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A future fuel alternative for Fugro vessels

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GRADUATION THESIS

A future fuel alternative for Fugro vessels

by

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Preface

From sails to steam and from steam to the diesel-fuelled engines we see nowadays, maritime propulsion has always been transitioning. At this moment in time, a larger and more difficult transition than ever before emerges. The transition to clean marine fuels, in order to drastically reduce the emissions of the world fleet. This transition is difficult, because the transitions in the past were fuelled by tactical advantages in naval battles or the ability to bridge larger distances more economically. Developments benefiting a navy or shipping company, whereas this transition doesn't benefit one maritime stakeholder, even more it brings difficulties to most. However, it benefits everyone living on this planet as it provides a way to make shipping sustainable and therefore requires all stakeholders to work together to come to a successful transition.

I'm content that the TU Delft and Fugro provided me with the opportunity to contribute to the transition ahead by conducting this graduation thesis. During the last year, I researched the application of alternative fuels in future Fugro vessels, as the final deliverable to obtain my Master degree in Marine Technology. I'm curious to see the road to cleaner shipping evolve and I'm hoping to be a part of that, starting with a small contribution by conducting this research.

First, I would like to thank my TU Delft supervisors. Edwin van Hassel and Koos Frouws for being very accessible and involved, even during the Covid pandemic. I'm also grateful for the feedback meetings and discussions on the topic we've had. I'm convinced that your extensive knowledge of and experience in the maritime industry proved valuable to this research. Additionally, I would like to thank Robert Hekkenberg for his questions and feedback during the last part of my graduation.

Also, I'm grateful for the opportunity to conduct this research at Fugro. Which Provides a practical environment to apply and benchmark my findings. A special thank you to Peter Toxopeüs, for helping me on a daily basis during this project, by providing the guidance, feedback and essential information this research required. But also for being a pleasant colleague and contact point at Fugro. Also, I want to thank Martijn van Helmond and Bastiaan de Jager for the supervision of this project. Your feedback and involvement were very useful for the content of this thesis and valuable for my work in general.

Moreover, I would like to thank all stakeholders at Fugro and other companies that were involved for their valued contribution by being available for interviews and participating in the stakeholder polls.

I'm thankful to my friends and family. It has been a difficult year and I'm very grateful for your support and friendship. I'd like to thank my girlfriend Kim for being there for me. And a thank you to my father, my brother and Merel for their support and help. And my nephew Oscar, for being a positive and cheerful note to last year.

Dedicated to my dear mother.

Michiel Nelissen
Rotterdam, February 2021

Abstract

To mitigate global warming, worldwide CO_2-emissions have to be cut. Similarly, the shipping industry has to drastically decrease it's emissions. Rules and regulation on emissions are becoming more stringent. Moreover, the public and clients are demanding less pollution from ship operators. While many shipping operators are looking at a suited fuel alternative, no consensus has been reached on the best alternative to entirely dispose of harmful emissions from shipping in the long-term. Fugro is one of the ship operators interested in entirely bringing down the emissions of their vessels that are built from 2030 onwards and therefore this research is conducted.

This thesis will research how and if Fugro can achieve the IMO target of 70 percent CO2 reduction in 2050, by deploying net zero-emission fuels in Fugro vessels as of 2030. An evaluation will be done to assess which alternative fuels are feasible and most suitable, based on current technologies and considering future scenarios around technology.

The research will approach this problem by firstly conducting an extensive literature research into alternative fuels and Multiple Criteria Decision Analysis methods first. Thereafter the Fugro fleet, potential future vessel developments, future scenarios and alternative fuels are researched to set up a technical framework for this case problem specifically. With this technical framework in place, the method itself is conducted. This is done in two ways. First, by conducting a more qualitative approach using the Analytic Hierarchy Process, also involving stakeholders from Fugro and the industry. Second, by carrying out a case application of the four best alternatives on a representative Fugro vessel.

This approach, including a qualitative approach extended with a more quantitative one results in a substantiated advise. Both methods complement each other on points where the other falls short. The AHP includes stakeholders and takes into account criteria that are difficult to quantify. The application approach tests the feasibility of the proposed alternatives and tests the potentially subjective or intuitive outcome of the AHP method.

With methanol scoring well in both approaches, the conclusion of this research is that methanol is the advised alternative fuel for future Fugro vessels. Liquid hydrogen is the highest rated fuel alternative from the AHP. The application example shows that this fuel isn't able to comply with the required Fugro operability however. Contrary to that, ammonia is a highly rated alternative in literature and is also scoring well in the application part of this thesis, but is not rated as a suitable alternative by stakeholders in the AHP. The last considered alternative in both parts of the method is synthetic diesel, which is comparable to MDO. This fuel scores well in both methods but is considered to remain too expensive to become a viable alternative in the coming ten years.

In this thesis, estimates of different fuel options are presented and some design concepts and considerations on the different alternative fuel applications are given. The next step for Fugro would be to work out a methanol concept, by going through the design spiral more than once and work out the design choices and challenges this fuel brings. With alternative fuels being more expensive than MDO, this thesis pointed out that the economic speed will change when using alternative fuels, which is another point that requires more research. While the AHP proved to be a suitable way to score fuel alternatives while including stakeholders and assessing criteria qualitatively, it also pointed out that it is difficult to solely base an alternative fuel advise on this method. Potentially, the AHP results would improve when the questionnaire is simplified by reducing the amount of considered criteria.

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Nomenclature

Abbreviations

AHP	-	Analytic Hierarchy Process
CAPEX	-	Capital Expenses
CBA	-	Cost-Benefit Analysis
CCS	-	Carbon Capture & Storage
CI (AHP)	-	Consistency Index
CI	-	Compression-Ignition Internal Combustion Engine
CR	-	Consistency Ratio
DF	-	Dual-Fuel (engine)
DME	-	DiMethylEther
DP	-	Dynamic Positioning
EEDI	-	Energy Efficiency Design Index
e-LNG	-	electric/synthetic Liquid Natural Gas
EMO	-	Engine Maintenance Onboard
ETS	-	Emission Trading Scheme
EU	-	European Union
FAS900	-	Fugro Autonomous Surveyor 900
FC	-	Fuel Cell
FC+R	-	Fuel Cell with Reformer
FMEA	-	Failure Mode & Effects Analysis
FOSCV	-	Fugro Offshore Coastal Survey Vessel
FSSV	-	Fugro Standard Survey Vessel
GHG	-	GreenHouse Gas
HAZOP	-	Hazard & Operability Study
HFO	-	Heavy Fuel Oil
HPCM	-	Hull & Propeller Condition Management
HT-PEMFC	-	High Temperature Proton-Exchange Membrane Fuel Cell
IBC code	-	International Bulk Chemical code
ICE	-	Internal Combustion Engine
IMO	-	International Maritime Organization
IRM	-	Inspection Repair & Maintenance
LCA	-	Life-Cycle Assessment
LNG	-	Liquid Natural Gas
LPG	-	Liquefied Petroleum Gas
MAUT	-	Multiple Attribute Utility Theory
MCA	-	Multiple-Criteria Analysis
MCDA	-	Multiple-Criteria Decision Analysis
MDO	-	Marine Diesel Oil
MGO	-	Marine Gas Oil
MSR	-	Molten-Salt Reactor
OPEX	-	Operational Expenses
PEMFC	-	Proton-Exchange Membrane Fuel Cell
PtoF	-	Power to Fuel
RE	-	Renewable Energy
RI	-	Random consistency Index
ROA	-	Real-Options Analysis
ROV	-	Remotely Operated underwater Vehicle
SAW	-	Simple Additive Weighting
SD	-	Synthetic Diesel
SEEMP	-	Ship Energy Efficiency Management Plan
SI	-	Spark-Ignition
SMR	-	Small Modular Reactor
SOFC	-	Solid-Oxide Fuel Cell
TRL	-	Technology Readiness Level
USV	-	Unmanned Survey Vessel
VPM	-	Voyage Performance Management

CO_2	-	Carbon Dioxide
CH_4	-	Methane
H_2	-	Hydrogen
LH_2	-	Liquid hydrogen
MeOH	-	Methanol
NH_3	-	Ammonia
NO_x	-	Nitrogen Oxides
SO_x	-	Sulphur Oxides

Definitions

Carbon Neutral	-	No emissions over entire Life-Cycle, tank-to-propeller emissions neutralised by carbon-negative production
Diesel-Electric	-	No direct drive, generator sets power electrical systems that drive electric propulsors
Hybrid Propulsion	-	Propulsion system driven by ICE or FC, combined with a battery pack
Net-zero emissions	-	No emissions over entire Life-Cycle, tank-to-propeller emissions neutralised by carbon-negative production

Symbols

B	-	Width	[m]
Cb	-	Block Coefficient	[-]
η_{D}	-	Propulsive Efficiency	[%]
η_{e}	-	Effective Efficiency	[%]
η_{trm}	-	Transmission Efficiency	[%]
GT	-	Gross Tonnage	[-]
h_f	-	Energy Density Fuel	[J/m^3]
k_p	-	Number of propellers	[-]
λ_{max}	-	Maximum Eigenvalue	[-]
Loa	-	Length Overall	[m]
Lpp	-	Length between Perpendicular	[m]
Lwl	-	Length Waterline	[m]
m_f	-	Fuel Flow	[m^3/day]
n	-	number of rows/columns	[-]
P_D	-	Delivered Power	[W]
P_E	-	Effective Towing Power	[W]
P_P	-	Propeller Power	[W]
Q_f	-	Heat Input	[J]
R	-	Resistance	[N]
t	-	Draft	[m]
v_S	-	Ship speed	[m/s]

1

Introduction, Problem definition & Approach

Global warming is one of the major issues that today's society has to deal with. Rules and legislation concerning the emissions of greenhouse gasses are coming into place and the public opinion that climate change must be abated is more widely heard. For these reasons, companies all over the world are looking for ways to reduce their carbon footprint.

In shipping, the call for cleaner technologies is also heard. As the maritime industry accounted for approximately 2,2% of global GreenHouse-Gas (GHG) emissions in 2012 (IMO, 2014). Until recently, most of the world fleet has been sailing using Heavy Fuel Oil (HFO), making the shipping industry a very large emitter of Nitrogen and Sulphur oxides (NO_x and SO_x). Global NO_x and SO_x emitted by all shipping represents about 15% and 13% of total global emissions respectively (IPCC, 2014). To reduce these emissions, regulation already came into place, limiting the amount of Sulphur a fuel can contain (IMO, 2020). To further reduce the emissions of the shipping sector, cleaner fuel alternatives like bio-diesel and LNG or a hybrid drive system, are increasingly being used (DNV GL, 2014). Ships that are using hybrid technology or fuels like LNG and bio-diesel are already in existence (World Maritime News, 2020) (Biofuels International Magazine, 2019). However, these are technologies that still rely on the combustion of fossil fuels that emit CO_2 when burned. In order to significantly or even completely reduce the carbon emissions of ships, other fuel alternatives must be implemented.

The maritime sector is expected to grow with 3% annually. Some scenarios see a growth in maritime energy consumption of 40-50% between 2012 and 2050. At this moment, maritime trade is responsible for 12% of total transport energy demand (Balcombe et al., 2019). For that reason, it is very important that the maritime sector adapts a more sustainable energy source.

This thesis will be carried out in cooperation with Fugro, a company that recognizes the need to carry out their operations in a more sustainable way. Fugro is the world's leading Geo-data specialist, collecting and analyzing comprehensive information about the Earth and the structures built upon it. Adopting an integrated approach that incorporates acquisition and analysis of geo-data and related advice, Fugro provides solutions. With expertise in site characterisation and asset integrity, clients are supported in the safe, sustainable and efficient design, construction and operation of their assets throughout the full life-cycle. A large part of these operations takes place at sea. Therefore, Fugro owns 26 ships to carry out and support these operations (Fugro, 2020).

The Fugro fleet consists of highly specialized and innovative vessels and is comprised of three different ship types. These are geotechnical vessels, subsea/IRM vessels and survey vessels. The geotechnical fleet is capable of deep-water drilling operations at offshore sites. Fugro owns multiple of these specialized geotechnical vessels. The second type of ship owned by Fugro, the Subsea/IRM vessels, are built to carry out tasks in the fields of subsea installation, construction support, Inspection Repair Maintenance (IRM) and decommissioning. These vessels are both owned by Fugro as well as chartered from third parties. Lastly, the biggest part of the Fugro fleet consists of survey vessels. These state-of-the-art survey vessels are divided into two categories; deep-water and coastal (up to 200m water depth) survey vessels. All of these vessel types could be applicable for a zero-emission replacement, as the whole Fugro fleet is sailing on Marine Diesel Oil (MDO) at this moment. Recently, Fugro also commissioned their first of a fleet of Unmanned Survey Vessels (USV). These vessels are all using fossil fuels.

1.1 Problem definition

Literature about cleaner alternative fuels is already widely available. However almost no examples of large-scale zero-emission alternative fuel applications in ships are present to date. Besides, it is still unclear which clean fuel alternatives will be developed further in the future and which are feasible as a large-scale propulsion fuel for ships at all. Fugro already investigated how they could reduce their carbon footprint on the short- and medium-term. Now Fugro wants to go one step beyond that and research if and how a number of vessels could operate without emitting greenhouse gasses on the long term.

