the financial perspective. The operational department considers the environmental criterium, including safety, as most important. The technological and social-political criteria are the least important, according to the experts.

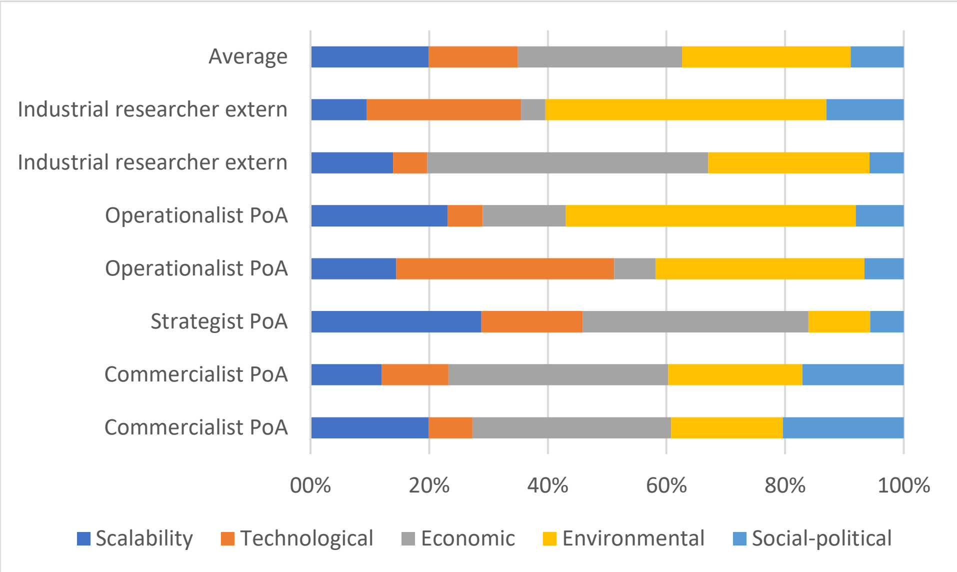

Figure 13: Relative importance of main criteria according to marine fuel experts

The standardised scores per (sub)-criteria, weight factors and final scores are put together in the final performance matrix, which is presented in Table 30. The range of the standardised scale is from 0 until 100, where 0 represents the least preferred performance and 100 the most preferred performance.

Table 30: Final performance matrix

Criteria	Sub-criteria	Biodiesel	Bio LNG	Bio methanol	C. Hydrogen (700 bar)	L. Hydrogen	E-methanol	$NaBH_4$	Weights
Scalability	Availability of primary inputs	93	100	46	0	0	0	0	**12.2%**
	Added value Amsterdam port	100	50	100	0	0	100	100	**7.7%**
Technological	Maturity	100	75	50	100	100	0	50	**3.3%**
	Energy efficiency	28	17	31	100	56	38	0	**4.4%**
	Energy density	100	40	45	0	9	45	52	**7.3%**
Economics	Infrastructure	100	33	67	0	0	67	0	**10.0%**
	Propulsion system cost	100	94	100	56	56	100	0	**5.8%**
	Operational expenditure	100	0	68	42	38	4	4	**11.9%**

Environmental	GHG emissions	21	0	67	84	84	100	99	**6.6%**
	Local pollutants	0	79	93	100	100	93	100	**5.8%**
	Safety	50	0	50	0	0	50	100	**16.0%**
Social-political	Social acceptability	20	20	20	0	20	80	100	**2.0%**
	Governmental support	0	33	33	100	100	67	100	**3.5%**
	Regulations and classifications	100	100	50	50	50	50	0	**3.5%**
	Final scores	**72**	**41**	**61**	**33**	**31**	**51**	**47**	

Figure 14 contains a visualisation of the criteria performance per alternative fuel. Biodiesel is preferable from scalability, technological and economic perspective. Sodium borohydride has the best performance on the environmental criterium. The hydrogen-based alternative fuels are most desirable from a social-political perspective.

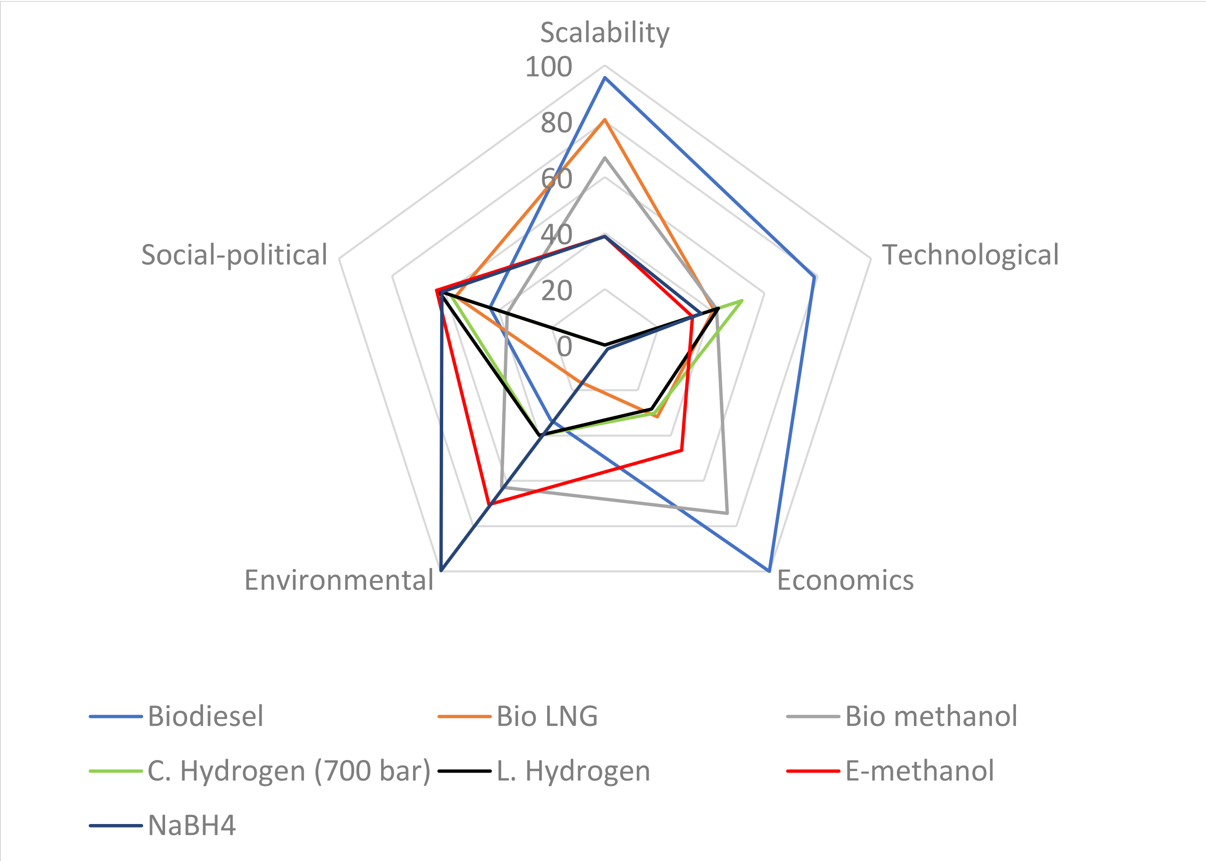

Figure 14: Spider plot criteria scores per alternative fuel

3.5. Sensitivity analysis

The final scores of the performance matrix are checked on their robustness. First, several scenarios are outlined wherein criteria scores are varied. After, the outcomes are checked according to score and weight factor uncertainties. Then, different standardisation methods are applied to some criteria. At last, the criteria are checked on independency.

3.5.1. Long-term scenario

The scores of the multi-criteria analysis are estimated for the year 2030. It is interesting to see how the final scores will change on the long-term. Therefore, expected criteria score changes for 2040 and 2050 are put in the model. The expected changes for 2040 are:

- The availability of hydrogen will grow with 70% between 2030 and 2040, which is in line with projections of the International Renewable Energy Agency (IRENA, 2019).
- All fuel production and propulsion technologies are fully mature (TRL 9).
- The fuel cost of hydrogen-based alternative fuels will drop by 30% between 2030 and 2040, which is also in line with the IRENA projections.
- Regulatory frameworks and classifications schemes for alternative fuels exist without regulatory gaps.

And the expected changes for 2050 are:

- The availability of hydrogen will grow with another 70% between 2040 and 2050, which is in line with the IRENA projections.
- The fuel cost of hydrogen-based alternative fuels will drop by 20% between 2040 and 2050, which is also in line with the IRENA projections.

The results of this scenario are presented in Figure 15. The outcomes imply that e-methanol and sodium borohydride are more preferred than bio LNG and bio methanol in 2040 and later. Also, their performance becomes comparable to biodiesel over time. Compressed and liquid hydrogen are, despite their improved scores over time, the least favourable alternative fuels for coastal and inland vessels in 2040 and 2050.

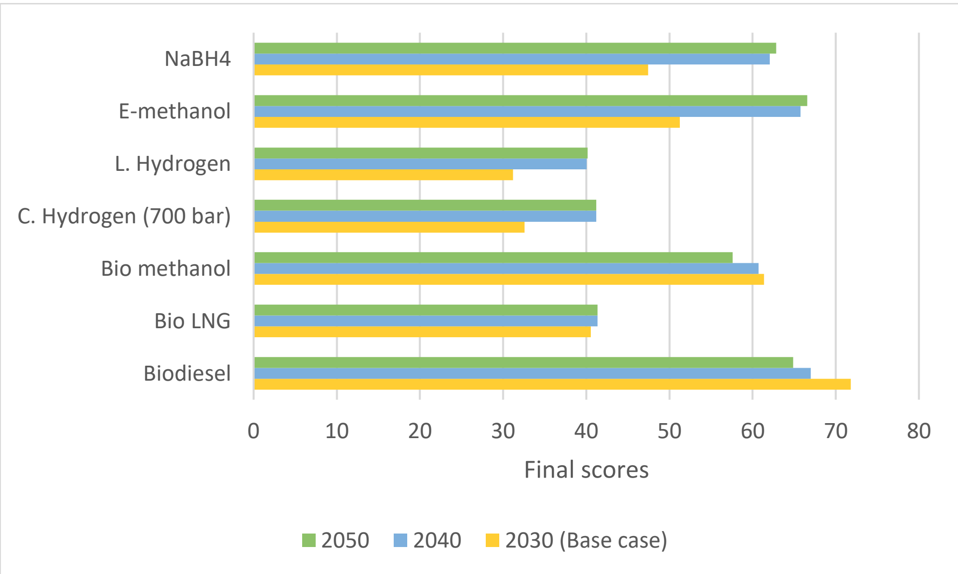

Figure 15: Sensitivity analysis - Long-term scenario

3.5.2. Hydrogen ICE scenario

The multi-criteria analysis has based scores of compressed and liquid hydrogen on propulsion by fuel cell systems. Hydrogen could also be used in internal combustion engines for vessel propulsion. The following criteria scores change for compressed and liquid hydrogen in combustion scenario:

- The efficiency of an ICE (33%) is lower than a fuel cell system (52%) due to heat losses (El-Gohary, 2009).
- The CAPEX for hydrogen ICE's is €906 per kW instead of €2632 per kW for fuel cells (Taljegard et al., 2014).
- NO_x emissions are formed during combustion due to the heat of the engine. There are no recent emissions test data found, so the value of 3 g NOx per kWh is used which is retrieved from methanol combustion engines.

Figure 16 visualises the results of this scenario. The final scores for vessel propulsion based on hydrogen ICE's are lower than for fuel cells. The lower propulsion system cost of the hydrogen combustion engine is thus not worth the trade-off for lower propulsion efficiency and higher NO_x emissions according to the MCDA framework.

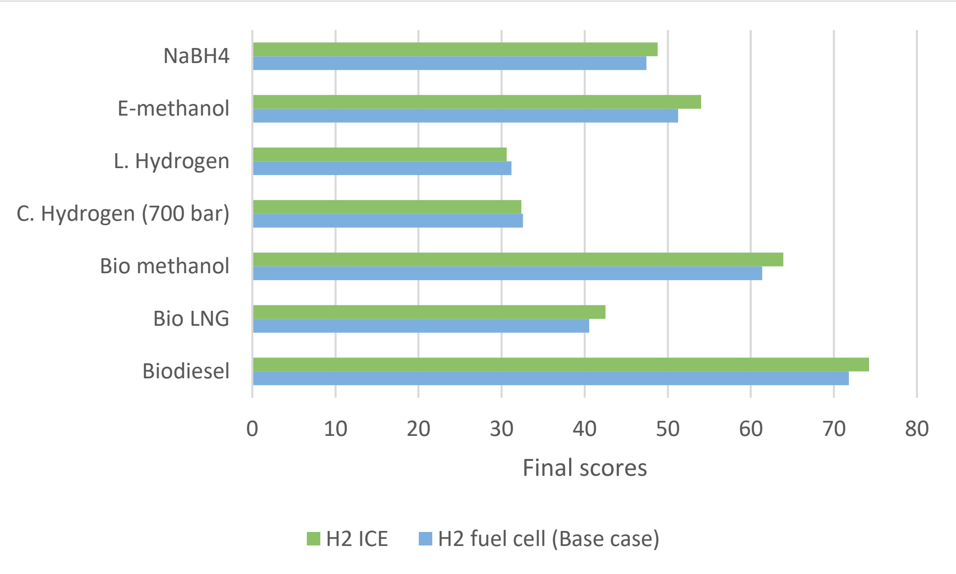

Figure 16: Sensitivity analysis - Hydrogen ICE scenario

3.5.3. Methanol fuel cell scenario

The analysis of this study uses values for bio methanol and e-methanol based on propulsion by an internal combustion engine. Vessel propulsion could also be based on methanol fuel cell systems. Hereby, methanol is decomposed in hydrogen and carbon dioxide during a dehydrogenation process. The hydrogen is used in a hydrogen fuel cell propulsion system which is described in Section 3.2.4. The following criteria scores change in this scenario:

- The dehydrogenation of methanol is an endothermic reaction with an efficiency of 78% (Marin, 2020b). The change of propulsion system results, therefore, in a drop of propulsion efficiency from 48% to 40%.
- The capital expenditures of a methanol fuel cell system consist of €2632 per kW for fuel cells plus €1872 per kW for a dehydrogenation reactor (Marin, 2020b).
- The use of fuel cell eliminates all local emissions.

The results of this scenario are given in Figure 17. The final scores for bio methanol and e-methanol are lower in this scenario than in the base case. Vessel propulsion based on a methanol fuel cell system is thus not preferred according to the multi-criteria analysis framework. The elimination of local emission seems not worth the trade-off in lower energy efficiency and higher propulsion system cost.

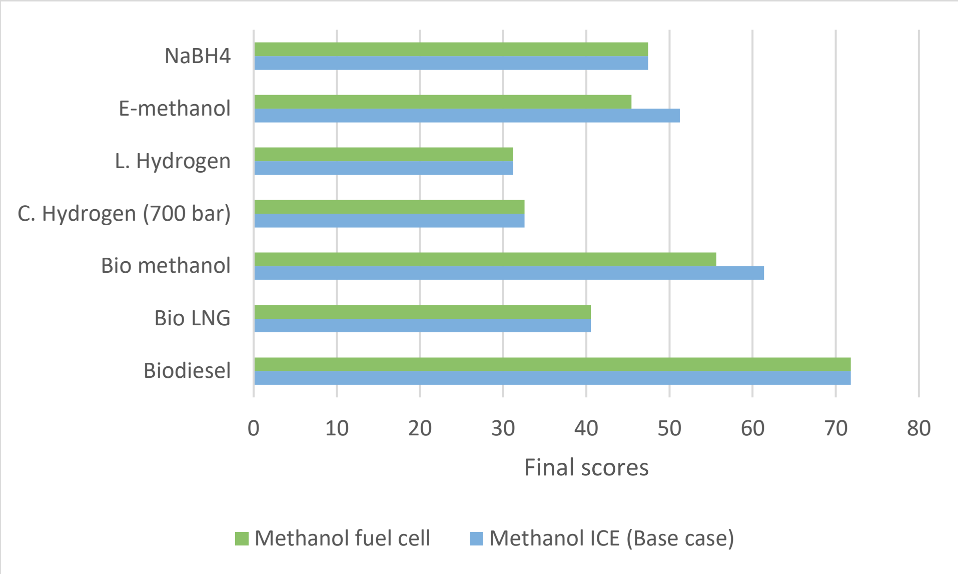

Figure 17: Sensitivity analysis – Methanol fuel cell scenario

3.5.4. Score and weight factor uncertainties

The scores and weight factors are varied to check the robustness of the ranking of the alternative fuels. There is most inconsistency in the literature about the scores of Propulsion system cost, Marine fuel cost, GHG emissions, and Local pollutants. These criteria are subject to a score uncertainty of 35% since this covers the reliable and applicable input data variation of this research. The other criteria are checked with a score uncertainty of 15% since their corresponding input data is relatively certain. The weight factor uncertainty is also defined as 15% as the input of seven experts in the maritime sector are assumed to be reliable.

The sensitivity analysis results of the DEFINITE Bosda 3.1 software are visualised in Figure 18. The larger the circle, the higher is the probability of the position in the ranking despite included uncertainties. The results imply that the chances of biodiesel and bio methanol to change in the ranking are low. The position of sodium borohydride is less certain since it has a small probability to become a more preferred alternative fuel than e-methanol and a fair probability to become less preferred than bio LNG. Further, there is a fair probability that compressed and liquid hydrogen interchange positions.

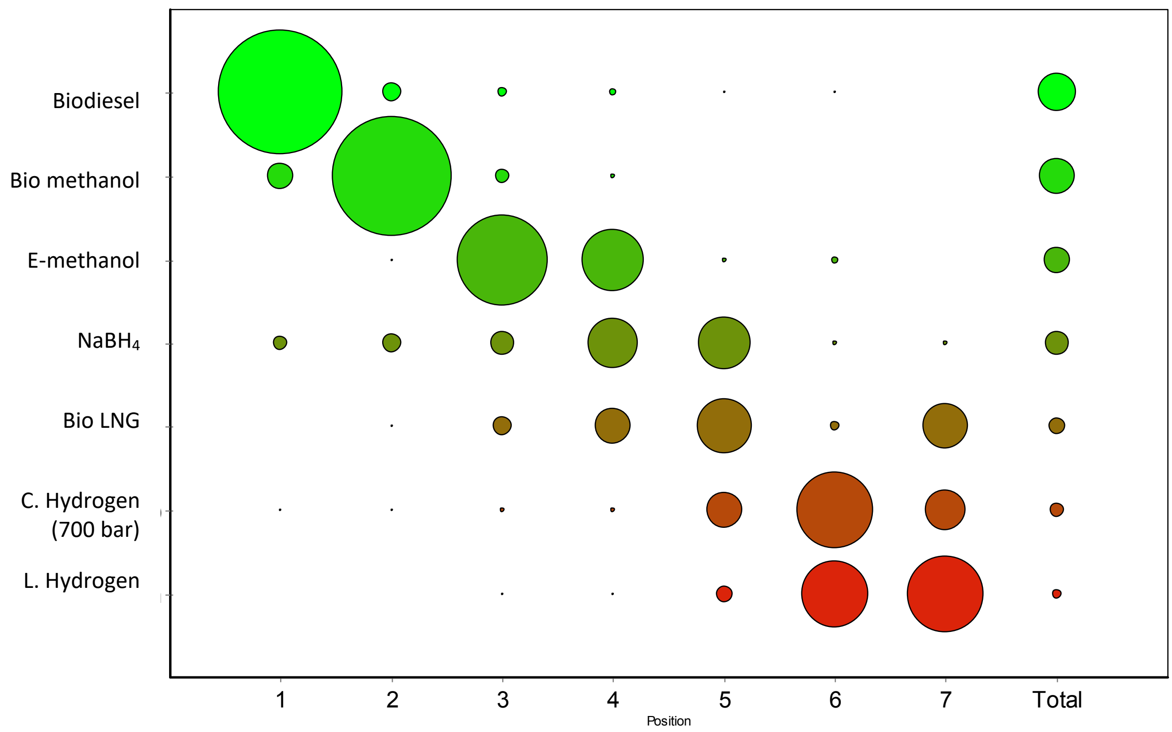

Figure 18: Sensitivity analysis - Score and weight factor uncertainties

3.5.5. Different standardisation method

The scores of the criteria in the analysis of this research are standardised according to the interval standardisation method. The scores could also be standardised with different methods. Some criteria could be converted according to the goal standardisation method. Goal standardisation means that scores are linear interpolations between a specified minimum and maximum. The standardisation methods of following criteria are changed to goal standardisation:

- The criteria that are initially scored on a qualitative ordinal scale are changed whereby the lowest ordinal score category is the minimum and the highest category the maximum. This is the case for the sub-criteria: Added value Amsterdam port, Infrastructure, Safety, Social acceptability, Governmental support and Regulations and classifications.
- The sub-criteria GHG emissions and Local pollutants have a clear goal to be zero. Therefore, these scores are standardised with a specified maximum of zero emissions.
- The standardisation methods of the other criteria are not changed since other methods do not apply. For example, an energy efficiency of 100% is theoretically unfeasible. Also, the propulsion system cost or fuel cost of zero euros is unrealistic.