Fugro is committed to several innovative programs concerning fleet development. They are a leading party in researching remotely operated shipping for example. Moreover, to mitigate climate change, Fugro set up their own sustainability program. A large part of this program focuses on the emissions of Fugro's fleet, as these emissions accounted for 79% of the company's total emissions in 2019. Therefore, it aims to drastically reduce the CO_2-emissions of this fleet. Targeting a reduction of 20% in 2025, relative to Fugro's vessel emissions in 2020. Moreover, Fugro is aiming at the IMO targets of a 40 and 70 percent reduction in 2030 and 2050 respectively (IMO, 2018a). These reduction targets are measured against a baseline of emissions in 2008, as shown in figure 1.1 below. In order to achieve this, Fugro already started short-term initiatives like bunkering bio-diesel mixes and researching shore-power connections. Besides, for the middle- to long-term, the company researches refits of existing vessels, providing the option to install hybrid propulsion installations. However, to reach the ambitious IMO goals as stated above, net zero-emission vessels are needed from 2030 onwards. Older Fugro vessels are eligible for a net zero-emission replacement at that time. Whether and how these zero-emission replacements could operate without emissions will be researched and elaborated on in this research thesis. A decision-making method will be used to evaluate which strategy on alternative fuels is best, based on current technologies, stakeholder interviews and considering future Fugro fleet and technology scenarios.

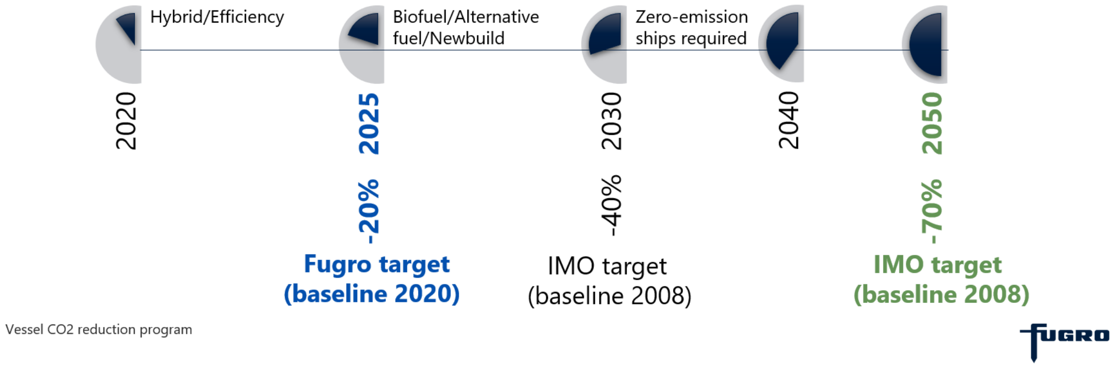


Figure 1.1: Vessel CO_2 reduction program Fugro

1.2 Research objective

This thesis will research how and if Fugro can achieve the IMO target of 70 percent CO2 reduction in 2050, by deploying net zero-emission fuels in Fugro vessels as of 2030. An evaluation will be done to assess which alternative fuels are feasible and most suitable, based on current technologies and considering future technology scenarios.

1.3 Research approach

The first part, chapter 2, of this research will elaborate on the literature study carried out to analyze available fuel alternatives in the shipping industry. Also, assessment methods and literature on future developments are investigated. As there is a wide range of alternatives available, it is key to concisely narrow down the selection to four or five suitable fuel alternatives. Each with a set of most relevant converters.

Chapter 3 contains an analysis of Fugro's fleet. Necessary to evaluate whether and how a future fuel alternative can be applied onboard of a Fugro vessel. All Fugro vessel types will be reviewed for this part of the research. During this part of the research, the operational profile of Fugro vessels will be analyzed. Port calls, range, autonomy and technical specifications of relevant vessels will be collected.

Because this study researches a long-term drastic solution to mitigate carbon-emissions, only newly commissioned Fugro vessels are considered. This research will project alternative fuel solutions on newly built vessels. These are vessels of which the building process starts after 2025. For this reason, an assessment of changing requirements with regards to the existing fleet will be made by means of interviews, Fugro vessel data, Clarkson's vessel register and available literature on legislation and CO_2-reduction measures in chapter 4.

The above-mentioned research into fleet and vessel parameters doesn't account for technological developments of alternative fuels in the long-term. These developments influence technology cost, maturity and availability and are therefore very important to make a substantiated decision. For that reason, already available forecasts in literature and the insights from the previous chapter will project developments of different fuel alternatives in shipping. These forecasts will assist in assessing the feasibility and suitability of future alternative fuels for Fugro vessels. Based on these forecasts, scenarios about availability, costs and technological readiness are made to be used in the last part of this research. In chapter 5, these scenarios are presented.

At this stage, a lot of information influencing what will be the best alternative has been established and assessed. These are including but not limited to, technological readiness, emissions, gravimetric- and volumetric density, costs and infrastructure availability of alternative fuel systems as of today. Port calls, range, autonomy, conversion suitability and technical specifications (e.g. installed power, fuel capacity, machine room size) of existing Fugro vessels are also known. Besides these present-day criteria, future parameters of these criteria will be based on developed scenarios of future prospects regarding alternative fuels. This produces a large number of varying parameters for the posed criteria, of which some are difficult to quantify at this moment in time. Technical and economic parameters change for different types of technological readiness scenarios for example. To analyze all information from this technical framework and to include all these parameters influencing a possible strategy, a structured assessment method has to be used. Therefore, the best strategy on alternative fuels will be evaluated using a decision support method. Which Multiple-Criteria Decision Analysis method is used will be elaborated on in chapter 6.

The next part of the research, stated in chapter 8, applies the Analytic Hierarchy Process (AHP) to cope with above stated problem. This method is used because of the nature of this problem. It is one of many criteria, of which some uncertain and or difficult to quantify at this stage. The AHP provides a methodology to deal with these kind of uncertain criteria outcomes. The information used to score the different alternatives in the AHP is outlined in chapter 7. Moreover, it provides the opportunity to assess and include stakeholder opinions in this problem. Lastly, it offers a way to include the different scenarios that are developed for the development and evolution of alternative fuels in the coming years.

As a second part of the solution synthesis, a case study is included in chapter 9 of this thesis. The fuels that are deemed most suitable from the executed AHP method, are applied in a case study specifically for Fugro vessels. Using the collected parameters and operational profile, the different alternatives are quantified for this case based on available information found in literature. Besides graphs that review the most important parameters of the alternative fuels, a dashboard is presented that shows how these most important parameters compare relative to the current MDO installation. Thereafter, one Fugro vessel is chosen to assess practical implications of applying alternative fuels on board of Fugro vessels. This vessel is the Fugro Offshore Coastal Survey Vessel (FOCSV). Several concepts are evaluated to investigate how vessel parameters, vessel lay-out and operational speeds change due to the application of alternative fuels. Together with the outcome of the AHP and dashboard it is believed that this provides a solid foundation to advise on a best fuel alternative to be used by Fugro vessels in the long-term.

1.4 Research relevance

This section discusses the relevance of this research thesis. A part of the relevance of this research can already be derived from the background section of this chapter, however the coming paragraphs discuss all identified parts where this study adds relevance in depth.

1.4.1 Industrial relevance

First of all, this thesis can proof relevant to Fugro when planning newbuildings. To choose a propulsion fuel when a new vessel has to be built, this thesis can be used as a reference work to base this decision on. If this thesis doesn't provide a decisive answer on one type of fuel that is considered most suitable, it still could be followed by stakeholders as a decision aid to choose a novel fuel for their ship.

As no large-scale applications of zero-emission alternative fuels are in operation as of today, many more shipping companies besides Fugro need to decide on their future alternative fuel strategy. For this reason this thesis can provide a framework to these industry players to decide on their future alternative fuel strategy.

The choice for a novel alternative fuel is dependent on a lot of stakeholders besides shipping owners, such as for instance engine manufacturers, class societies and regulators. These entities need to decide on their approach on Research & Development and novel designs to serve the market. But also port operators and fuel suppliers responsible for fuel infrastructure are of importance. Therefore, choosing a novel alternative fuel requires that all of these stakeholders need to develop a strategy. Moreover, the decision on a new fuel can be compared to the problem of chicken and egg, who embarks first on implementing which new fuel? Operators, manufacturers or regulators? Therefore, it is very important to cooperate along the whole value-chain. Even more, it can be important to state a preferred strategy, to enable other stakeholders to respond to that demand. This thesis intends to bundle different stakeholder opinions on alternative fuel criteria to motivate a feasible decision on a novel fuel technology. Besides, it can be used as a reference work if Fugro wants to state their preferred strategy on fuels to cooperate with other industry stakeholders.

1.4.2 Scientific relevance

The scientific relevance of this thesis can be found in both the alternative fuel study as the assessment method that will be chosen. The study into alternative fuels provides a case study into application of zero-emission fuels applied to this particular type of vessel. This provides an overview of available technologies, technology readiness levels and parameters important for application. Up to now, studies that assess bio-fuels and LNG as alternative fuels are mostly found in literature. Studies that assess electro-fuels in depth, taking into account stakeholders preferences can provide additional insights.

Using an assessment method to provide insight into alternative fuel choices has been done by researchers before. Substantiating the choice for a specific assessment method for this case study specifically does add to the scientific relevance however. Besides, documenting and carrying out one of the assessment methods can be relevant for science. Moreover, stakeholder opinions and case-specific parameters used in the assessment method are valuable for science. Besides, criteria that are of interest when carrying out this assessment method on alternative fuels are identified.

1.4.3 Societal relevance

While shipping is still the most efficient way of transport when considering emissions, it is a significant polluter that is responsible for about 3% of total annual CO_2-emissions. As described in the research background at the start of this chapter, it is evident that shipping emissions have to be reduced in order to achieve global CO_2-reduction goals. This thesis will research ways to reduce shipping emissions by studying cleaner alternative fuels. For that reason, this study provides to reduced global CO_2-emissions and the accompanying goals stipulated in the Paris Agreements.

1.5 Research questions

To a certain extent, the research objective can be captured in several research questions. Literature has to be collected and sought after in order to answer some of these research questions. Therefore, the research questions can aid to determine a literature search plan. These questions can be subdivided into one main question and seven sub-questions. The identified **main question** is expressed as follows:

> *What is the best fuel alternative for future Fugro vessels?*

The following **sub-questions** are identified:

- *Which alternative fuels will be considered in this research?*
- *What are the operational profile and corresponding vessel parameters of future Fugro vessels?*
- *What are the criteria influencing the decision on alternative fuels?*
- *What are future scenarios on exogenous factors, and how will these influence the choice on alternative fuels?*

- *What is the best method to score each of the criteria of different alternative fuels?*
- *How are the fuel alternatives scoring on these criteria?*
- *What is the best method to decide on the choice for an alternative fuel?*

2

Literature Study

Now that the objective and research questions of this thesis are clear, a targeted literature search can be commenced. Literature can be assessed for relevance in order to acquire information on the research topic. Of the research questions posed in section 1.5, several can already be answered using the results found during the literature study.

2.1 Search plan

The following sections will address the course of the literature research and state the relevance of each search step. The initial search, which was carried out to outline the topics researched in this thesis, is discussed first. The detailed search, elaborating on the found topics, afterwards. The literature sources will also be discussed in this section.

2.1.1 Initial search

The first step of this search plan is to investigate what research is already done on future, more sustainable alternative fuels. Using an online library in Mendeley, references on alternative fuels are bundled in a folder. The references up till now are analyzed based on a quick assessment. After these references are collected, a more thorough analysis is carried out and references that are considered useful are marked and a small summary of information is noted. Something that becomes evident fairly quickly is that quite some research has been done on this topic, but that results vary for each research and case. The reason for this variation is that many references describe that the choice for a novel alternative fuel is one of many stakeholders and different criteria. Moreover, this choice is dependent on expected future developments that constantly change over the years, becoming more unambiguous however, in recent years. Therefore, it becomes clear that this research needs a structured method in order to assess the most feasible future alternative fuel for the specific case of this thesis.

Therefore, the search plan is extended beyond alternative fuels and literature on forecasting and assessment methods is included in this literature study as well. Literature on forecasting models using agent-based simulation are found and assessed (Bas et al., 2017) (Van Vliet et al., 2010). It could add value to make assessments on the feasibility of a fuel by forecasting demand and supply of alternative fuels using agent-based models. To develop an entire agent-based model to forecast a few criteria potentially valuable to the original research objective of this study would add a lot of work. Therefore, it is decided that this would go beyond the scope and workload of this graduation thesis. Different assessment methods and literature useful for setting up future scenarios are searched however.

2.1.2 Detailed search

After the initial literature search on alternative fuel studies and assessment methods, literature on alternative fuels is searched for in more detail. This search was carried out by doing an exploratory search into alternative fuels first. This search step is both aimed at scientific literature and industry publications. It helped to get an idea of alternative fuels considered in recent years and alternative fuels that apply to this case specifically. This search step pointed out that LNG and bio-fuels have been researched extensively in the past years and are nowadays starting to get applied at a larger scale. It also pointed out that these fuels have a high CO_2-reduction potential but are not carbon-neutral and therefore not relevant to this study. Moreover, the fuels that are carbon-neutral or zero-carbon are identified. These are so called electro-fuels. Therefore, the next step is to search more specifically on the available literature for these kind of fuels. The identified fuels that were recognized are now researched separately, and the more detailed findings, concerning the state-of-the-art of the different electro-fuels for example, are stated in different sections.

As mentioned in the paragraph describing the initial search, literature about different assessment methods and literature aiding in forecasting methods and technology assessment was sought after. Other ways to forecast are found besides agent-based modelling. For example, Aronietis et al. (2016) uses literature, expert opinions and present-day bunker volumes for forecasting. Literature found on which future technology assessments, vessel developments or scenarios can be based include references about future vessel requirements, emission reduction measures, legislation and technology readiness levels. Besides the literature about future developments on which assumptions can be based, the Delphi method can be used as forecasting method as well. Therefore, a literature search on this topic is also carried out. Lastly, literature on scenario planning is assessed to be able to set up scenarios using the information on future developments found in literature, Fugro data and interviews. In that way, it is also the intention to assess and bundle existing data, stakeholder input and assumptions based on literature in order to substantiate assumptions on technology developments or changing Fugro vessel parameters.

In order to make a motivated choice considering the many criteria and uncertainties of choosing an alternative fuel, this research study also goes into different assessment methods. Literature on assessment methods and alternative fuels is found and bundled. As the choice for an alternative fuel is one of many criteria, found references often use Multiple-Criteria Decision Analysis (MCDA). Besides MCDA, more assessment methods are found and are elaborated on in order to choose the most suitable assessment method for this thesis.

2.1.3 Sources

The literature search is mostly carried out using sources found on the internet. It was difficult to visit the TU Delft, TU Delft library and other libraries due to circumstances because of the COVID-19 pandemic during the creation of this literature study. Regarding internet sources; Google Scholar, Mendeley, ScienceDirect, Springer, the TU Delft Library website and the TU Delft repository are valuable information providers on scientific literature. Moreover, Google, class societies, Ammonia Energy Association and other websites contributed most in the search for industry publications.

2.2 Exploratory literature search

First, an exploratory literature search was carried out. Many different references on alternative fuels were consulted. Of which the most useful were filtered and are set out in the following sections. These are divided in found literature and publications from scientific and industrial sources.

2.2.1 Scientific literature

Bouman et al. (2017) reviews about 150 articles concerning GHG reductions in shipping. Bouman reviewed articles published after 2009, the articles were chosen based on a qualitative analysis. Six mitigating measures were chosen to review. Of these six, one measure is relevant for this part of the research, as it entails fuel and alternative energy sources. Bouman concludes that various measures are needed to sufficiently cut GHG emissions from shipping and summarizes reduction potentials of different measures. The key take-away for this literature research is that this article provides prominent studies concerning alternative fuel and energy sources.

First of the studies referenced by Bouman that researches CO_2-abatement by utilizing alternative fuels is Eide et al. (2013). This study uses a Monte Carlo model to analyze outcomes of different abatement pathways. It provides an insight for this alternative fuel part of the study as it concludes that either bio-fuel with financial incentives or nuclear power provides the desired GHG reductions for shipping. However, it lacks the inclusion of other zero-emission fuel alternatives besides LNG, bio-fuel and nuclear.

Other prominent studies mentioned by Bouman are the second IMO study into the reduction of GHG emissions Buhaug et al. (2009) and Lindstad (2013). These studies present a large number of GHG reduction methods, but don't yet comment on other alternative fuels besides bio-fuels and LNG. It is argued that these fuels weren't relevant then as the capacity of onshore renewables wasn't sufficient at the time of reporting. Therefore, these studies are useful to provide insight in shipping emissions and necessary reductions, but lack information on zero-emission fuel replacements.

Another researcher that was found from the review of Bouman is Paul Gilbert. His research assesses full life cycle air-emissions of multiple alternative fuels (Gilbert et al., 2018). This life-cycle emission is important when considering alternative fuels in this part of the research. Because one of the most important criteria of alternative fuels in this literature study is the amount of emission per fuel alternative. While Gilbert's study is complete on the alternatives mentioned, not all known fuel alternatives are taken into account, examples of potential marine fuels not mentioned in this research are ammonia, synthetic fuels and nuclear energy.

According to Balcombe et al. (2019), bio-fuels, hydrogen, nuclear energy and carbon capture and storage (CCS) could all decarbonise much further, but each faces significant barriers around their economics, resource potentials and public acceptability. Part of this research is relevant for the study on fuel alternatives as it assesses fuel alternatives for their potential impacts. LNG, methanol/ethanol, hydrogen with fuel cells, electric and nuclear propulsion are discussed. According to Balcombe a balance between cost-effective fuels and improved efficiency measures is essential to minimize costs. Moreover he states that it is important to further consider fuels like hydrogen and nuclear in future, adding to the relevance of this research.

All above-mentioned literature considers reduction methods not only focusing on alternative fuels, but GHG reduction methods in general, of which the part on alternative fuels is useful to assess different fuel alternatives. The reduction measures can be analyzed to assess future vessel performance in a later stage of this research.

Another study referenced in the review of Bouman is (Brynolf, 2014). This study solely discusses potential alternative fuels to reduce GHG emissions. In specific, LNG, liquefied biogas (LBG), methanol and bio-methanol. Moreover, Brynolf discusses aspects to consider when choosing an alternative marine fuel. These aspects can be useful when determining alternative fuel criteria later on in this research. Alternative fuels considered in this paper, are discussed using these aspects. These are technical, economical, environmental and *other* aspects. Brynolf concludes, using a life-cycle analysis, that fuels like LNG or methanol produced from natural gas will have more-or-less the same impact on climate change as the use of fossil fuels. Fuels like LBG or bio-methanol, made from biomass, will reduce emissions, but this feedstock still has an environmental impact. Methane and methanol produced from excess electricity is briefly mentioned as a carbon neutral fuel alternative in future. However, these electro-fuels are not discussed in detail within this paper.

On these electrofuels, Vergara et al. (2012) writes; ”in fact, GHG-free sources can produce, collect and transform energy into a fuel suitable for ocean-based propulsion. These energy forms can be synthetic hydrogen-rich fuels to be used in fuel cells or thermal machinery.” On biofuels Vergara mentions that it could entail problems concerning food scarcity and deforestation, making it difficult or expensive fuels to largely apply in shipping. Vergara briefly mentions hydrogen as a fuel but sees difficulties in its low volumetric density. Lastly nuclear energy is considered as development for the far future, at this stage major issues arise concerning safety, security and nuclear waste management.

2.2.2 Industrial publications

Besides above-mentioned scientific articles, information on alternative fuels is also abundantly available from white papers published by industry. When using these sources, one should keep in mind that some publications could be biased. That is because some companies publishing literature are trying to sell or promote their preferred technology. Of the publications discussed in the following paragraphs, class societies as well as consortia cooperating with universities, can be considered relatively unbiased as they do not necessarily benefit from promoting one certain alternative. Class societies publish literature on the subject of alternative fuels to inform their clients on future developments and possibilities for instance. Literature published by fuel or propulsion system producers have to be assessed carefully as these type of companies could be biased on alternative fuel technologies to sell their own products.

DNV GL both published a presentation and white paper on the energy transition outlook. The presentation (DNV GL, 2019c) makes an interesting distinction between three ”family types”. These are fossil-, bio- and electricity-based fuels. Of these three family types, electricity-based fuels are most relevant as these are carbon-neutral or zero-carbon (Bureau Veritas, 2020). The white paper published by DNV GL (DNV GL, 2019a) is an important reference to this thesis as it provides a lot of information on different fuel types. DNV GL scores different fuel types based on price, infrastructure, regulation, scalability, environmental impact, technology, CAPEX and OPEX. Methanol can be a carbon-neutral fuel when made using hydrogen and CO_2, DNV GL is brief on this type of methanol, as it only states that it will be more expensive than methanol produced from natural gases, and thus, conventional fuels. Scalability of green methanol isn't discussed. Another electro-fuel mentioned in this white paper is hydrogen. Today, 95% of hydrogen is produced from fossil fuels but it can be produced using electrolysis powered by renewable energy. Hydrogen is costly comparable to HFO, difficult to store but very scalable as water is one of the main components of production. DNV GL uses Power to Fuel (PtoF) as a collective name for electro-fuels and foresees a significant increase in availability from 2035 onwards, and therefore believes in application from about 2030. At this moment, these fuels are costly to produce and no measures have been taken to offset this costs so far. A useful addition to this research is that DNV GL summarizes different production efficiencies of PtoF methods.

According to Korean Register (2020), the development and provision of zero-carbon or fossil-free fuels has to be pursued to enable the shipping sector to assess and consider decarbonization in the second half of the century. They recognize LNG, biofuels, ammonia, methanol, hydrogen and batteries as possible fuel alternatives. Ammonia, methanol and hydrogen are considered relevant as these fuels can be produced without emitting greenhouse gasses. Korean Register analyzes the production of carbon-neutral fuels and concludes that ammonia is cheapest to produce. The report is very specific on ammonia and provides useful information on ammonia cost, technology, scalability and production.

Other industry players that contribute to literature by publishing white papers are engine manufacturers. Especially Wärtsilä and MAN have multiple publications on alternative fuel technologies. Also ABS, John Deere and Caterpillar PON are engine manufacturers who can be contacted for information on future fuel developments and their views on this subject as potential stakeholders. However, these companies can be subjective on some topics as they benefit from selling their own or preferred technologies. At an attended webinar on bio-LNG it was noticeable that the information communicated was focused on promoting one specific kind of technology.

Moreover, industry has formed multiple knowledge centers and consortia on alternative fuels and subsequent technologies. Examples are International Transport Forum (ITF) (ITF/OECD, 2018), Methanol Institute, Hydrogen Europe, Ammonia energy association and IEA energy technology network (IEA, 2013). These references can be used for specific or additional information on characteristics of for example methanol. In the Netherlands, consortia and regulators are also active. Examples are Maritiem Kennis Centrum (MKC), the Dutch Ocean Technology Center, Platform Schone Scheepvaart, Green Deal zeevaart (GD230) and the European Union (EU). (European Commission | Institute for Energy and Transport, 2016) explores alternative fuels for shipping. In many of these consortia the TU Delft and TNO play a crucial role by providing their knowledge. (TNO, 2020). (Bergsma, ’t Hart, Pruyn, Verbeek, 2020) provides a very useful overview of alternative fuels including technology readiness. These are important contributions to this research and valuable for table 2.1. This research also contributes as different fuel prices are estimated and test cases using Dutch vessels are performed. Most recently, a Danish consortium, including Maersk, publicly announced that they will cooperate on the production and use of green methanol in future.

2.2.3 Summary

Previously stated research into alternative fuel literature can be considered exploratory. The distinction between fossil-, bio- and electro-fuels is a key take-away from above literature. Only electro-fuels will be discussed in this thesis, section 2.2.4 will emphasize on the reasoning for this decision. A summary of the information about electro-fuels found in the already discussed literature is shown in table 2.1 on the next page.

2.2.4 Conclusion

Using the distinction between different alternative fuel types, the amount of considered fuels is narrowed down for the first time. Fuels acquired from fossil feedstock, e.g. hydrogen or methanol from natural gas, can be zero-emission when tank-to-wake emissions are considered. When the well-to-tank emissions of these alternative fuels are considered however, these fuels sometimes emit more than MDO does. For that reason, in order to come up with a truly sustainable fuel alternative, it is important to consider the well-to-wake emissions of each fuel. Bio-fuels provide a more sustainable solution. However, studies considering bio-fuels all emphasize that the scalability of these fuels is difficult as these fuels need a feedstock that interferes with food production and forest conservation. Besides, most bio-fuels are not carbon-neutral when used as ship fuel.

Fuel alternatives increasingly mentioned in literature that have potential to be zero-carbon or at least carbon-neutral are so called electro-fuels. These fuels will be elaborated on further.

Author	Eide	Buhaug	Lindstad	Gilbert	Balcombe	Brynolf	Vergara	Lloyd's Register	DNV GL	Korean Register	Platform duurzame brandstoffen
Year	2013	2009	2013	2018	2018	2014	2012	2017	2016	2020	2019
Conclusion	-	Not enough renewable energy to consider production of electro-fuels	Not enough renewable energy to consider production of electro-fuels	The viability of hydrogen, or other synthetic fuels crucially depends on decarbonisation of the production process	Important to further consider fuels like hydrogen and nuclear in future, adding to the relevance of this research	Production of electro-fuels is still in its infancy, and many challenges need to be overcome before these products are brought to market on a large scale	Difficulties hydrogen storage, nuclear energy issues concerning waste and safety	Hydrogen and ammonia most promising, however costly and less payload available	Application from about 2030. At this moment, these fuels are costly to produce and no measures have been taken to offset this costs so far.	No fuel superior to other fuels. Ammonia is the relatively cheapest electro-fuel.	Before the introduction of sustainable fuels, e.g. biofuel, dedicated instruments will be necessary.
Electro-fuels	Nuclear	-	-	Renewable liquid hydrogen	Hydrogen, Nuclear	Fischer/Tropsch, DME, methane, methanol, liquid hydrogen	Hydrogen, nuclear	Batteries, hydrogen, ammonia	Fischer/Tropsch, methane, methanol, ammonia, hydrogen	Methanol, ammonia and hydrogen	Fischer/Tropsch, methane, methanol, ammonia, hydrogen

Table 2.1: Perspectives on electro-fuels from different sources

2.3 Detailed literature search - Alternative fuels

The electro-fuels to be considered are derived from table 2.1. These are nuclear, energy (batteries), hydrogen, ammonia, methane, methanol, DME, and synthetic (Fischer/Tropsch) diesel. All considered electro-fuels are synthetic carbon-neutral fuels produced using Renewable Energy (RE), water and captured nitrogen or carbon, depending on the fuel. The synthetic or electro-fuels are considered most promising for this thesis. This chapter will motivate why and which fuels will be investigated further during this thesis. The technology required to operate using electro-fuels is in some cases already fit for operation. LNG and bio-fuels will not be further considered in this research. Electro-fuels will be, and the state-of-the-art of these fuels will be discussed in the coming paragraphs and in more detail in chapter 7.