The final scores with different standardisation methods are calculated with DEFINITE Bosda 3.1 software and presented in Figure 19. The results show that the different standardisation method does not change the final ranking. The final scores of all alternative fuels increase due to the different method. Especially, bio LNG, compressed hydrogen and liquid hydrogen have a relatively better final score.

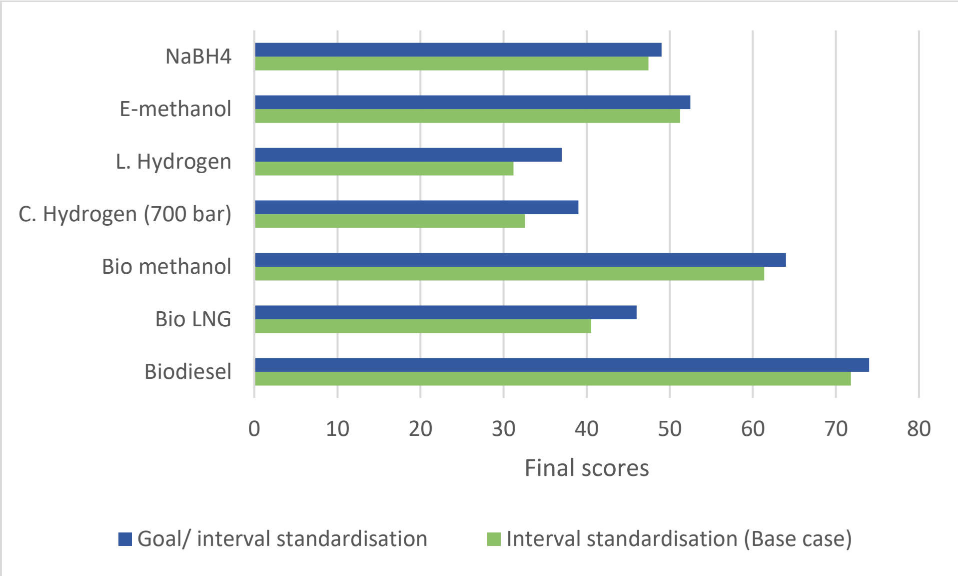

Figure 19: Sensitivity analysis - Different standardisation method

3.5.6. Criteria independency check

The DEFINITE Bosda 3.1 software is used to check on correlations between criteria. A correlation coefficient of 1.0 shows a perfect positive correlation and a coefficient of -1.0 a perfect negative correlation. A coefficient of zero means no correlation. The correlation results, retrieved from the Bosda 3.1 software, are visualised in Figure 20.

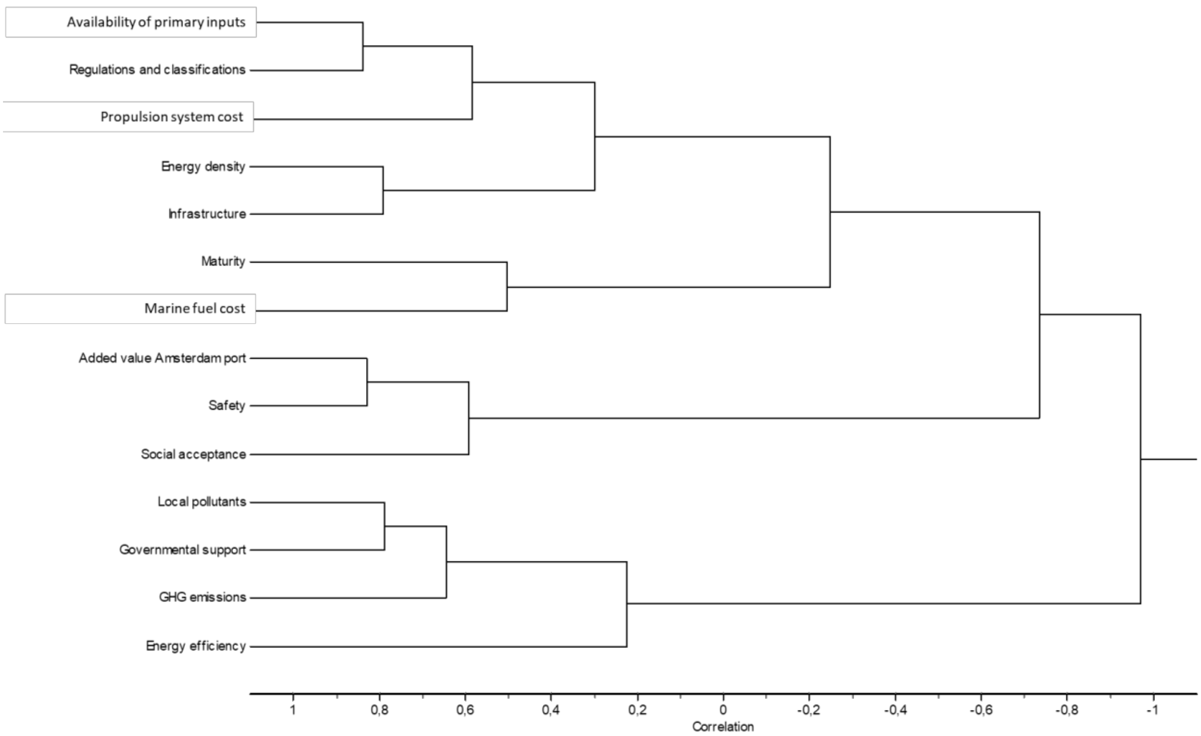

Figure 20: Correlations between criteria

The results show a strong correlation between Availability of primary inputs and Regulations and classifications. The reason could be that biobased alternative fuels are better available and have existing regulations and classifications since they have been longer in use by the maritime sector.

There is a strong correlation as well between Energy density and Infrastructure. This would mean that more energy-dense alternative fuels fit better in the current infrastructure, which is assumed to be unlikely. The correlation is probably caused by compressed and liquid hydrogen that poorly fit in current infrastructure and have a low volumetric energy density.

Further, the outcomes show a strong correlation between Added value Amsterdam port and Safety. In other words, safer alternative fuels cause a higher added value to the Amsterdam port region. This is true since the Amsterdam port is located near the city of Amsterdam and which increases safety requirements.

The last strong correlation is between Local pollutants and Governmental support. The different governmental maritime agencies have put several local pollution regulations in place, which could be the reason for this correlation.

All in all, Added value Amsterdam port and Safety are considered depended to a certain level as well as Local pollutants and Governmental support. These criteria could be combined to improve the independency among criteria of the analytical framework. The other criteria are correlated by different reasons or by accident and justified to be independent.

4. Conclusion

This research aimed to identify, assess and compare different alternative marine fuels that could actively contribute to a sustainable future of the maritime and port sector, which would also fit within the commercial and operational environment of Port of Amsterdam. The resulting main research question addressed in this study was:

What is the commercial and operational most promising alternative marine fuel for coastal and inland shipping in 2030 and beyond in order to decarbonise the Amsterdam port?

Answering this research question went hand in hand with setting up an analytical framework in the form of multi-criteria decision analysis. This method allowed to combine qualitative and quantitative assessment criteria, which is crucial for this decision-making process. Also, the criteria could be weighted according to their relative importance. Hereby, Availability of primary inputs, Infrastructure, Marine fuel cost, and Safety are defined as the most important criteria.

It can be concluded that biodiesel, or more specific hydrotreated vegetable oil (HVO), is the most commercial and operational preferable alternative marine fuel for coastal and inland shipping in 2030. Biodiesel allows for high scalability potential since different types of biomass feedstock can be used for production, including second-generation non-edible vegetable oils, waste oil, and animal fats. Moreover, widely available lignocelluloses could improve its future scalability even more. Also, HVO fits perfectly in the current infrastructure since its characteristics are similar to conventional diesel. This offers economic benefits for Port of Amsterdam because it prevents disruption of currently available assets such as storage terminals, blending facilities and bunker stations. Furthermore, biodiesel is the most attractive alternative fuel for shipping companies from a business perspective as it has the lowest estimated fuel price and propulsion system investment cost for 2030. Besides, it is subject to the most moderate loss of cargo with resulting missing revenues due to its high volumetric energy density. Nevertheless, the downsides of biodiesel have to be recognized. Due to the combustion process, the production of biodiesel can result in local emissions onboard, which clashes with the Tier III NO_x regulation. Also, there are societal concerns about the use of biofuels in general, related to the CO_2 reduction potential, food versus fuel issues, loss of biodiversity and use of chemicals and fertilizers.

Methanol is another alternative marine fuel that positively stands out in the results of this research. Methanol could be sustainably produced via biomass or green hydrogen. Bio methanol is more preferred than e-methanol in 2030 due to its better availability, higher maturity, and lower fuel price. However, the long-term scenario of the sensitivity analysis showed that e-methanol is likely to become more interesting towards 2040 and beyond as a consequence of growing electrolyser capacity and decreasing green hydrogen production costs. Moreover, e-methanol has a higher greenhouse gas reduction potential. Bio methanol and e-methanol could strengthen each other's potential since their storage, bunker and engine requirements are similar. A supply chain for methanol fits well in the Amsterdam port since it does not come with exceptional safety or environment requirements. Nonetheless, methanol is a corrosive liquid and has a relatively low viscosity which requires small adaptions to the current infrastructure. Furthermore, the planned hydrogen and CO_2 infrastructure in the Amsterdam port region is beneficial for the development of e-methanol production plants. A weakness of methanol in comparison with biodiesel is the 50% lower volumetric energy density. This weakness could be offset for coastal and inland vessels by methanol storage in ballast tanks. Also, the issue with the absence of existing regulations could be solved soon by the integration of methanol in the Safety of Life at Seas (SOLAS) regulatory framework. This could accelerate the adoption process of methanol and complementary methanol propulsion systems. The sensitivity analysis shows the preference for methanol internal combustion engines instead of fuel cell systems onboard due to the higher energy efficiency and lower propulsion system cost.