2.3.1 Nuclear

Nuclear fuels could be a possible solution for zero-emission ship propulsion. Small Modular Reactors (SMR) are technically feasible to install as ship propulsion machinery. (Jacobs, 2007) An example of such a reactor is the Molten-Salt Reactor. These MSR reactors are roughly 20% smaller, 40% less heavy and 70% cheaper than conventional Pressurized Water Reactors (PWR). The MSR reactors are also more safe than their conventional counterparts. This is, among others, because Molten-Salt Reactors don't require pressures above five bars, pressures can't increase and the salt and coolant are chemically inert (Freitas Neto et al., 2020). Chisholm et al. (2018) describes the possible failure mechanisms of a MSR. In this study he recommends that HAZOP studies and FMEA analysis need to be carried out on each of the possible source terms in a novel reactor design. By analyzing the whole reactor design in this way, it becomes possible to estimate the likelihood and frequency of hazardous event sequences. When applying nuclear propulsion systems at a larger scale, prices can be competitive to other zero-emission fuels. Capital expenses would be higher than conventional expenses on diesel installations and fuel costs would decrease. However, to be applied at large scale, legislation and policy incentives are a must. Changes in operation, crew education and safety would all incur major changes in shipping practices. This together with the public opinion on nuclear energy makes that this alternative is very difficult to implement. (Royal Academy of Engineers, 2013) Technically there are no show-stoppers in nuclear fuelled vessels, according to prof. Kloosterman of the TU Delft. To be a viable option however, large-scale application has to be considered. To achieve this in the long-term; legislators, engineers, operators and other stakeholders must cooperate in order to setup a framework in which nuclear shipping is feasible. This shift is not considered achievable in the time span this thesis focuses on.

2.3.2 Batteries

Batteries can be used as an energy-carrier in commercial shipping. At this time, the most technologically advanced battery is the Lithium-Ion battery. Because power is directly distributed to the electromotor, no additional converter is needed onboard. Therefore, the utilization of batteries can be an efficient way of zero-emission ship propulsion. Batteries can be recharged using the power grid at shore. The major downside of batteries however, is the weight and size. Compared to other fuels, batteries have a far higher volumetric [kWh/l] and gravimetric density [kWh/kg] (Lloyd's Register, 2017) (DNV GL, 2019a). For these reasons batteries are an interesting option for short-sea shipping applications. Ferries for example are suitable to operate using batteries powered by the grid (Royal Academy of Engineers, 2013). However, Fugro vessels operate worldwide often making long transits to do so. For this reason, batteries are simply not competitive or even feasible for this type of vessels. Battery systems that are able to store sufficient amounts of power would be too large, heavy and costly. Therefore batteries are not assessed in this thesis.

2.3.3 Hydrogen

One of the zero-carbon alternative fuels that is often-mentioned in literature is hydrogen. It can be stored as a gas, a liquid at cryogenic conditions or as a solid using Sodium Borohydride. When produced using Renewable Energy (RE), hydrogen is a fuel that entirely takes away emissions. This form of hydrogen-production is not yet existent on a large-scale (Refhyne, 2020). While hydrogen is the most easy to produce and therefore cheapest fuel alternative, a drawback that is often mentioned in literature is the low volumetric energy density of this fuel. Hydrogen can be used in both Fuel Cells (FC) and Internal Combustion Engines (ICE) (DNV GL, 2019a), (Royal Academy of Engineers, 2013), this is elaborated on in chapter 7.

2.3.4 Ammonia

A more dense hydrogen-carrier that can be used as ship fuel is ammonia. It can be produced carbon-neutral using excess nitrogen and Renewable Energy (Korean Register, 2020). Ammonia is already being produced on a large scale as an industrial commodity, this form is not produced without life-cycle emissions however. Multiple consortiums are researching ammonia as future alternative fuel. (Ammonia Energy Association, 2020a) (Ammonia Energy Association, 2020b). It can be used in both Fuel Cells and Internal Combustion Engines. Applications are under development (MAN, 2019). One of the problems to be coped with when applying ammonia, is the high toxicity and potential damage to the environment of this substance.

2.3.5 Hydrocarbon fuels

Another potential pathway to more sustainable fuels is the use of synthetic fuels. These synthetic fuels consist of hydrocarbons that are produced using RE. In literature, these fuels are also often referred to as power-to-gas/liquids/fuel, electro-fuel, e-fuel or synthetic fuel. These fuels are produced using hydrogen from RE electrolysis and captured or stored CO/CO_2. The mixture of hydrogen, carbon mono-oxide and carbon dioxide is called syngas. Using syngas, several synthetic fuels can be produced. These are methanol, ethanol, methane, DiMethylEther (DME) and synthetic diesel (Transport Environment, 2018). Due to carbon capture and fuel synthesis, more energy on top of the already required energy for electrolysis is needed. However, the production and application of these types of fuel is beneficial as it requires no extra storage space relative to conventional MDO and it can be used with existing infrastructure. Fuel synthesis and carbon capture are relatively unknown technologies that haven't been used at a large scale up until now. Therefore the technology readiness levels are not yet mature enough for large-scale production. Because of the technology maturity and the required electricity, synthetic fuels are more costly than conventional fuels. Financial incentives are necessary to encourage investments in this type of fuel. Multiple sources expect the application of this fuel from 2030 onwards.(DNV GL, 2019a), (Royal Academy of Engineers, 2013), (ITF/OECD, 2018) The technological challenges of hydrocarbon fuels are mostly present in the synthesis of these fuels. Just like hydrogen and ammonia, methanol, ethanol and DME are already available on a large-scale. However, these fuels have a polluting production process at this moment. To produce green hydrocarbon fuels, other refinement technologies are required in order to be produced. Again, renewable hydrogen is also necessary to produce hydrocarbon fuels. Most of the required technologies to produce hydrocarbon fuels are already demonstrated in existing refinement processes.

However, the whole production chain of hydrocarbon fuels shows a TRL that complies to the validation of the process, but no demonstration of a system prototype yet. Consulted references expect no commercial production facilities until 2025.(Malins, 2017), (Landälv et al., 2017), (Schmidt et al., 2016) Vessels sailing on clean hydrocarbon fuels are not yet in operation, as there are no significant amounts of electro-fuels available for shipping yet. When there is, different vessels require different technologies to use different hydrocarbon fuels. Synthetic diesel can be used in ICE's currently used by the largest part of the world-fleet. Methanol would require an adjusted ICE, which is already operational on a German ferry. (Stena-line, 2015) Ethanol is not yet used in ship engines, but has been used in diesel engines for road transport. DME/methane would require the same dual-fuel installations already operating on existing LNG-vessels. Some hydrocarbon fuels like methanol are also being researched to be used in Fuel Cells to achieve higher efficiencies compared to existing ICE's.(Ellis & Tanneberger, 2015)

2.3.6 Summary

Using table 2.2 below, the properties of all stated electro-fuels that will be assessed in this thesis, are summarized. Technological readiness, storage and fuel costs are shown. The values for different fuel properties shown in table 2.2 are acquired from the literature reviewed in this chapter. A more thorough review of the alternatives that are considered in this study can be found in chapter 7.

Fuel	Converter	TRL 2030	Fuel cost 2030			Fuel storage			
		Fuel production	DNV GL ($/MWh)	Brynolf literature study (€/MWh)	Brynolf reference scenario (€/MWh)	Mass energy density (MJ/kg)	Volume energy density (MJ/L)	Storage pressure (bar)	Storage temperature (deg C)
MDO	ICE					∼45,6	∼36		
Hydrogen	FC / ICE	10	80-155			120	8,5	1	-252,8
Ammonia	FC + R / ICE	6-8	140-180			18,6	12,7	1	-33,6
Methane	ICE	6-8	120-195	10-641	100-290	55,6	25	1	-160
Methanol	FC / ICE	6-9	130-215	60-400	100-260	19,9	15,8	1	amb
Ethanol	ICE					26,8	24	1	amb
DME	ICE			110-173	100-310	28,4	19,3	1	amb
FT Diesel	ICE	6-9	130-210	45-3500	110-340	∼45,6	∼36	1	amb

Table 2.2: Electro-fuel properties

2.3.7 Conclusion

From the previous paragraphs it can be concluded that there are challenges concerning technologies to use or produce alternative fuels. However, the biggest challenges lay in the production infrastructure (e.g. large-scale production of RE), costs and the implementation on ships of these kind of fuels. For an electro-fuel to be adopted, it is therefore important that the whole value-chain is cooperating. For that reason it is identified that the choice for an alternative electro-fuel incurs many stakeholders and different criteria. A structured method to assess the different fuel options is important for that reason.

2.4 Detailed literature search - Assessment methods

The problem of choosing a novel fuel technology is one of many considerations. Economic, technological, political and societal aspects all influence the decision on a certain alternative fuel.

Even more difficult is that the relevant aspects that influence this strategy choice are subject to high uncertainty. This uncertainty comes forth from developing technologies and not yet existing legislation for example. In order to make a motivated choice it is therefore important to consistently assess and/or score the available alternatives. This can be done using different methods, of which the ones considered most relevant will be discussed in this chapter. First, the method of making Decision Trees will be assessed. Thereafter, Cost-Benefit Analysis (CBA) and Real-Options Analysis (ROA) will be discussed as potential financial assessment methods. Then, the Life-Cycle Analysis (LCA) will be treated. Afterwards, the Even-Swap Method will be discussed. Lastly, this study will elaborate on Multiple Criteria Decision Analysis (MCDA) methods.

2.4.1 Decision Trees

A decision tree is a graph that shows different paths leading to different nodes. Square nodes often showing a decision, round nodes showing a chance-event. The goal of this tree is a more clear and concise overview of different alternatives and accompanying attributes. Using the tree-like structure of this graph, the difficult decision is divided into smaller decisions that are more easy to be made. Moreover, the decision tree can be used to analyze which paths lead to achieving a certain goal, in this case choosing a novel alternative fuel. The goal when using this overview is to simplify a decision-making procedure.(Harvard Business Review, n.d.) In this thesis, a decision-tree could map the different fuel alternatives and their converters in an orderly manner. Also, it could be used to qualitatively state emissions or costs of different alternatives, using round nodes to show possible emission legislation or cost incentives.

2.4.2 Cost-Benefit Analysis

A Cost-Benefit Analysis (CBA) is a tool often used to assess investment choices in the transport sector. CBA is used to score different alternatives on their monetised cost in comparison to their benefits, like emission reductions in the case of this thesis. Future costs and benefits of a certain choice, and thus present value, are calculated using a discounted cash flow (Mishan, 1971). CBA is explained in detail and compared to multiple-criteria analysis methods for sustainability assessments by Beria et al. (2012). It states that one of the disadvantages of CBA is that some intangible aspects are difficult or not possible to monetise. On the other side, it can be beneficial for large projects concerning sustainability. Moreover, CBA could be used together with an MCDA method - which will be discussed later - to acquire a deeper analysis of a decision problem.

2.4.3 Real-Options Analysis

CBA as explained above, uses a discounted cash flow in order to assess future costs and benefit of different alternatives. This discounted cash flow is assumed under uncertainty. This assumption is taken away by Real-Options Analysis (ROA). ROA also uses a monetizing approach to decide on future strategy choices, adding flexibility compared to CBA. ROA enables to differ, abandon or expand investments and therefore eliminates the choice of one assumed discount rate. This is done by performing multiple evaluations of the investment along time. According to Buurman and Babovic (2016) ROA can positively add to flexibility while evaluating costs and benefits of different alternatives. It requires that information can be quantified however. According to Bowman and Moskowitz (2001) ROA provides a formal quantitative valuation model without taking the strategic side into consideration. Besides a financial analysis, strategic analysis are also very important when assessing Renewable Energy problems.

2.4.4 Life-Cycle Assessment

The Life-Cycle Assessment (LCA) method approximates the performance of a product along it's lifetime. This could be environmental impact or costs for example. In the case of environmental impact it is important to note that LCA provides a way to look at the well-to-wake emissions of an alternative. In that way, the sustainability of an alternative can be assessed thoroughly. The lifetime of a product entails the material acquisition, production, use and disposal of the product. (Christiansen et al., 1995) A study by Brynolf (2014) assesses fuel alternatives environmental performance using a LCA method. In the case of this thesis, the alternative fuel or necessary converter could be scored on environmental impact based on a LCA method. As LCA is only capable of environmental indicators, it is not capable of fully achieving a sustainability analysis of different alternatives. (Campos-Guzmán et al., 2019)

2.4.5 Even-Swap method

The Even-Swap method provides a coherent framework to make decisions. Based on a consequences table that is set up showing all different alternatives and consequences of the different objectives. This table can be used to provide a clear overview of different alternatives and their parameters. (Hammond et al., 1998) It can be stated that this is a simplified Multiple-Criteria Decision Analysis method as it assesses different criteria and their quantitative/qualitative score, but doesn't provide a decisive calculation method but depends on the (subjective) decisions of the problem-owner carrying out this procedure.

2.4.6 MCDA

Multiple-Criteria Decision Analysis (MCDA) or Multiple-Attribute Decision Making (MADM) is a discipline that aims to provide decision makers a tool to choose an optimal solution for a problem that entails multiple, sometimes conflicting, criteria.(Tzeng & Huang, 2011) ”Multi-Criteria Analysis (MCA) models and methods naturally gained an increasing relevance and acceptance in the appraisal of energy technologies and policies in a vast range of energy planning problems at different decision levels (strategic, tactical, operational) and timeframes (from long-term planning to near real-time control) (Greco et al., 2016).” Both of these references state that MCDA methods are useful to assess problems in the field relevant for this thesis. The appraisal of a novel energy carrier with multiple interests and stakeholders. Compared to most of the earlier-mentioned methods, MCDA methods entail economic, technical, environmental and social criteria. Because of the integration of these different criteria, MCDA methods have the capacity to aid decision-making in sustainability problems. (Jeswani et al., 2010) MCDA methods can be somewhat less decisive on technical criteria and can therefore be combined with LCA to adress this weakness. (Campos-Guzmán et al., 2019) Another shortcoming of MCDA methods is that it not provides a framework to deal with uncertainty. For this reason, MCDA can be combined with scenario planning. (Ram et al., 2011) The steps in a MCDA can be roughly summarized as follows: (Dubios & Prade, 1980) (Tzeng & Huang, 2011)

1. Define the nature of the decision problem.
2. Develop a hierarchy system for this decision problem.
3. Select an appropriate evaluation model.
4. Obtain the relative weights and performance score of each attribute with respect to each alternative, based on literature and stakeholders in this case.
5. Determine the best alternative using chosen method.

6. Extra outranking step when results are fuzzy.

2.4.7 Summary

The considered assessment methods discussed in this chapter are summarized on the next page in table 2.3. A short description is presented together with advantages and limitations of each method.

2.4.8 Conclusion

The problem of choosing an alternative fuel is one of multiple stakeholders and a wide range of criteria. This makes MCDA a more preferred method compared to the other stated methods. CBA and ROA enable the assessment of mostly financial criteria, in which some intangible criteria of this problem are not taken into account. LCA only considers the environmental indicators, but can aid in quantifying the environmental criteria of a MCDA. Answering the fourth subquestion stated in section 1.5, CBA, ROA and LCA can be used to score criteria concerning costs and environmental impact. Especially an LCA can be very beneficial as it is important to take into account all emissions along the value chain of a fuel alternative. From well-to-wake. MCDA methods are considered useful to provide a framework when decisions on multiple, often conflicting, objectives have to be made. Advantages of MCDA are that it takes economic, technical, environmental and social criteria into account and provide ways to deal with subjectivity in decision making. Uncertainty can be dealt with by adding different scenarios to a MCDA method and analyse the difference in outcome of the MCDA iterations. By reviewing the literature regarding different assessment methods, it can be concluded that MCDA is the best suited method to aid in the decision for a new alternative fuel choice for Fugro.

2.5 Conclusion

This literature study was commenced in order to get an overview of the research topics of this thesis. Moreover, it assisted in identifying a methodology to carry out this research in a structured way. The foremost part of this literature study however, lays in the fact that this study could give answers on some research questions posted in order to achieve the objective.

The sub-questions that can be or are answered using found literature are the following; First, the alternative fuels that are considered in the research are identified by searching and assessing relevant literature. The scope of this thesis is narrowed down to a smaller amount of alternative fuels, only electro-fuels will be considered. Moreover, the decision on the best method to assess these different alternative fuels is narrowed down to different MCDA methods. The criteria influencing the choice for an alternative fuel are mostly found in literature discussed in this report, but also dependent on stakeholder interviews. The score of different criteria will be largely determined using the literature mentioned in the alternative fuel parts of this research study. Also, some criteria within the MCDA method can be scored using other assessment methods discussed in this report, these are CBA, ROA or LCA for example. Future scenarios can not yet be entirely set up based on assessed literature, but the literature found will play a key-role in doing so. Scenarios will be based on expert opinions and data as well. For that reason, found literature on scenario planning and the Delphi method will be used to correctly carry out this research. Moreover, literature to underpin assumptions about future vessel designs and parameters was discussed. Together with found Fugro data and information from stakeholders, this partially answers the question on future operational profile and parameters of Fugro vessels. Therefore, it can be concluded that this literature study is of significant importance in assessing the most feasible alternative fuel for Fugro.

The thesis itself will continue to elaborate on found literature and use the literature to analyze case-specific data and process expert opinions to acquire the necessary information to achieve the goal of this thesis.

Method	Description	Advantages	Limitations
Decision Trees	Tree-like structure consisting of branches and nodes giving an overview of different events leading to different decisions	- Clear organization of different alternatives and decisions - Difficult decision is subdivided in multiple smaller, easier decisions - Abilitiy to include exogenous events to implement scenario's	- No implementation of quantitive methods to score alternatives - No criteria weighing by different stakeholders - Small change in start of tree can have large impact on structure of tree
Cost-Benefit Analysis	Assesment of investment choices by scoring monetized cost in comparison to their benefits	- Utility of investment is analyzed to assess whether alternative is suitable - Cost versus sustainability can be thoroughly investigated - Possible to combine with some MCDA methods	- Difficult to monetise intangible aspects of an alternative - Each iteration only takes one discount rate into account - Hard to include technical parameters and technology readiness - No criteria weighing by different stakeholders
Real-Options Analysis	Comparable to CBA but with more evaluations of investment along time, producing a kind of CBA tree	- Including evaluations provides possibility to add scenarios to ROA - Multiple discount rates can be applied in one iteration - Flexible method	- Formal quantitative method, doesn't consider strategic side of decision - Difficult to monetise intangible aspects of an alternative - No criteria weighing by different stakeholders
Life-Cycle Assessment	Approximates the performance of an alternative along it's lifetime. Acquisition, production and disposal	- Entire sustainability score of an alternative is taken into account concisively using this method - Can be combined with other assessment methods	- Can take only one set of criteria into account at once - Difficult to implement scenarios - No criteria weighing by different stakeholders
Even-Swap Method	Decision table to get an overview of different alternatives and their scores	- Overview to score and show different alternatives and their criteria - Multiple criteria can be scored and included in this method	- No decisive calculation method to continue when criteria and alternatives are mapped - No criteria weighing by different stakeholders
Multiple-Criteria Decision Analysis	Tool to choose an optimal decision on a problem consisting of multiple, conflicting criteria, using stakeholder input	- Multiple criteria can be scored and used in this tool to choose the best alternative - LCA, CBA can be included to score criteria - Scenarios can be included to run the tool several times - Stakeholders can weigh criteria in order to decide on the best alternative	- No framework provided to deal with uncertainty - When not combined with LCA, difficult to score technical criteria

Table 2.3: Different assessment methods

3

Fugro Fleet

Multiple carbon-neutral alternative fuels can be solutions to operate ships sustainable in future. However, not one fuel is the best candidate as each alternative has specific advantages and drawbacks. For that reason, the best fuel alternative is case specific and has to be investigated for each application specifically. This thesis investigates the best fuel for Fugro vessels. To be a case specific solution, it has to be tailored to the vessels Fugro is operating. Therefore, Fugro's fleet is researched and this chapter will outline and present the acquired results about Fugro's fleet. This information forms a part of the technical framework behind the choice for the best fuel alternative for Fugro.

First, the fleet will be analyzed to investigate what kind of fleet Fugro is operating. Thereafter, the operational database required to set up the operational profile is presented. This is done because the operational profile is one of the most important vessel parameters to base a design choice, or in this case a alternative fuel study, on. This data is to be used in the case study of the method of this thesis. While this data is collected for all Fugro vessels, a set of most representative Fugro vessels is chosen to collect detailed information. This to narrow down the scope and to bring about the most suitable vessels to base the case study on. Lastly, the acquired parameters deemed necessary as technical framework are discussed for these vessels.

3.1 Fleet details

Fugro manages a range of 26 specialized vessels, of which 23 are owned by Fugro. The vessels range from 224 to 9285 tons displacement and fulfill a variety of operations. As also mentioned in the Introduction, these are subdivided in different divisions; geotechnical site characterization, geophysical site characterization and asset integrity.

The division of geophysical site characterization comprises of a fleet that is capable of deep-water drilling operations at offshore sites. Fugro owns six of these specialized geophysical vessels. Three of these vessels were purpose-built between 2009 and 2015 and are the largest of the Fugro fleet. Three smaller and older vessels were bought and converted to carry out geophysical operations.

The second division is asset integrity. The fleet of this division comprises of Subsea/IRM vessels which are built to carry out tasks in the fields of subsea installation, construction support, Inspection Repair Maintenance (IRM) and decommissioning. These vessels are both owned by Fugro as well as chartered from third parties. The four vessels in this division are all built between 2007 and 2015 and are slightly smaller than the drilling vessels mentioned above. One of these vessels was purpose-built by Fugro, the other three were bought.

Lastly, the biggest part of the Fugro fleet consists of sixteen survey vessels. These fall within the business called site characterization geotechnical. All types of geodata operations are carried out by this branch, being the main difference that the earth or seabed isn't touched during these operations. Arrays and various types of equipment are used to carry out different tasks. The vessels used by this branch are state-of-the-art survey vessels divided into two categories; deep-water and coastal (up to 200m water depth) survey vessels. The build year of this part of the fleet ranges from 1982 to 2017. A large part of this division consists of purpose-built vessels. Most recently Fugro built their own two classes of survey vessels, the FSSV65 (Fugro Standard Survey Vessel) and FOCSV (Fugro Offshore Coastal Survey Vessel). The other vessels in this division are both purpose-built as well as converted survey vessels ranging from 225 to 3600 m^3 displacement.

3.2 Vessel operational database

The choice for the best alternative fuel is dependent on the vessel type. Therefore the suitability of an alternative depends on the parameters of the specific vessel. Besides design parameters like length or installed power, operational parameters are also important for the choice of a novel fuel alternative. This section will discuss the database that Fugro maintains and that is used in this thesis to get an insight into operational parameters of the Fugro fleet. Operational parameters that are useful to assess are about autonomy, fuel consumption, operating modes and corresponding speeds. These parameters are useful to decide whether a specific fuel alternative is capable of achieving the required power output and autonomy.

A wide range of data of the vessels that are managed by Fugro is recorded on a daily basis. This data is aggregated in a database that Fugro made available for this thesis. This database holds numbers on consumables, crew, fuel bunkers, operating mode and location for example. These values are based on input from daily reports filed by the vessel crews. The database runs from January 2018 up till June 2020. With minor modifications and operations, this data holds the operational parameters that are deemed useful for this research. The following paragraphs will describe how fuel consumption, time in different operating modes and the amount of port calls were acquired to aid in the comparison between suitable future alternative fuels later on.

The propulsion installation will demand different power outputs and subsequent fuel quantities depending on the mode in which it is operating. Fuel consumption in different modes can be acquired from the database. This is important to calculate the fuel consumption using different alternatives. The modes of which the fuel consumption is determined are the same modes that Fugro uses in their daily log system. These are alongside, anchor, DP out of ops, operation and transit. The definitions of the different operating modes are shown in table 3.1 below. The database only holds one number on fuel consumption per 24 hours, not dependent on the mode. If a vessel has been in transit for six hours and in operation for 18 hours it is therefore not possible to figure out the fuel consumption during those two modes individually. To find the fuel consumption for each mode specifically, a column was added to the database that identifies a mode when in effect for 24 hours. Using input of time spent in a mode for 24 hours and the total fuel consumption during that 24 hours, the average fuel consumption for that mode that time can be calculated. When a ship is in transit for 24 hours, also the average transit speed during those hours is logged. This to see if the speed in practice is comparable to design speeds of the fleet. Using this method, a table is obtained that shows the average fuel consumption for each vessel in different modes and counts the amount of 24 hour events that were used to acquire this average. This table can be filtered for vessel, year and operating mode.

One of the parameters that can also be acquired from the database is the amount of time spent in total in different modes. Being one of the most important parameters of the operational profile, this

Mode	Description
Alongside	Vessel alongside in port
At anchor	Vessel idle at anchor
DP out of ops	Dynamic Positioning while idling
Operation	Vessel in operation, e.g. surveying or sub-sea works
Transit	Vessel in transit

Table 3.1: Vessel modes

aids in making assumptions on operational spans, but also the occurrence of transits for example. These amounts are summed hours that were logged in different daily reports over the years, this doesn't need to concern 24-hour events only. The amount of time that vessels were and weren't available for work is summed and logged. The percentage of time available for work and the percentages of time spent in different modes are calculated using the total hours in a year. The outcome of the total hours and percentages are also shown in tables. Using these values, the operational profile of different Fugro vessels can be investigated, the resulting operational profile will be discussed in the following section. It is also possible to filter these tables on vessel, year and operating mode. The operational requirements for a novel fuel alternative can be derived using these values. Downtime of the conventional installation can be analyzed as well as the duration of high or low power demands can be assessed in this way. Moreover, it aids in the assessment of fuel consumption as described in the previous paragraph.

Another important parameter that was acquired from the database are the port calls of Fugro vessels. This parameter is important to know where and how often Fugro vessels could be bunkered. If a period of hours is registered as alongside in the database, it can be assumed that the vessel is alongside in port. If this is the case, the date of the first day in port and the port itself are added to a column in the database. This data is then used as input for a table. These tables show the amount of port calls in the specified duration, as well as the average, minimal and maximal amount of days between port calls. This data is available for all ships and is used to acquire insight into the amount of port calls and thus, operational profile. This results in an assessment of the autonomy of Fugro vessels. This assists in the assessment of bunker times and availability of different fuel alternatives.

3.3 Operational profile

Using the database as described in the previous section, an assessment of the operational profile based on historical data of Fugro vessels can be made. In this way, different fuel alternatives can be compared on their ability to satisfy the operational requirements of Fugro vessels. For each vessel, the time spent in different modes is shown in the tables. Moreover, charts show the different durations in operational modes, dependent on the selected vessels, years and modes. Also, the time available for work and the time spent in different modes of all ships combined is plotted in a stacked column.

Vessel-specific values on operability will be looked into at a later stage of this research. Looking

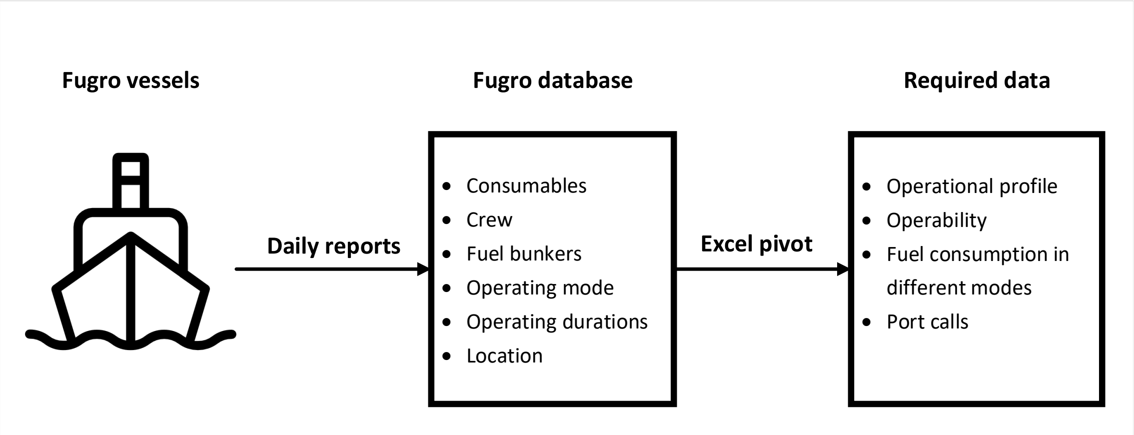


Figure 3.1: Fugro database to operational data

into fleet-wide specifics on operability, the following two graphs are obtained. These show that all Fugro vessels were available for work between 85 and 90 percent in 2018, 2019 and the first half of 2020. The other time, not available for work, is due to planned maintenance or downtime due to breakdowns, poor planning or other incidents. When looking at the operational profile of the entire Fugro fleet over all years, graph 3.2 show the following average time share between operating modes; Alongside in port (31%), at anchor (6%), in DP out of operations (3%), in operation (44%) and in transit (16%). Again these values show an average fleet-wide. This provides an estimate on the operational profile that Fugro vessels have. This operational profile can be assessed later on in this research to analyze how well different fuel alternatives are able to perform under a comparable operational profile.