Sodium borohydride ($NaBH_4$) has a particular interest by Port of Amsterdam as it will be the fuel for their new port authority vessel. This alternative marine fuel is ranked fourth in the final performance matrix of this study. Sodium borohydride is preferred from an environmental and social-political perspective. It comes with the least amount of emissions and pollution during upstream activities and operational use. Furthermore, it is the safest alternative fuel since production and propulsion processes only contain small amounts of hydrogen, and there are no serious hazards involved. However, there are technological and economic issues to be overcome to increase its potential. The efficiency of the regeneration process off-board needs to be improved. Also, the practical implementation of fuel residue return system from the ship to land needs to be developed. Nevertheless, the potential of the fuel is present, as storage and bunker facilities for sodium borohydride are expected not to be sophisticated since it is a solid powder that has analogies with grain. Furthermore, the long-term scenario confirms its potential towards 2040 and beyond as a consequence of full matureness and lower fuel prices. The expected decreasing cost of fuel cell systems are not included in this scenario but could lead to an even higher preference level.

Bio LNG, compressed hydrogen and liquid hydrogen are the lowest-ranked fuels in this research. Bio LNG has relatively high production costs, a limited GHG emission reduction potential and flammability hazards. However, bio LNG does come with a high scalability potential. Hydrogen, either compressed or liquefied, are scoring the worse in the final performance matrix. The low volumetric energy density makes hydrogen in a pure form less desirable as fuel for long-distance coastal and inland shipping. Also, large-scale hydrogen production and bunker facilities come with flammability and explosivity risks that require safety measures with the city of Amsterdam in proximity. The improved preferability of hydrogen in 2040 and beyond does not change the final ranking. Moreover, the sensitivity analysis implies that the use of hydrogen combustion engines onboard instead of fuel cell systems would not improve its potential. Nevertheless, hydrogen production and infrastructure are essential for the development of hydrogen-related marine fuels. Therefore, hydrogen as a marine fuel keeps interesting for short-distance coastal and inland shipping.

5. Discussion

This chapter contains interpretations, implications, limitations, suggestions for further research related to the analytical framework and the results of this study. The section is finalised with recommendations for Port of Amsterdam.

5.1. Analytical framework

The analytical framework is set up to assess and compare alternative marine fuels which are difficult to directly assess by decision-makers due to diverse characteristics and contradictory strengths and weaknesses. Also, the framework had to be able to combine quantitative and qualitative data of tangible and intangible aspects. The chosen multi-criteria decision analysis framework turned out to be appropriate as the alternative fuels were successfully analysed from different perspectives without missing scores. The performance matrix gave a clear overview of the strengths and weaknesses of the fuels relative to each other. Also, the final ranking is reasonable, according to discussions with marine fuel experts. Further, the framework allows for the integration of other alternative fuels and could be used by other ports and stakeholders. Ammonia has already been successfully integrated during internal sessions at Port of Amsterdam with valuable outcomes for business strategy purposes.

Criteria

Five assessment criteria and fourteen sub-criteria are considered to be relevant in the assessment of alternative marine fuels based on academic and industrial research, and interviews conducted at Port of Amsterdam. The primary condition was heterogeneity and independency among the criteria. Ren & Lützen (2017) called for the incorporation of a check on interdependences among criteria used for the sustainability assessment of alternative energy sources for shipping. This study did so by checking correlations using the DEFINITE Bosda 3.1 software. The sub-criteria Added value Amsterdam port and Safety strongly correlate, which could imply combining them. However, there are strict safety requirements in the Amsterdam port because of its proximity to the city of Amsterdam, which affected fuel supply chains with severe hazards. Several other ports are located in less densely populated areas with less strict safety regulations. This could result in a lower correlation between Added value and Safety. Future decision-makers should consider this before combining the criteria. Local pollutants and Governmental support strongly correlate too. Governmental maritime organisations aim at reducing local pollution by putting emission regulations and limitations in place. The primary role of the IMO is to realise safe international shipping with the prevention of pollution (IMO, 2020). Safety and pollution are both covered by other criteria which makes the Governmental support sub-criteria otiose.

The analytical framework does not count for the presence or absence of carbon molecules in alternative fuels. It became apparent during the external interviews that the absence of carbon is an important driver in the decision-making process for alternative marine fuels (Maritime expert, personal communication, 1-7-2020). The absence of carbon benefits compressed hydrogen, liquid hydrogen and sodium borohydride. An assessment criterium on the presence or absence of carbon could be added to improve the framework for future use.

Weight factors

The criteria are weighted according to their relative importance based on the opinion of seven experts in the field of alternative marine fuels. The results showed that the judgements of the experts vary over different criteria. The judgement seemed to be based on personal interest as the experts working in the commercial department considered the economic criterium as most important, and the operational employees found the environmental criterium, including safety, as most important. Future research could be done on the opinion of other stakeholders, such as shipping companies or bunker companies. Thereby, judgements of different departments of the companies are desired to be gathered to prevent subjective weight factors.

Measurement scales
At last, the measurement scales of some criteria could be specified in future studies. The sub-criterium Availability of primary inputs was measured on a global scale since reliable local data was not available. However, research is going on in estimating the sustainable biomass feedstock potentials and the clean hydrogen market is rapidly developing, which could give local insights soon. The availability of local primary inputs could be compared with the yearly bunker volumes of marine gas oil (MGO) and marine diesel oil (MDO) of Port of Rotterdam which represent the coastal and inland shipping market of North and West Europe. Also, the sub-criteria Added value Amsterdam port and Infrastructure were measured on an ordinal scale. Future research could include measuring these criteria on a monetary level to make the outcomes more accurate.

5.2. The results

The results indicate that biodiesel is the most promising alternative fuel for coastal and inland vessels in 2030. Also, methanol has an excellent commercial and operational potential, whereby bio methanol is most interesting for 2030 and e-methanol for 2040 and beyond. Further, the long-term potential of sodium borohydride is confirmed by the study. Bio LNG, compressed hydrogen and liquid hydrogen turned out to be less preferable for coastal and inland shipping purposes. These outcomes are robust since no changes occurred in the final ranking during the sensitivity analysis. The use of different propulsion systems for hydrogen and methanol did not improve their potential. Moreover, the use of different standardisation methods and the inclusion of score and weight factor uncertainties showed that the probability of change in the final ranking is small.

Interpretations and implications
Recent comparable studies regarding marine fuels showed similarities and a few different outcomes, mostly because of a different approach or scope. Ryste (2019) agrees on the excellent applicability of biodiesel (HVO) for maritime purposes but has concerns about the fuel cost and availability. Biodiesel is scoring well from scalability and economic perspective in this research. However, Ryste (2019) is comparing alternative fuels with LNG, which is cheap and widely available, while this research is comparing alternative fuels with each other. Hansson et al. (2019) compared alternative fuels with HFO and LNG for deep-sea shipping in 2030, whereby LNG, HFO and fossil methanol were ranked highest followed by biofuels. This study indicates that it is difficult for all alternative fuels to become competitive with fossil fuels in 2030 due to economic and availability reasons. Hansson et al. (2019) also point out that biofuels are more attractive than hydrogen on the short-term, which is in line with the outcomes of this research. Bergsma (2020) prefers bio methanol and bio LNG above biodiesel as alternative marine fuels towards 2030 since it has the same cost but is not produced via food-based biomass feedstocks. The analysis of this study showed that biodiesel could also be produced via non-edible sources, which should be an essential condition for further biodiesel development. Moreover, Bergsma (2020) points out the role of bio methanol and bio LNG in a transition towards e-fuels. E-LNG is not analysed in this study but could offer long-term opportunities. Further, The Platform Duurzame Brandstoffen (2018) qualitatively investigated the readiness of biobased marine fuels in 2030 and found biodiesel (HVO) most attractive. Only, questions are being raised regarding the availability of biomass feedstock for biodiesel (HVO) production. Namely, biodiesel (HVO) is now mainly produced via limited available waste oils and fats. The challenge is to find other sustainable sources of non-edible oils or to develop production methods via lignocelluloses biomass.

The amount of analysed alternative fuels in this study was limited to seven due to time reasons. The initial review of this research excluded several other alternative fuels with long-term potential. Ammonia, one of the excluded fuels, had rising interest from the maritime sector during this research because it does not contain carbon molecules. However, the toxicity of ammonia causes severe hazards that are hardly manageable for coastal and inland shipping according to several interviewees of this research. Future research could be done to confirm these statements. Also, e-diesel, e-LNG, formic acid, iron powder and liquid organic hydrogen carriers could be further analysed on their long-term potential since these fuels have some favourable characteristics.

Limitations

Some criteria scores have limitations regarding collected data or comparability issues. The Availability of primary input criterium is based on the sustainable potential of biomass feedstock and the expected electrolyser capacity. However, the probability that both inputs become fully available for the maritime and port industry is nihil. The margins of biofuels and hydrogen for road transportation and the chemical industry are higher than for the maritime industry (Maritime consultant, personal communication, 25-3-2020). Furthermore, the sustainable potential does not necessarily need to be completely deployed. Further, the energy efficiency comparison is based on the production efficiencies of biobased fuels and hydrogen-based fuels. The fairness of this comparison is debatable since biomass and hydrogen are different sources of energy. Also, available reliable data for e-methanol and sodium borohydride was limited, which resulted in less accurate criteria scores. This is reflected in the GHG emissions of e-methanol, and sodium borohydride, which are scored lower than for compressed and liquid hydrogen. This is an unlikely result since e-methanol, and sodium borohydride are produced via hydrogen. At last, most criteria scores are estimated for 2030, which comes with uncertainties. Unforeseen market developments could take place that affect these predictions. Therefore, future studies should always interpret the quantitative results of this study together with newer research insights.