Another important aspect of the operational profile is the operational load of the propulsion installations of the Fugro fleet. To compare different fuel alternatives, this could be of importance to assess whether the propulsion installations are suited to perform under these conditions. A large part of the Fugro fleet is equipped with Dynamic Positioning (DP) capabilities for example. During operations and when in DP out of operations, these capabilities need to be facilitated by the propulsion installation. Moreover, many Fugro vessels carry out operations in which surveys are carried out at speeds between 3 and 4 knots. The instruments used don't incur a high load to be towed however. Based on 1406 entries of 24-hour transit events, an average transit speed of 8,5 knots is obtained. When alongside or at anchor, only hotel facilities need to be powered by the propulsion installation. Again, using the obtained data, transit speeds and operational loads of some vessels specifically will be assessed later.

The last part important to the operational profile is the area of operation of the Fugro fleet. The Fugro fleet works worldwide on different projects. As opposed to the most freight ships, that are sailing on more or less fixed routes. This could be of importance when investigating fuel availability in different regions and to be able to make an assessment of the required endurance. Therefore it is also important to look at the amount of time between port calls. As these port calls were also found from the database, an assessment on endurance could be made based on the available data. On average, it was found that all vessels make a port call each fifteen days because of consumables and crew changes. The vessel parameters show that a larger autonomy would easily be possible.

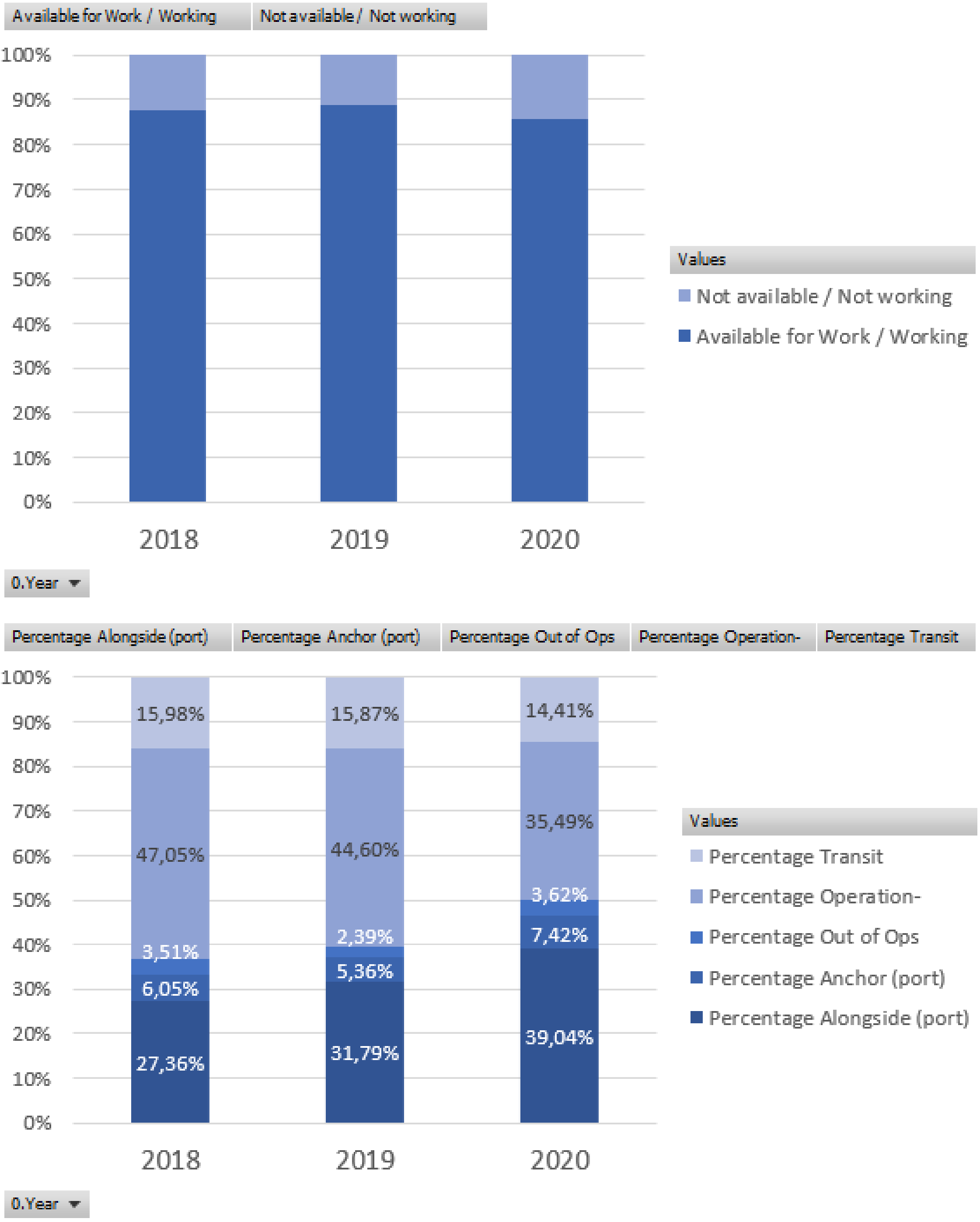


Figure 3.2: Fleetwide operability

3.4 Vessel parameters

Of all vessels in Fugro management, a table was set up containing relevant vessel parameters in order to get an overview of the Fugro fleet and subsequently chart the requirements for the alternative fuels. Moreover, these vessel parameters are to be used as a base case later on in this research. Firstly, the division, name and if applicable, the vessel type were reported. The year of build and area of operation are also shown. The main parameters, like length, breadth, draught and displacement are all recorded in this table. To assess the installed power, drive configuration and redundancy, the amount of engines and power of the propulsion installations was noted. Lastly, the fuel type, which is MDO for all Fugro vessels, and fuel tank capacity was recorded. These parameters can be used in endurance calculations later.

As described in section 3.2, the average fuel consumption for each vessel in different modes is acquired using the daily data of the Fugro fleet. These values are also shown in the vessel parameters database. These values for fuel consumption enable multiple calculations on energy usage and endurance of the entire Fugro fleet. The energy usage in different modes can be calculated because the MDO consumption is known. Moreover, based on the time spent in different operational modes, an average fuel consumption over all modes can be calculated. Using the fuel storage capacity and the average fuel consumption overall or transit fuel consumption, the endurance in days in transit or average operational profile is calculated for each vessel. In a later section, these values will be assessed in detail for the relevant vessels. This data is of importance to compare to the possible performance of the fuel alternatives.

3.5 Baseline vessels

To narrow down the scope and to make sure that this solution is tailor-made for the most relevant Fugro vessels, a selection of baseline vessels is presented in this paragraph. Only these vessels will be assessed in detail. The most important dimensions, the propulsion arrangement and operational profile are presented. These parameters are deemed most important as they decide, among other things, how much space is available for an alternative, how the propulsion arrangement has to be altered and to calculate fuel consumption. Of the 26 vessels owned by Fugro, some are converted, some are purpose-built. Fugro owns a wide variety of different vessel types, almost all of the vessels built from 2009 onwards belong to different purpose-built classes of vessels. Older vessels are often one-of-a-kind and/or converted from already existing vessels. The purpose-built vessel classes will be used as reference vessels to base vessel parameters on. These parameters can be used to set up different case studies for the alternative fuels. These vessel classes and their main parameters are shown in table 3.2. These specific vessels are chosen to assess in detail for two reasons; First of all, these are the most modern vessels owned and operated by Fugro. Secondly, these vessels are purpose-built by Fugro specifically for the tasks these vessels have to carry out. Assuming the operations carried out by these vessels will be more or less the same in ten years, these vessel designs can be used as baseline. The identified classes are two drilling vessel types, two types of survey vessel types and a subsea vessel. These vessel classes will be elaborated on in the coming paragraphs. The fuel consumption and autonomy of the baseline vessels is shown in table 3.3.

Type	**Year**	**Length [m]**	**Beam [m]**	**Draft [m]**	**Displ. [m3]**	**Total installed power [kW]**	**Fuel capacity [m3]**	**Average transit speed [kts]**	**Design speed [kts]**
FOCSV	2014	53,7	12,5	3,1	1149	1488	244-305	8,5	10
FSSV65	2010-2013	66,7	14,0	4,2	1850-1920	3752	375	8,4	10
FSSV65+	2017	71,5	15,4	5,6	2888	4210	464	9,9	10
Drilling	2013-2015	82,9	19,8	5,7	7076	7920	800	10,2	11-12
Drilling+	2009	103,7	19,7	6,3	9285	10940	1357	9,4	10-12
SubSea	2015	82,6	18,0	5,5	5421	5590	1059	(-)	11

Table 3.2: Baseline vessel parameters

Type	Fuel cons Alongside [m3/day]	Fuel cons Anchor [m3/day]	Fuel cons DP Out of Ops [m3/day]	Fuel cons Operations [m3/day]	Fuel cons Transit [m3/day]	Autonomy average fuel [days]	Autonomy transit [days]
FOCSV	0,86	0,98	1,49	2,00	4,84	131-164	50-63
FSSV65	1,78	2,11	2,19	3,84	7,58	96	49
FSSV65+	1,44	1,50	0,00	3,34	7,97	140	58
Drilling	3,60	3,89	10,03	12,02	15,25	78	52
Drilling+	4,66	0,00	9,41	10,67	20,88	125	65
SubSea	2,21	3,05	0,00	5,68	10,50	169	101

Table 3.3: Fuel consumption and autonomy

3.5.1 FOCSV

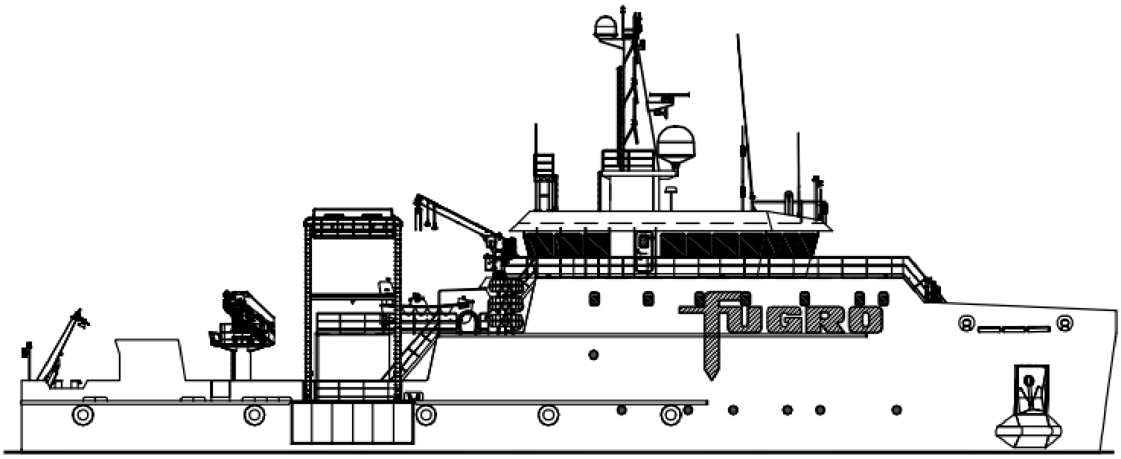


Figure 3.3: Fugro Offshore Coastal Survey Vessel (FOCSV)

The first class of vessels discussed are the Fugro Offshore Coastal Survey Vessels (FOCSV). These vessels were specifically built in 2014 to carry out geotechnical and to a lesser extent, geophysical operations. A draft measuring only 3 meters, makes these vessels suitable to operate in coastal areas. With a displacement of 1500 m^3, these vessels belong to the smaller vessels owned by Fugro. All vessels in this class are equipped with four 372kW generator sets, which propel two steerable thrusters and one bow tunnel thruster. In total these four generator sets provide 1488 kW. In this class, two vessels are equipped with DP0, one vessel has DP1 capabilities. Fuel capacities vary from 244 to 306 m^3. A summary of these vessel parameters and fuel consumption is found in tables 3.2 and 3.3 respectively. The operational times are shown in figure 3.5.

When looking at the fuel consumption of the FOCSV class, two information sources are relevant. Firstly, vessel data sheets provide values for fuel consumption. Secondly the values retrieved from the database as described in 3.2 provide numbers on the fuel consumption of these vessels. The retrieved values from both the brochure and database differ. Regarding fuel consumption in transit, the database shows a lower value, this is because transit speeds are mostly lower than ten knots in actual practice. A difference in fuel consumption during operations can also be seen, this could be attributed to the commercial nature of the data sheets. Moreover, two different dynamics positioning fuel consumptions were found, the fuel usage from data shows a value when out of operations, while the data sheet shows a number when stationairy, possibly during operations. For alongside and anchor modes, the database values are leading in this case.

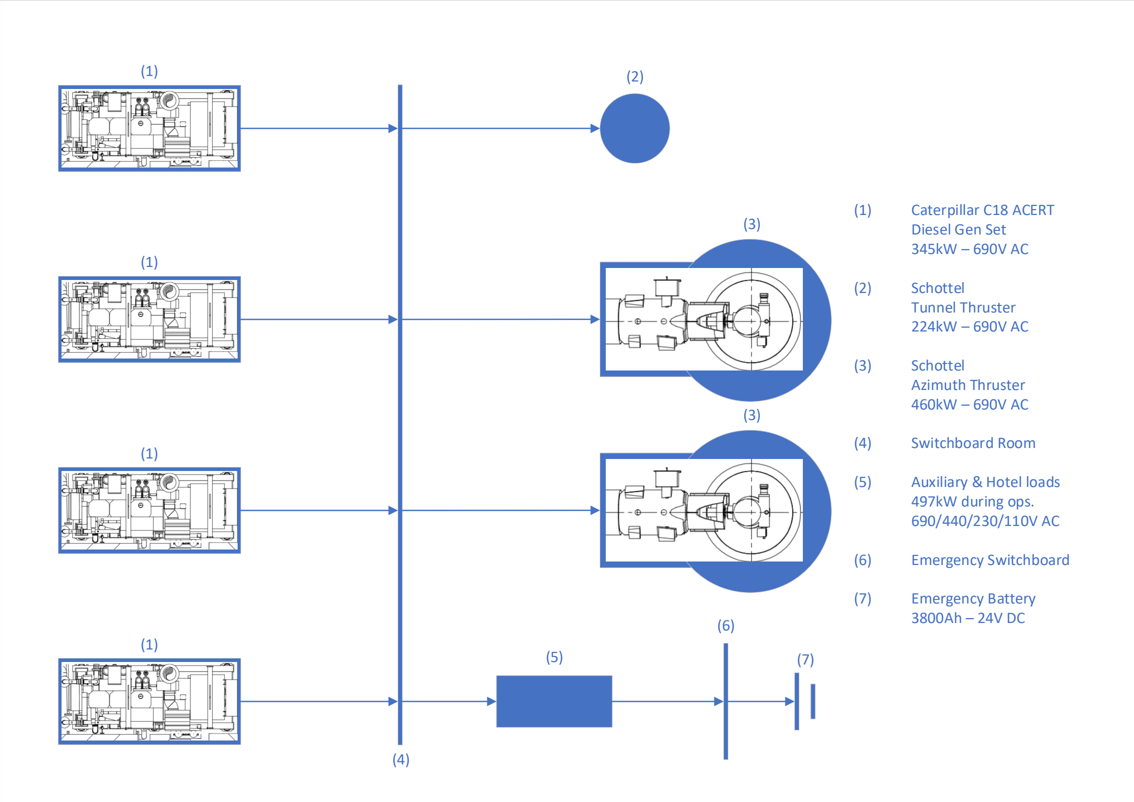


Figure 3.4: FOCSV propulsion arrangement

When looking at the operability of the FOCSV, it can be seen that these vessels have been out of service due to planned maintenance alternately the previous three years. On average, these three vessels were available to work 95% of the time since january 2018. When operational, 9% of the time is spent in transit. Approximately 52% is operational time, the vessels are at anchor and in DP out of ops 6% and 3% of the time respectively. These time approximates are also shown in figure 3.5 below.

Considering the autonomy of the FOCSV it is found that this type of vessel could sail in transit at the found average speed for 50 to 63 days, depending on the tank volume. When looking at the operational mode time percentages and the corresponding fuel consumption values that were found, an average fuel consumption can be assumed. Illustrated by a simplified example, this would mean when the vessel sailed with a fuel consumption of 1 for 3 days and 10 for 7 days, the average fuel consumption would be $(3*1+7*10)/10 = 7.3\,\frac{1}{day}$. In the same way, an average fuel consumption was calculated for all vessels. Calculated using the tank volume, the FOCSV could operate for 131 to 164 days on this average fuel consumption. This applies to the autonomy when only looking at the fuel volumes. However, often crew changes and provisions are leading in the duration of each cycle a vessel is out of port. At Fugro, crew changes are usually performed every four weeks. Moreover, the port calls could be retrieved from the database. This shows that the vessels in the FOCSV class make a port call every 13 days on average.

3.5.2 FSSV65

Another class of dedicated modern survey vessels is the Fugro Standard Survey Vessel (FSSV65). Also built to carry out geotechnical operations and if required also capable of carrying out geophysical tasks. This vessel class consists of five vessels. Four of which were built between 2010 and

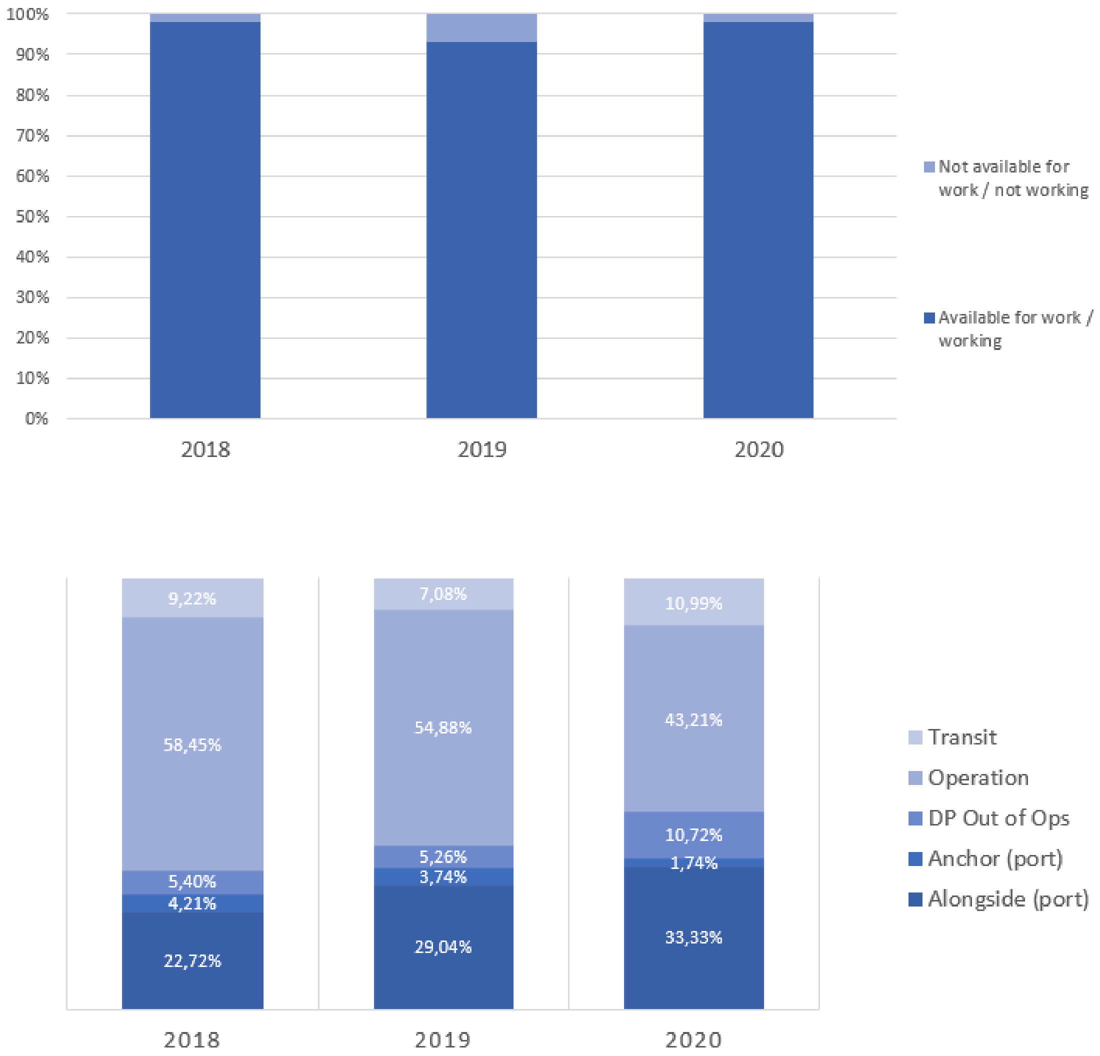


Figure 3.5: FOCSV operability and operational mode percentages

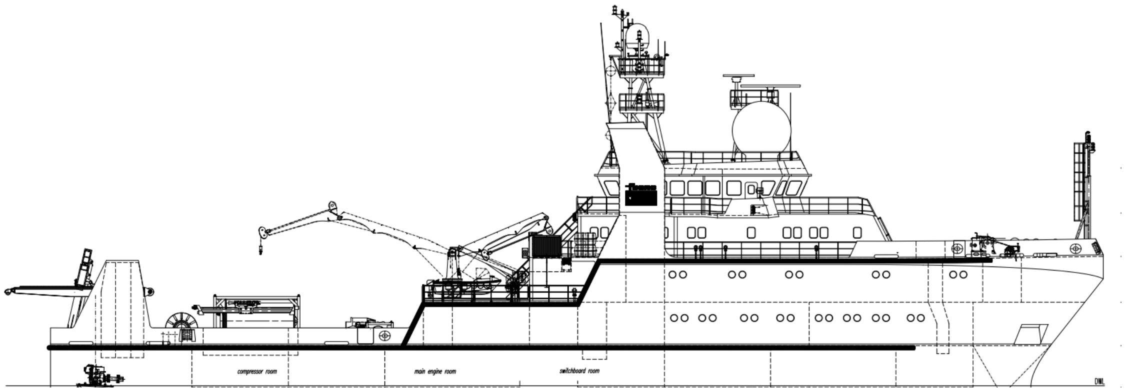


Figure 3.6: Fugro Standard Survey Vessel FSSV

2013. These four vessels are almost identical and have a displacement of approximately 1900 m^3. In 2017, Fugro built the fifth vessel of this class, the Fugro Venturer. This is a further development of the previous four vessels which has a larger displacement of 2880 m^3. The vessels have a variety in engine configurations, with installed power ranging from 2900 to 3550 kW. All propulsion configurations are diesel-electric with two steerable thrusters and a bow tunnel thruster. DP1 capabilities are present on all ships in this class. The four older vessels have a fuel capacity of 375 m^3, Fugro Venturer has a fuel capacity of 464 m^3.

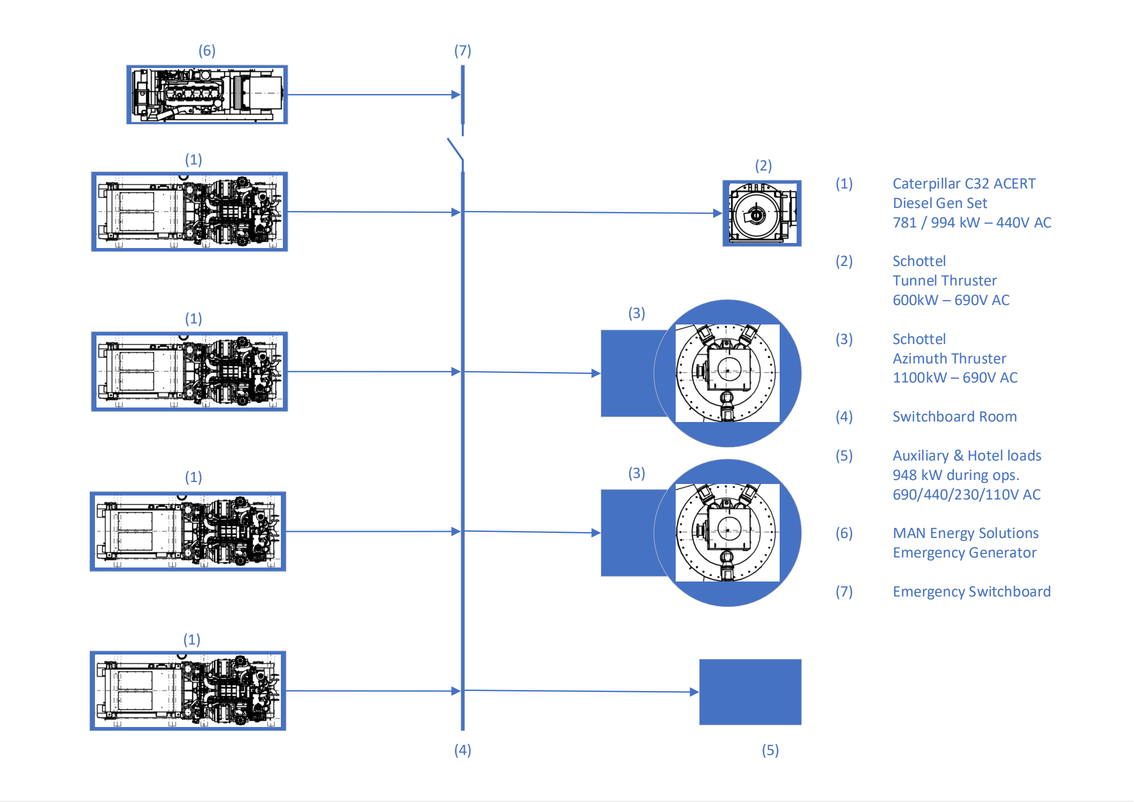


Figure 3.7: FSSV65 propulsion arrangement

No fuel parameters are available in the data sheets of the FSSV65 vessels. For that reason, the fuel consumption is approximated by the available data from the values as explained in section 3.2. As these vessels have different propulsion installations installed, it is difficult to compare the fuel usage values. The values are close enough to each other to possibly use the average as a benchmark of energy usage of a similar vessel as the FSSV65 class. The exact values are shown in table 3.3.