Overview

The outcomes of this study are robust and in line with other studies which indicates a decent level of research reliability and validity. The research question is clearly answered. However, the analytical framework could be further improved, additional research is required on specific criteria and fuels, and markets could develop unforeseen. Despite these limitations, the research forms a substantial base for an outlook on the expected development of alternative marine fuels. This outlook contains attractive fuels for coastal and inland shipping which are plotted against the related opportunities in the Amsterdam port. The outlook is visualised in Figure 21. Biobased marine fuels could play a significant role in the maritime industry as it is the most feasible alternative on the short-term, and it could drive the implementation of hydrogen-related fuels on the long-term.

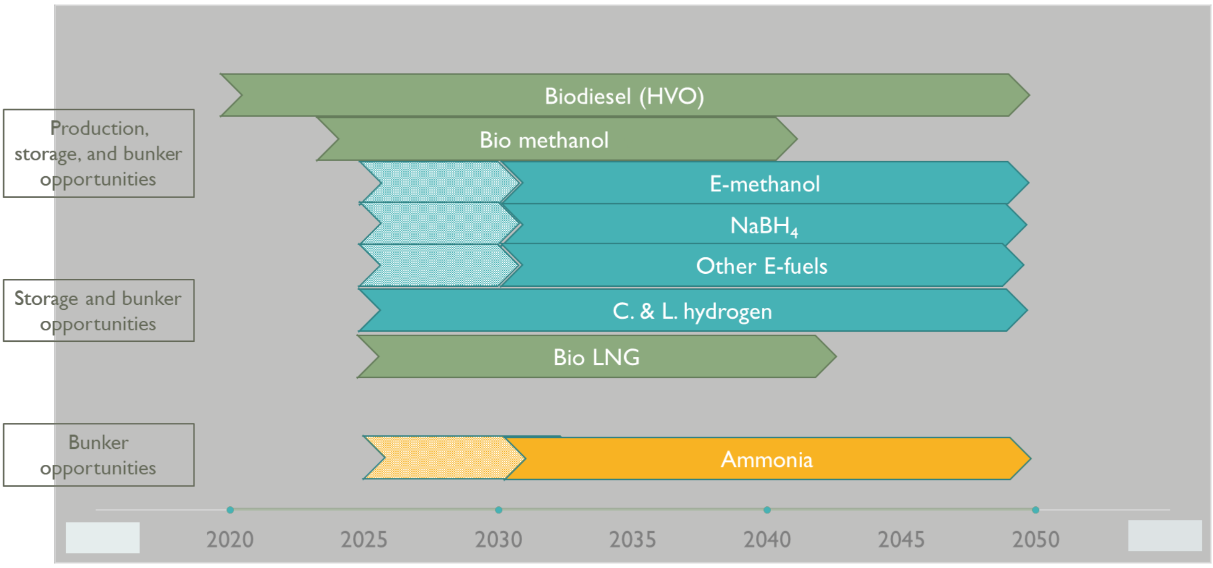

Figure 21: Attractive alternative fuels for coastal and inland vessels according to added value Amsterdam port

5.3. Recommendations

Port of Amsterdam was looking for clarity in future dominant marine fuels, to comply with climate goals, to design alternative fuel supply chains, to support propulsion system development and to decrease its share of fossil-fuel related revenues. This research, including conducted interviews, provides with valuable insights related to this problem. First, alternative fuel-specific recommendations are formulated, followed by overall recommendations.

5.3.1. Alternative fuel-specific recommendations

Biodiesel

- Focus on Hydrotreated vegetable oil (HVO) rather than FAME biodiesel. HVO is better compatible with maritime diesel engines and is not subject to blending limitations.
- Be critical on the sustainability of biomass feedstocks to deal with societal concerns. Biomass feedstock should not be competitive with the food industry and should not let to a loss of biodiversity. Moreover, upstream emissions during harvest, transportation and pre-treatment are desired to be avoided as much as possible.
- Investigate possibilities of exhaust gas cleaning onboard. The combustion of biodiesel produces significant amounts of NO_x emissions that could clash with Tier III regulations.

Bio and e-methanol

- Support the production of bio methanol via gasification of lignocelluloses instead of production via glycerol or biomethane. Glycerol is dependent on biodiesel production, which makes the supply uncertain. Biomethane is more effectively used directly.
- Discover opportunities for methanol storage in ballast tanks. Methanol has a 50% lower volumetric energy density than MGO which could (partly) be offset in this way.
- Support the development of maritime methanol engines to limit NO_x emissions.

Sodium borohydride ($NaBH_4$)

- Execute an economic feasibility study on the supply chain of sodium borohydride. Sodium borohydride shows analogies with grain which implies a relatively simple infrastructure. Confirmation by a financial analysis could accelerate further development.
- Support the development of the regeneration process since the energy efficiency needs to be improved.

Bio LNG

- Support stakeholders that attempt to solve methane slip issues. Methane slip is the main cause of the significant amount of GHG emissions related to the use of bio LNG.
- Facilitate the uptake of fossil LNG as a marine fuel as bio LNG has the same characteristics and will be a logical successor.

Compressed and liquid hydrogen

- Reserve suitable port areas for hydrogen-related activities. Hydrogen has severe flammability and explosivity hazards which limits the number of suitable areas in the Amsterdam port.
- Only consider hydrogen as a fuel for short-distance coastal and inland shipping since its volumetric energy density is very low.
- Keep in mind that hydrogen production and infrastructure are essential for the development of hydrogen-related marine fuels. These developments can drive the use of hydrogen as a marine fuel for short-distance coastal and inland shipping.

5.3.2. Overall recommendations

- Include a holistic approach among stakeholders and other ports to overcome the 'chicken or the egg' dilemma related to the supply and demand side of alternative fuels. Every stakeholder – including fuel supply chain, bunker, and shipping companies – should be given a specific role so that both sides can develop at the same pace.
- Make the port 'alternative fuel ready' by setting the right conditions for alternative fuels. The right conditions include hydrogen production, hydrogen infrastructure, CO_2 infrastructure, and precise environmental and safety requirements. The alternative fuel market is still too uncertain to focus only on a few particular fuels, so concentrate on the most promising mix and regularly research in further market development.
- Focus on developing alternative fuels for the coastal and inland shipping market instead of deep-sea in the Amsterdam port. This market is expected to switch to alternative fuels earlier and fits better to size and available assets in the Amsterdam port. Large-scale fuel 'production' for the deep-sea market is better appropriate in ports like Rotterdam.
- Investigate the local, sustainable biofuel availability (via GoodFuels) and compare it with the bunker volumes of MDO and MGO in Rotterdam. These volumes are representative for the West/ North European coastal and inland shipping market.
- Develop a model that gives financial insights into fuel supply chains and bunker facilities of alternative fuels. Financial insights are required to make specific and effective investment plans. Also, the effects of financial incentives on the competitiveness of alternative fuels could be analysed.
- Utilise synergies with aviation fuel development and other industries in the port for more efficient and effective alternative fuel development processes.
- Be critical on the use and hazards of ammonia as a bunker fuel. Amsterdam does not have favourable conditions for production and storage, which limits the associated added value for the Amsterdam port region.

The latter overall recommendations originate from conducted external interviews. These statements must be considered in the holistic approach among stakeholders in the transition to alternative marine fuels.

- Use a suitable approach for the inland shipping sector. This sector contains small, often family, businesses with little investment power. Innovative financial instruments are required if these businesses are to be able to invest in new propulsion systems.

- Keep an eye on financial incentives that make alternative fuels competitive. Shipping companies will not start adopting alternative fuels on a large scale until they become financially attractive. Namely, fuel costs are roughly forty per cent of the total costs of shipping companies.
- Support global market-based financial incentives. Local incentives affect the international competitive position, and non-market-based incentives drain money out of the maritime and port sector.
- Do not focus too much on storage terminals in the transition to alternative fuels. These parties cannot be the frontrunners in the transition since terminals come in place when decent volumes of a specific fuel are traded.
- Investigate opportunities for aquatic biomass. The Netherlands has many suitable water bodies which could provide with large-scale local biomass production.
- Use the massive visibility of Dutch ports in the transition to alternative fuels to make an impact already with small projects.

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Appendix I

The alternative fuels of the initial review (Section 3.1.) are briefly described in this appendix. Also, companies with (potential) interest for Port of Amsterdam are mentioned as well as the action per fuel. The action is no further action, further analysis, or long-term potential. First, the biobased alternative fuels are addressed, then hydrogen fuels, to conclude with hydrogen-based fuels. A distinction is made in hydrogen-based fuels that do and do not contain carbon.

Biobased marine fuels

Biobased alternative marine fuels are made from biomass feedstock. These include biodiesel, bioethanol, bio LNG, and bio methanol.

Biodiesel

Description
Biodiesel can be produced from 1st and 2nd generation biomass feedstocks such as vegetable oils, lignocelluloses, waste, and residues. Hydrotreated vegetable oil (HVO) and fatty acid methyl acid (FAME) are the most promising biodiesels for the marine sector (Ryste, 2019). HVO is produced via a transesterification process catalysed by hydrogen and FAME is produced via transesterification process catalysed by methanol. Biodiesel can be blended with heavy fuel oil and marine gas oil or purely be used in conventional marine diesel engines. Also, biodiesels can relatively easy be implemented in current infrastructure which results in low overall investment costs (Bengtsson et al., 2012; Hansson et al., 2019; Taljegard et al., 2014).

There are opportunities for the production and storage of biodiesels in the Amsterdam port. Also, blending facilities and waste collectors are available, which could be beneficial for the development of biodiesels. However, it is debatable whether there is sufficient feedstock available to facilitate the whole marine sector. Moreover, there is competition for the use of biodiesel with road transport. Therefore, the expectation is that biodiesel fits the coastal and inland shipping market better than the deep-sea shipping market due to bunker volumes (Maritime consultant, personal communication, 19-3-2020; Maritime manager, personal communication, 20-3-2020).

Companies
GoodFuels, Argent Energy

Action
Further analysed in the multi-criteria analysis of this research because biodiesel is highly mature and well-applicable as a marine fuel.

Bioethanol

Description
Globally, bioethanol is the most produced biofuel. The US and Brazil are large producers of bioethanol with maize, sugarcane, and sugar beets as feedstock. These days, second-generation feedstocks such as agricultural residues, are becoming more attractive as these have no direct competition with food production. The production process via these residues involves pre-treatment, hydrolysis, fermentation, and distillation (Bengtsson et al., 2012; Gilbert et al., 2018). Despite mixing possibilities with marine gas oil or heavy fuel oil, there is not any commercial usage of ethanol as marine fuel known (Brynolf et al., 2014). Reasons are that ethanol cannot substitute conventional fuels entirely, and

ethanol experiences heavy competition with road transport. Production and storage could take place in the Amsterdam port.

Companies
-

Action
No further action due to its lack of interest by the maritime industry and its heavy competition with the road transportation sector.

Bio LNG

Description
Bio LNG is another potential marine fuel. It can be produced through anaerobic digestion of agricultural and animal waste. Other production options are gasification and Fischer Tropsch synthesis of 2nd generation biomass feedstock such as lignocelluloses. Bio LNG has the same characteristics as fossil LNG, which makes it compatible with the current LNG infrastructure (Hobson & Márquez, 2018). The LNG infrastructure is properly developed in North-West Europe, which offers opportunities for bio LNG in the Port of Amsterdam. However, the prospects of large-scale use of bio LNG in the marine sector are moderate due to the limited biomass supply and competition with other industries. Further, the issue of methane slip applies to bio LNG as it does to fossil LNG (Maritime consultant, personal communication, 19-3-2020; Maritime manager, personal communication, 11-3-2020).

Companies
-

Action
Further analysed in the multi-criteria analysis of this research because bio LNG is relatively mature and could be a successor of fossil LNG.

Bio methanol

Description
Methanol is one of the most handled chemical compounds worldwide with a yearly global production of more than 95 billion litres. It is mostly (99%) produced from coal and natural gas but can also be formed from biomass and renewable energy. Biomass such as willow or forest residues undergoes a fermentation or gasification process, where after bio methanol is formed in a synthesis reactor (Deniz & Zincir, 2016; Ryste, 2019). Methanol is good applicable as marine fuel due to its liquid phase under standard conditions and its compatibility with conventional marine engines with a few adjustments (Krasae-In et al., 2010; Ryste, 2019). It can also be mixed with marine gas oil or heavy fuel oil. There are production and storage opportunities for in the Amsterdam port since the methanol safety, and environmental requirements are manageable. A disadvantage is that the energy density of methanol is lower than traditional fuels, which makes this fuel most appropriate for coastal and inland shipping (Maritime consultant, personal communication, 12-3-2020; Maritime manager, personal communication, 11-3-2020).

Companies
Green Maritime Methanol project, BioMCN, LowLands Methanol Neveskes Energy, BASF (Germany), Enerkem (NL/ Canada), New Fuel (Denmark), Nordic Green (Denmark)

Action
Further analysed in the multi-criteria analysis of this research because bio methanol is well applicable to vessels, and the supply chain fits well in the Amsterdam port.

Hydrogen marine fuels

This section contains hydrogen in its pure form as a marine fuel, which is either compressed or liquefied.

Compressed hydrogen

Description

Hydrogen in its pure form can also serve as a marine fuel. Clean production of hydrogen involves an electrolysis process whereby renewable electricity is used to split water molecules in hydrogen and oxygen. This zero-emission fuel can be burned in an internal combustion engine or used in a fuel cell for vessel propulsion. Required technologies are proven, but the experience of application in the marine sector is little. Further, hydrogen is compressed for transport applications since its energy density under standard conditions is very low. Even in a compressed state, hydrogen requires six or seven times more space than HFO for the same energy content which makes it unsuitable for deep-sea shipping and only applicable for short-distance coastal and inland shipping (Eppinger & Huang, 2017; Pérez-Fortes et al., 2016). Hydrogen infrastructure is starting to develop in the Amsterdam port region including a hydrogen production location of Tata Steel. Besides, several pilots occur aimed at hydrogen vessel propulsion. Flammability and explosivity hazards of hydrogen must be taken in mind in these projects. The current hydrogen developments in Amsterdam could also lead to advancements regarding other hydrogen carriers (Maritime manager, personal communication, 12-3-2020; Maritime manager, personal communication, 20-3-2020).

Companies

H2Ships project

Action

Further analysed in the multi-criteria analysis of this research because there is much interest in hydrogen in Amsterdam.

Liquid hydrogen

Description

Other than compressing, hydrogen can also be liquefied to increase energy density. Energy per volume is almost doubled relating to 700 bar compressed hydrogen. The higher volumetric energy density results in lower required storage volumes. However, this liquefaction process requires additional energy consumption since the condensation point is -253 degrees Celsius. Furthermore, it needs to be stored in relatively expensive cryogenic tanks to maintain its liquid phase. Then, the hydrogen can be evaporated onboard before use in an internal combustion engine or fuel cell to power ships. Liquid hydrogen production is in a mature state, but there is currently little experience around its use in the maritime sector (Gruber et al., 2019; Samavati et al., 2018). Liquid hydrogen production and storage could occur in the Amsterdam port (Maritime consultant, personal communication, 25-3-2020).

Companies

H2Ships project

Action

Further analysed in the multi-criteria analysis of this research because there is much interest in hydrogen in Amsterdam.

Carbon hydrogen-based marine fuels

Assessed hydrogen-based marine fuels that contain carbon are formic acid, e-diesel, e-LNG, and e-methanol.

Formic acid

Description

Formic acid is initially used in the textile, pharmaceutical and food industry. During the last years, there is growing interest in formic acid for fuel purposes. This liquid could serve as a source of hydrogen or could directly be used in fuel cells. Formic acid can be produced via a zero-emission synthesis process wherein carbon dioxide is combined with clean hydrogen. Beneficial are its non-toxicity, low flammability and possible integration in current diesel infrastructure. Research is going on the further development of formic acid as a fuel, and the first commercial activities are arising (Götz et al., 2016). DENS is a start-up in the Netherlands that commercially sell formic acid to the construction sector. There is interest in expanding their business to the marine sector on the long-term whereby the planned CO_2 infrastructure in the Amsterdam port could offer opportunities (DENS, personal communication, 2-4-2020).

Companies

DENS

Action

Long-term potential as formic acid has favourable characteristics to the maritime sector. However, more research and development is required.

E-diesel

Description

Diesel can also be made via renewable energy sources such as wind and solar. This process consists of combining clean hydrogen and CO_2 in a Fischer Tropsch synthesis reactor. The CO_2 could be captured from the atmosphere or carbon-emitting factories. Resulting e-diesel has the same characteristics as fossil diesel which eliminates investments costs for vessels (Horvath et al., 2018). Gasunie, EBN, Port of Amsterdam and Tata steel are currently investigating the opportunities for CO_2 infrastructure including CO_2 capture. These developments could be beneficial for electric fuels in the Amsterdam port (Maritime consultant, personal communication, 25-3-2020). However, e-diesel production processes are costly, and combustion causes pollution. Therefore, the prospects of this marine fuel are low on short-term.

Companies

-

Action

Long-term potential as e-diesel has the same characteristics as fossil diesel.

E-LNG

Description

LNG produced via renewable electricity is also an option for the marine sector as it could be used in regular LNG infrastructure. This synthetic fuel is formed out of renewable hydrogen and CO_2 in a methanation process. The required CO_2 or CO needs to be retrieved from an external source. This fuel is directly applicable to conventional marine LNG engines. Drawbacks of e-LNG are its relatively low efficiency and high costs. Different pilots involving this fuel have occurred, but the technology is still in an early development phase (Horvath et al., 2018). Further, LNG could leak during production and combustion processes which has a greenhouse gas impact. The estimation is that this fuel is not economically feasible before 2040 for coastal and deep-sea vessels (Hobson & Márquez, 2018).

Companies

-

Action

Long-term potential as it could be a successor of fossil and bio LNG. However, substantial developments are required.

E-methanol

Description

E-methanol a synthetic fuel just as e-diesel and e-LNG and is made from the same basic requirements, clean hydrogen and captured CO_2. These molecules are combined in a methanol synthesis process, after which e-methanol is formed (Giddey et al., 2017; Lan et al., 2012). This marine fuel is not yet widely adopted, but there is, unlike e-diesel and e-LNG, commercial production by CRI in Iceland and Innogy in Germany (Ryste, 2019). The Amsterdam port offers suitable production and storage locations for e-methanol, whereby the planned CO_2 infrastructure could play an essential role. This marine fuel is most interesting for coastal shipping (Maritime consultant, personal communication, 24-3-2020).

Companies

Vattenfall, BioMCN, CRI (Iceland), Innogy (Germany)

Action

Further analysed in the multi-criteria analysis of this research because commercial production already exists whereby its potential is confirmed.

Zero-carbon hydrogen-based marine fuels

Assessed hydrogen-based marine fuels that do not contain carbon are ammonia, iron powder, sodium borohydride and liquid organic hydrogen carriers.

Ammonia

Description

Ammonia is a widely produced compound mainly destined for the fertilizer and chemical industry. Ammonia is now primarily produced via natural gas but can also be formed by combining renewable hydrogen and nitrogen in a Haber-Bosch process. For application as a marine fuel, hydrogen could be recovered onboard, or ammonia could directly be used in solid oxide fuel cells. Green ammonia production and the use of solid oxide fuel cells is not very mature yet (Teichmann et al., 2012). Ammonia can easily be liquefied and is carbon-free. Drawbacks are the lack of infrastructure and its toxicity (von Wild et al., 2010). This toxicity is the main barrier for the production and storage possibilities of ammonia in the Amsterdam port. The marine sector is not used to this compound which could cause accidents that affect the city of Amsterdam. However, there is a lobby from the commodity sector and several large shipping companies, which could stimulate development for the use of ammonia as a marine fuel (Maritime consultant, personal communication, 19-3-2020; Maritime consultant, personal communication, 24-3-2020)

Companies

MAN Energy Solutions, Wärtsilä and C-Job are developing ammonia engines. Pilot projects for ammonia powered vessels in Norway and Japan.

Action

No further action due to its severe toxicity risks. Methanol is discussed, analysed and compared with ammonia in internal sessions at Port of Amsterdam. Methanol is preferred above ammonia from technological, economic and environmental perspectives. The only strength of ammonia is its non-carbon nature. At the moment, research is going on the safety measures related to the bunkering of ammonia. The use of ammonia as a marine fuel has to be discouraged if the outcomes confirm the toxicity issues.

Liquid organic hydrogen carriers

Description

Hydrogen can also be stored in liquid organic hydrogen carriers (LOHC's) such as toluene and benzene. Hydrogen is bonded to the carrier in a hydro generation reactor and decomposed in dehydrogenation reactor whereto it could be used in internal combustion engines or fuel cells to power vessels. The liquid phase of LOHC's enables efficient and safe handling in the current infrastructure of liquid fossil fuels (Vopak, 2019). The volumetric energy density up to 70 kg H_2 per m^3 is comparable to liquid hydrogen (Lloyds Register, 2018). Vopak has signed an agreement to invest in the development of LOHC's, which could theoretically lead to storage in Amsterdam (Mao & Gregory, 2015; Muir & Yao, 2011). Besides, H2-Industries and Lloyd's Register have started a collaboration to develop an electric vessel with LOHC technology (TU Delft, n.d.). There are no developments known regarding LOHC's for marine application in the Netherlands which makes this potential fuel unlikely to play a role around 2030 in the Amsterdam port.

Companies

Vopak

Action

Long-term potential if the development of LOHC's makes them more attractive from an economic point of view.

Iron powder

Description

Iron powder is a metal hydrogen carrier. Iron powder can be combusted onboard to generate heat which is used to drive a turbine for vessel propulsion. The leftover rust can, off-board, be upgraded to iron powder in combination with hydrogen. This circular process requires one-time extraction of iron. There is not any carbon involved in these reactions, which eliminates GHG emissions. Nitrogen oxide, sulphur oxide and PM emissions are also minimal, which makes this fuel beneficial from an environmental perspective. The volumetric energy density of iron powder is better than conventional fossil fuels. However, a huge downside is the low gravimetric energy density which requires additional buoyancy of vessels. Iron powder is developed by a Dutch student team called Team Solid. Opportunities for Port of Amsterdam are there as an iron powder production, storage and bunker system could fit in the port (Team Solid, personal communication, 21-4-2020).

Companies

Team Solid

Action

Long-term potential if the issues around the low gravimetric energy density can be solved.

Sodium borohydride

Description

Sodium borohydride is a metal hydrogen carrier which could be used as a marine fuel. Its solid-state eliminates the need for high-pressure vessels or cryogenic tanks. Sodium borohydride is produced by combining sodium metaborate with hydrogen and decomposed in a hydrolysis process. The US Department of Energy disqualified this compound as a potential transportation fuel in 2007. However, much research has been done on the reaction catalysts since then what resulted in higher hydrogen storage capacity and lower cost processes (TU Delft, n.d.). The TU Delft and H2Fuel-Systems BV, both located in the Netherlands, are focussing on the use of this carbon-free fuel in the marine sector (TU Delft, n.d.). Furthermore, production, storage and bunkering of $NaBH_4$ fits in current safety contours of Port of Amsterdam.

Companies

TU Delft, H2Fuel-Systems BV

Action

Further analysed in the multi-criteria analysis of this research because of the particular interest of Port of Amsterdam as their new port authority vessel will be fueled with sodium borohydride.

Appendix II

This appendix includes the selected and unselected criteria for this research. These are presented in Table 31. The selected criteria are pointed out in green.

Table 31: Selected and unselected assessment criteria

Criteria	Sub-criteria	Number of times mentioned in interviews	Notes
Scalability	Availability of primary inputs	III	
	Added value Amsterdam port	II	
	Synergies with other industries		
Technological	Maturity	I	
	Reliability		
	Energy efficiency	II	
	Energy density	I	Including volumetric and gravimetric energy density
Economic	Infrastructure	5	
	Cost of disruption		Integrated in the sub-criterium Infrastructure
	Propulsion system cost	7	
	Retrofit adaptation		
	Marine fuel cost	6	
	Cost of lost cargo space	II	Integrated in the sub-criterium Energy density
Environmental	GHG emissions	IIII	Including CO_2, CH_4 and N_2O
	SO_x reduction	IIII	Integrated in the sub-criterium Local pollution
	NO_x reduction	IIII	Integrated in the sub-criterium Local pollution
	PM reduction	IIII	Integrated in the sub-criterium Local pollution
	Safety	IIII	
Social-political	Social acceptability	III	
	Governmental support	I	
	Political feasibility		Integrated in the sub-criterium Governmental support
	Regulations	III	
	Job creation		

(GtZ, 2020; Hansson et al., 2019; Ren & Lützen, 2017; Slaper & Hall, 2011)

Appendix III

This appendix contains the internal and external interview templates. Both templates have been further specified according to the type of company and expertise of the interviewee.

Internal interview template

Name: … *(XX-XX-2020)*

Company: Port of Amsterdam
Department: …
Position: …

Introduction study program and research

Step 1) Selection of alternative marine fuels

- Which alternative marine fuels have the highest potential for Port of Amsterdam and why?
- What do you think about the following alternative fuels?
  - Ammonia
  - Biobased marine fuels
  - Compressed and liquid hydrogen
  - LNG
  - Methanol
  - Synthetic fuels
  - Other fuels (Formic acid, Iron powder, Sodium borohydride ($NaBH_4$))
- On which term are these fuels going to play a role in the maritime and port sector?

Step 2) Selection of production pathways

- What are attractive production pathways for alternative fuels in the Amsterdam port?
- What parts of the supply chain related to alternative fuels could be commercially attractive to Port of Amsterdam? (Production, storage, bunkering, ship building for instance)
- What could be barriers to the development and adoption process of alternative marine fuels?

Step 3) Selection of stakeholders

- What stakeholders could have valuable input to this research?
- How willing are the stakeholders to make the transition to alternative fuels?
- How do deep-sea, coastal, and inland vessels differ on the applicability of alternative fuels?

Step 4) Selection of criteria

- What criteria are essential in assessing alternative marine fuels?

Any other comments on or questions about this research?

External interview template

Name: … *(XX-XX-2020)*

Company: Biofuel company (example)
Department: …
Position: …

Introduction study program and research

- Can you explain your background and position in the company?
- Can you explain about the main activities of your company?

Step 1) Selection of alternative marine fuels

- Currently, your company is producing FAME biodiesel. Is FAME the future biofuel? Or do you think that other biofuels might be more interesting for the maritime sector?
- Which other biofuels are under development at your company?
- Currently, biofuels are mainly blended with fossil fuels. How big is the step to vessel propulsion based on 100% biofuels?
- Sufficient available sustainable feedstock is a global concern related to biofuels. What do you think about that? How easy is to increase volumes?
- Synthetic fuels and biofuels are both alternatives for fossil bunker fuels. How do you expect the development and competition between those two fuels types?
- What specific synthetic fuels is your company focussing on? And why?

Step 2) Selection of production pathways

- How do the (future) fuel production pathways look like?

Step 3) Selection of stakeholders

- Do you notice a growing interest in biofuels? How come?
- What could Port of Amsterdam do to accelerate/ support the development of alternative fuels?
- What are the advantages or barriers to the development of alternative fuels of Amsterdam? (In comparison with Rotterdam or other ports)
- Does your company work together with other organisation in the development of alternative fuels?

Step 5) Criteria scores

- What are the main challenges for your company regarding the infrastructure of alternative fuels?
- How do you expect the price development of biofuels in the next decade?

Any other comments on or questions about this research?

Appendix IV

The results of the survey per respondent are given in the tables beneath. The criteria are judged via pairwise comparison. The scale starts with 1, *equally important*, and ends with 5, *strongly more important*. Inconsistent judgments, judgements with a consistency ratio higher than 0.1, are not approved for this research and are not used for the definition of the weight factors.

Table 32: Results of the survey per respondent - Main criteria

			Main criteria			
	Scalability	Technology	Economics	Environment	Social-political	Weights
Scalability	1.00	4.00	0.33	1.00	1.00	0.20
Technological	0.25	1.00	0.33	0.33	0.33	0.07
Economics	3.00	3.00	1.00	1.00	2.00	0.34
Environmental	1.00	3.00	1.00	1.00	0.33	0.19
Social-political	1.00	1.00	0.50	3.00	1.00	0.20
					CR =	*0.06*

			Main criteria			
	Scalability	Technology	Economics	Environment	Social-political	Weights
Scalability	1.00	3.00	0.25	0.25	3.00	0.14
Technological	0.33	1.00	0.25	0.25	0.33	0.06
Economics	4.00	4.00	1.00	4.00	4.00	0.47
Environment	4.00	4.00	0.25	1.00	4.00	0.27
Social-political	0.33	0.33	0.25	0.25	1.00	0.06
					CR =	*0.05*

			Main criteria			
	Scalability	Technology	Economics	Environment	Social-political	Weights
Scalability	1.00	3.00	0.50	3.00	4.00	0.29
Technological	0.33	1.00	0.33	3.00	4.00	0.17
Economics	2.00	3.00	1.00	3.00	4.00	0.38
Environmental	0.33	0.33	0.33	1.00	3.00	0.10
Social-political	0.25	0.25	0.25	0.33	1.00	0.06
					CR =	*0.07*

			Main criteria			
	Scalability	Technology	Economics	Environment	Social-political	Weights
Scalability	1.00	0.25	3.00	0.25	4.00	0.14
Technological	4.00	1.00	4.00	1.00	5.00	0.37
Economics	0.33	0.25	1.00	0.25	1.00	0.07
Environmental	4.00	1.00	4.00	1.00	4.00	0.35
Social-political	0.25	0.25	1.00	0.25	1.00	0.07
					CR =	*0.07*

Main criteria						
	Scalability	Technology	Economics	Environment	Social-political	Weights
Scalability	1.00	2.00	0.33	0.50	0.50	0.12
Technological	0.50	1.00	0.25	0.50	2.00	0.11
Economics	3.00	4.00	1.00	1.00	4.00	0.37
Environment	2.00	2.00	1.00	1.00	1.00	0.23
Social-political	2.00	2.00	0.25	1.00	1.00	0.17
					CR =	*0.17*

Main criteria						
	Scalability	Technology	Economics	Environment	Social-political	Weights
Scalability	1.00	4.00	3.00	0.25	2.00	0.23
Technological	0.25	1.00	0.33	0.25	0.33	0.06
Economics	0.33	3.00	1.00	0.25	2.00	0.14
Environmental	4.00	4.00	4.00	1.00	4.00	0.49
Social-political	0.50	0.50	0.50	0.25	1.00	0.08
					CR =	*0.02*

Main criteria						
	Scalability	Technology	Economics	Environment	Social-political	Weights
Scalability	1.00	0.20	4.00	0.20	1.00	0.09
Technological	5.00	1.00	5.00	0.25	4.00	0.26
Economics	0.25	0.20	1.00	0.20	0.25	0.04
Environmental	5.00	4.00	5.00	1.00	5.00	0.47
Social-political	1.00	1.00	4.00	0.20	1.00	0.13
					CR =	*0.20*

Table 33: Results of the survey per respondent - Sub-criteria - Scalability

Sub-criteria - Scalability			
	Availability	Added value Amsterdam port	Weights
Availability	1.00	1.00	0.50
Added value Amsterdam port	1.00	1.00	0.50
		CR =	*0.00*

Sub-criteria - Scalability			
	Availability	Added value Amsterdam port	Weights
Availability	1.00	3.00	0.75
Added value Amsterdam port	0.33	1.00	0.25
		CR =	*0.00*

Sub-criteria - Scalability			
	Availability	Added value Amsterdam port	Weights
Availability	1.00	1.00	0.50

Added value Amsterdam port	1.00	1.00	0.50
		CR =	*0.00*

Sub-criteria - Scalability			
	Availability	Added value Amsterdam port	Weights
Availability	1.00	4.00	0.80
Added value Amsterdam port	0.25	1.00	0.20
		CR =	*0.00*

Sub-criteria - Scalability			
	Availability	Added value Amsterdam port	Weights
Availability	1.00	0.50	0.33
Added value Amsterdam port	2.00	1.00	0.67
		CR =	*0.00*

Sub-criteria - Scalability			
	Availability	Added value Amsterdam port	Weights
Availability	1.00	1.00	0.50
Added value Amsterdam port	1.00	1.00	0.50
		CR =	*0.00*

Sub-criteria - Scalability			
	Availability	Added value Amsterdam port	Weights
Availability	1.00	4.00	0.80
Added value Amsterdam port	0.25	1.00	0.20
		CR =	*0.00*

Table 34: Results of the survey per respondent - Sub-criteria - Technological

Sub-criteria - Technological				
	Maturity	Energy efficiency	Energy density	Weights
Maturity	1.00	3.00	2.00	0.55
Energy efficiency	0.33	1.00	2.00	0.26
Energy density	0.50	0.50	1.00	0.19
			CR =	*0.12*

Sub-criteria - Technological				
	Maturity	Energy efficiency	Energy density	Weights
Maturity	1.00	0.33	0.33	0.14
Energy efficiency	3.00	1.00	1.00	0.43
Energy density	3.00	1.00	1.00	0.43
			CR =	*0.00*

Sub-criteria - Technological

	Maturity	Energy efficiency	Energy density	Weights
Maturity	1.00	0.50	2.00	0.33
Energy efficiency	2.00	1.00	1.00	0.41
Energy density	0.50	1.00	1.00	0.26
			CR =	*0.21*

	Sub-criteria - Technological			
	Maturity	Energy efficiency	Energy density	Weights
Maturity	1.00	0.50	0.25	0.15
Energy efficiency	2.00	1.00	1.00	0.38
Energy density	4.00	1.00	1.00	0.47
			CR =	*0.05*

	Sub-criteria - Technological			
	Maturity	Energy efficiency	Energy density	Weights
Maturity	1.00	2.00	2.00	0.49
Energy efficiency	0.50	1.00	0.50	0.20
Energy density	0.50	2.00	1.00	0.31
			CR =	*0.05*

	Sub-criteria - Technological			
	Maturity	Energy efficiency	Energy density	Weights
Maturity	1.00	0.50	0.20	0.12
Energy efficiency	2.00	1.00	0.25	0.20
Energy density	5.00	4.00	1.00	0.68
			CR =	*0.02*

	Sub-criteria - Technological			
	Maturity	Energy efficiency	Energy density	Weights
Maturity	1.00	0.33	0.20	0.10
Energy efficiency	3.00	1.00	0.20	0.20
Energy density	5.00	5.00	1.00	0.70
			CR =	*0.12*

Table 35: Results of the survey per respondent - Sub-criteria - Economics

	Sub-criteria - Economics			
	Infrastructure	Propulsion system cost	Marine fuel cost	Weights
Infrastructure	1.00	2.00	2.00	0.49
Propulsion system cost	0.50	1.00	0.50	0.20
Marine fuel cost	0.50	2.00	1.00	0.31
			CR =	*0.05*

	Sub-criteria - Economics			

	Infrastructure	Propulsion system cost	Marine fuel cost	Weights
Infrastructure	1.00	1.00	0.33	0.20
Propulsion system cost	1.00	1.00	0.33	0.20
Marine fuel cost	3.00	3.00	1.00	0.60
			CR =	*0.00*

Sub-criteria - Economics

	Infrastructure	Propulsion system cost	Marine fuel cost	Weights
Infrastructure	1.00	1.00	1.00	0.33
Propulsion system cost	1.00	1.00	1.00	0.33
Marine fuel cost	1.00	1.00	1.00	0.33
			CR =	*0.00*

Sub-criteria - Economics

	Infrastructure	Propulsion system cost	Marine fuel cost	Weights
Infrastructure	1.00	3.00	1.00	0.42
Propulsion system cost	0.33	1.00	0.25	0.13
Marine fuel cost	1.00	4.00	1.00	0.46
			CR =	*0.01*

Sub-criteria - Economics

	Infrastructure	Propulsion system cost	Marine fuel cost	Weights
Infrastructure	1.00	2.00	1.00	0.40
Propulsion system cost	0.50	1.00	4.00	0.40
Marine fuel cost	1.00	0.25	1.00	0.20
			CR =	*0.48*

Sub-criteria - Economics

	Infrastructure	Propulsion system cost	Marine fuel cost	Weights
Infrastructure	1.00	5.00	4.00	0.66
Propulsion system cost	0.20	1.00	0.25	0.09
Marine fuel cost	0.25	4.00	1.00	0.24
			CR =	*0.48*

Sub-criteria - Economics

	Infrastructure	Propulsion system cost	Marine fuel cost	Weights
Infrastructure	1.00	0.20	0.20	0.09
Propulsion system cost	5.00	1.00	0.33	0.30
Marine fuel cost	5.00	3.00	1.00	0.62
			CR =	*0.12*

Table 36: Results of the survey per respondent - Sub-criteria - Environmental

Sub-criteria - Environmental				
	GHG emissions	Local pollutants	Safety	Weights
GHG emissions	1.00	0.50	0.25	0.13
Local pollutants	2.00	1.00	0.25	0.21
Safety	4.00	4.00	1.00	0.66
			CR =	*0.05*

Sub-criteria - Environmental				
	GHG emissions	Local pollutants	Safety	Weights
GHG emissions	1.00	3.00	0.33	0.28
Local pollutants	0.33	1.00	0.33	0.14
Safety	3.00	3.00	1.00	0.58
			CR =	*0.12*

Sub-criteria - Environmental				
	GHG emissions	Local pollutants	Safety	Weights
GHG emissions	1.00	2.00	2.00	0.49
Local pollutants	0.50	1.00	0.50	0.20
Safety	0.50	2.00	1.00	0.31
			CR =	*0.05*

Sub-criteria - Environmental				
	GHG emissions	Local pollutants	Safety	Weights
GHG emissions	1.00	1.00	1.00	0.33
Local pollutants	1.00	1.00	1.00	0.33
Safety	1.00	1.00	1.00	0.33
			CR =	*0.00*

Sub-criteria - Environmental				
	GHG emissions	Local pollutants	Safety	Weights
GHG emissions	1.00	2.00	0.25	0.21
Local pollutants	0.50	1.00	0.25	0.13
Safety	4.00	4.00	1.00	0.66
			CR =	*0.05*

Sub-criteria - Environmental				
	GHG emissions	Local pollutants	Safety	Weights
GHG emissions	1.00	0.50	0.25	0.13
Local pollutants	2.00	1.00	0.25	0.21

Safety	4.00	4.00	1.00	0.66
			CR =	*0.05*

Sub-criteria - Environmental				
	GHG emissions	Local pollutants	Safety	Weights
GHG emissions	1.00	1.00	0.25	0.17
Local pollutants	1.00	1.00	0.25	0.17
Safety	4.00	4.00	1.00	0.67
			CR =	*0.00*

Table 37: Results of the survey per respondent - Sub-criteria - Social-political

Sub-criteria - Social-political				
	Social acceptability	Governmental support	Regulations and classifications	Weights
Social acceptability	1.00	0.33	0.33	0.14
Governmental support	3.00	1.00	0.50	0.33
Regulations and classifications	3.00	2.00	1.00	0.53
			CR =	*0.05*

Sub-criteria - Social-political				
	Social acceptability	Governmental support	Regulations and classifications	Weights
Social acceptability	1.00	1.00	3.00	0.43
Governmental support	1.00	1.00	3.00	0.43
Regulations and classifications	0.33	0.33	1.00	0.14
			CR =	*0.00*

Sub-criteria - Social-political				
	Social acceptability	Governmental support	Regulations and classifications	Weights
Social acceptability	1.00	0.33	0.25	0.13
Governmental support	3.00	1.00	1.00	0.42
Regulations and classifications	4.00	1.00	1.00	0.46
			CR =	*0.01*

Sub-criteria - Social-political				
	Social acceptability	Governmental support	Regulations and classifications	Weights
Social acceptability	1.00	1.00	0.25	0.20
Governmental support	1.00	1.00	1.00	0.31
Regulations and classifications	4.00	1.00	1.00	0.49

			CR =	0.21

Sub-criteria - Social-political				
	Social acceptability	Governmental support	Regulations and classifications	Weights
Social acceptability	1.00	0.33	0.25	0.13
Governmental support	3.00	1.00	1.00	0.42
Regulations and classifications	4.00	1.00	1.00	0.46
			CR =	*0.01*

Sub-criteria - Social-political				
	Social acceptability	Governmental support	Regulations and classifications	Weights
Social acceptability	1.00	0.25	0.33	0.11
Governmental support	4.00	1.00	4.00	0.65
Regulations and classifications	3.00	0.25	1.00	0.24
			CR =	*0.12*

Sub-criteria - Social-political				
	Social acceptability	Governmental support	Regulations and classifications	Weights
Social acceptability	1.00	1.00	1.00	0.33
Governmental support	1.00	1.00	1.00	0.33
Regulations and classifications	1.00	1.00	1.00	0.33
			CR =	*0.00*