As also shown in figure 3.8 underneath, the operability is about 95% and therefore very similar to that of the FOCSV. Non-availability is again caused by planned maintenance and possible breakdown. Time spent in different modes is comparable to those as stated in subsection 3.5.1. However time in operation is less, this is compensated by more time spent alongside in port and transit. It can be noticed that the time spent in operations still remains behind to the previous years, this could be due to the fact that 2020 is shown till May and thus only ranges along the winter months. The COVID-19 pandemic could be a reason as well.

Using the average operational fuel consumption per day, this vessel class would have an average autonomy of 96 to 140 days. In transit, the autonomy is 49 to 58 days at the average transit speed in practice. According to the acquired data, this class of vessels calls at a port each sixteen days on average.

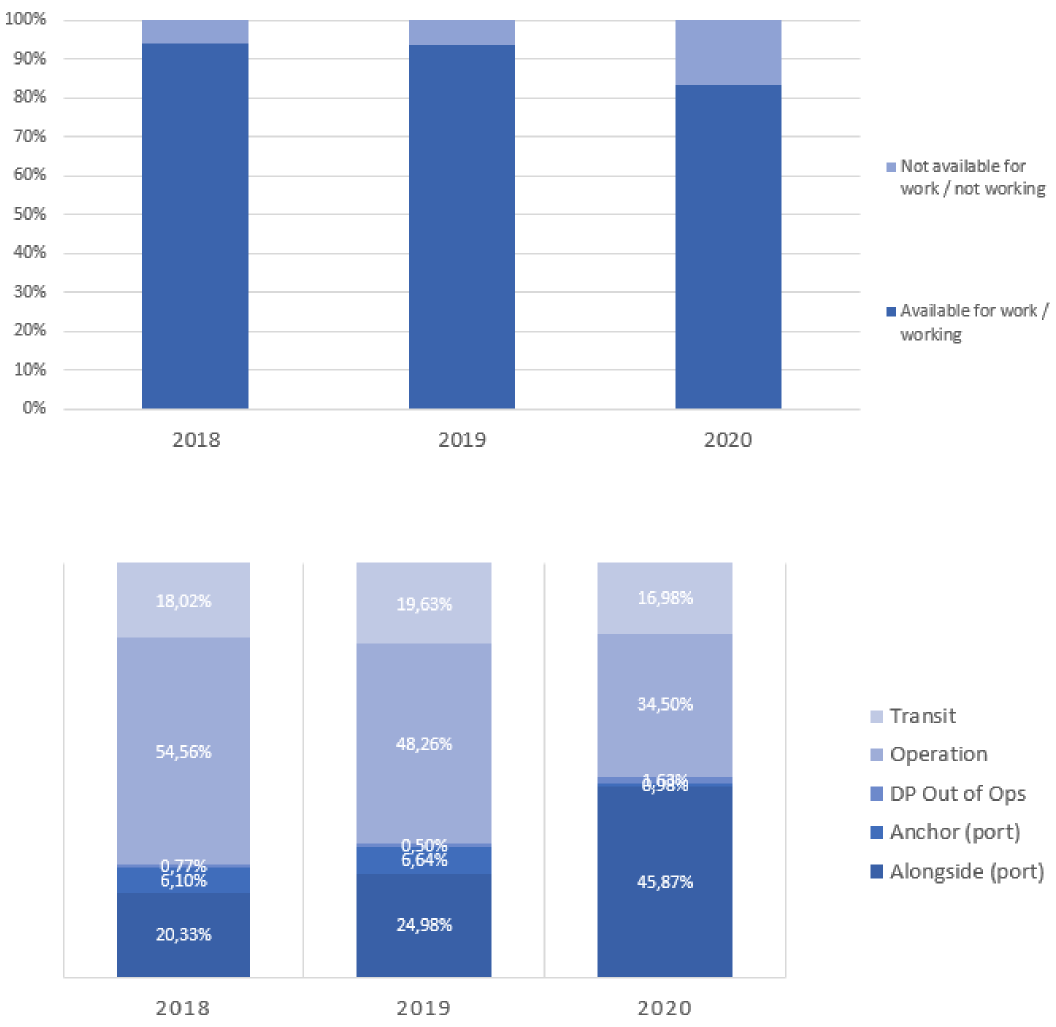


Figure 3.8: FSSV65 operability and operational mode percentages

3.5.3 Drilling

The three most recently built geotechnical drilling vessels Fugro owns are the Fugro Scout, Fugro Voyager and Fugro Synergy. These vessels are purpose-built and belong to the largest vessels of the Fugro fleet. The Fugro Scout and Fugro Voyager are sister ships, Fugro Synergy is a larger, but similar drilling vessel. The smaller vessels have a displacement of 7000 m^3, Fugro synergy has a displacement of 9300 m^3. Fugro Scout and Fugro Voyager have 4 installed generator sets with a total power of 7920 kW. The propulsion arrangement consists of two bow and two stern tunnel thrusters and two Controllable Pitch Propellers (CPP). These vessel have DP2 capabilities. Fugro Synergy has 5 generator sets totalling the power at 10940 kW. This vessel is equipped with two steerable podded propellers astern as well as two bow tunnel and one bow steerable thruster. This vessel is also equipped with DP2. The Fugro Synergy has a fuel capacity of 1357 m^3, the other two vessels are able to bunker 800 m^3 of fuel.

The fuel consumption for the three considered drilling vessels can be mostly based on the found values from the database. Commercial data sheets of these vessels provide fuel consumption numbers in transit and DP modes. As these drilling vessels are in DP during operation, the fuel

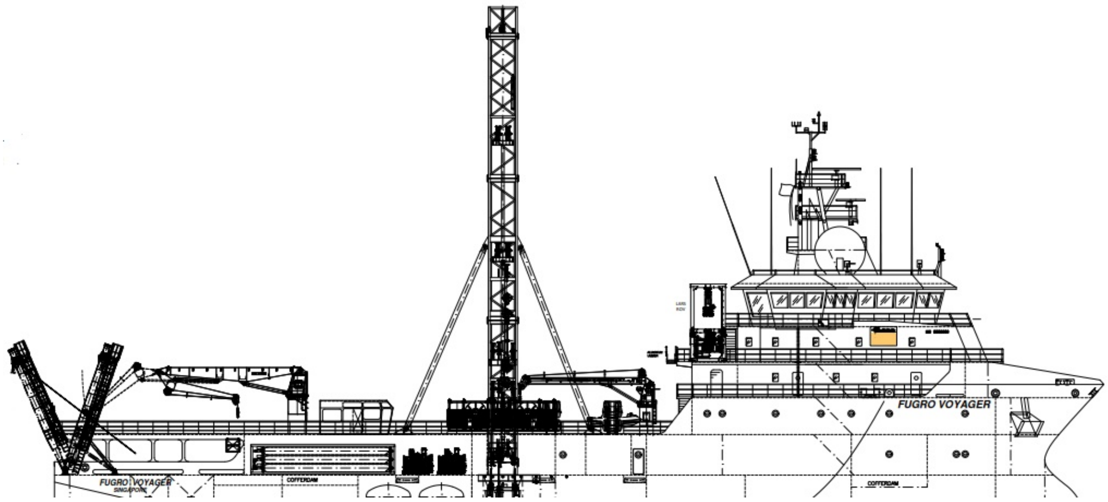


Figure 3.9: Drilling vessel ”Fugro Voyager”

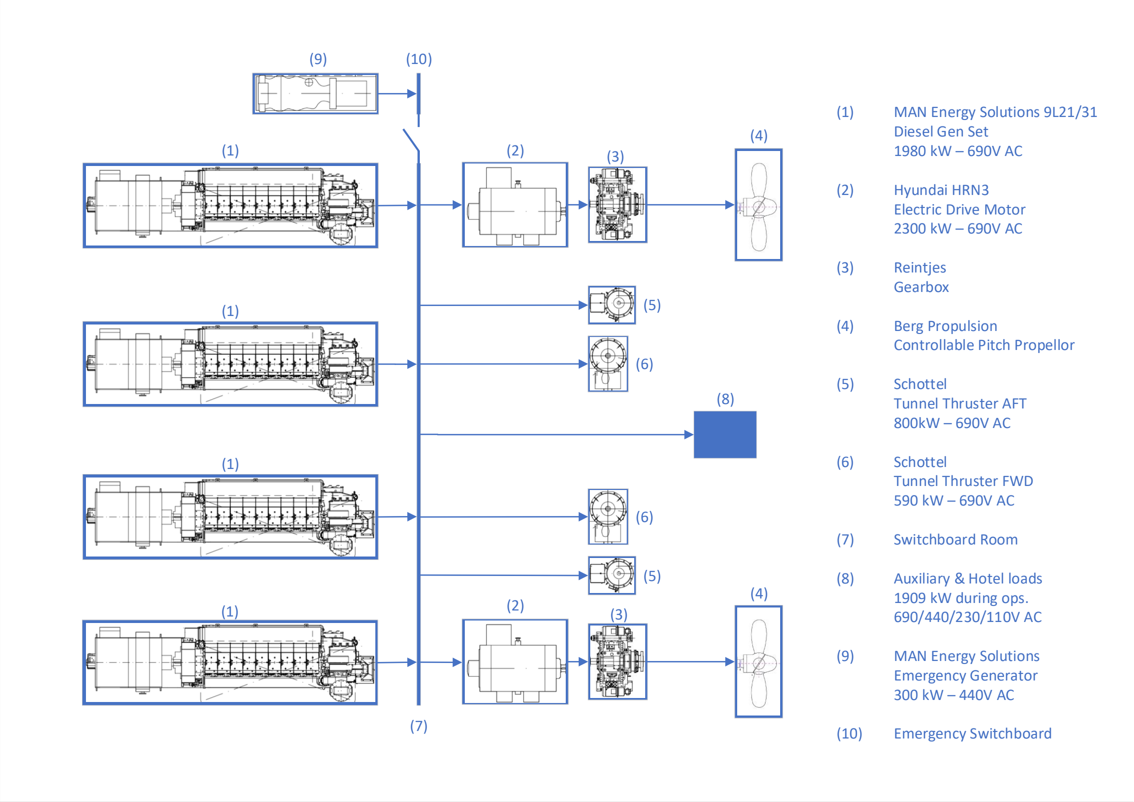


Figure 3.10: ”Fugro Voyager” propulsion arrangement

usage in operation found in the database can be compared to the fuel usage in the data sheet given under DP. Again, this provides comparable values, with the data sheet on the high side compared to actual practice found from the database. Probably also because of commercial reasons and the fact that the vessels transit at lower speeds than specified in the data sheet. The fuel consumption is shown in table 3.3.

Unlike previous vessels, the different drilling vessels achieve a slightly lower operability of 82,5% on average. The operational profile based on the different operational modes shows the longest

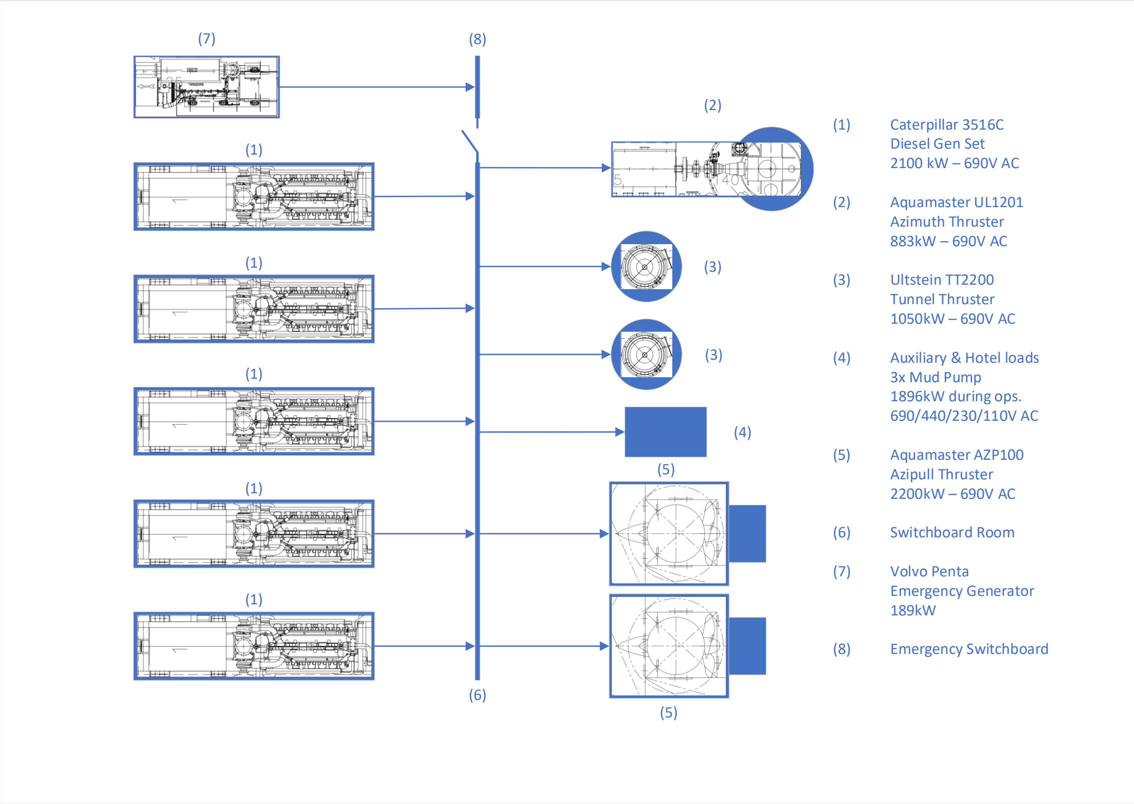


Figure 3.11: ”Fugro Synergy” propulsion arrangement

time spent in transit, at about 20%. Operations are carried out approximately 45% of the time, DP out of operations 6%. These vessels also spend most time alongside in port, compared to the other vessels. Thus, percentages in operations are slightly lower than those of the survey classes. Operational data is summarized in figure 3.12.

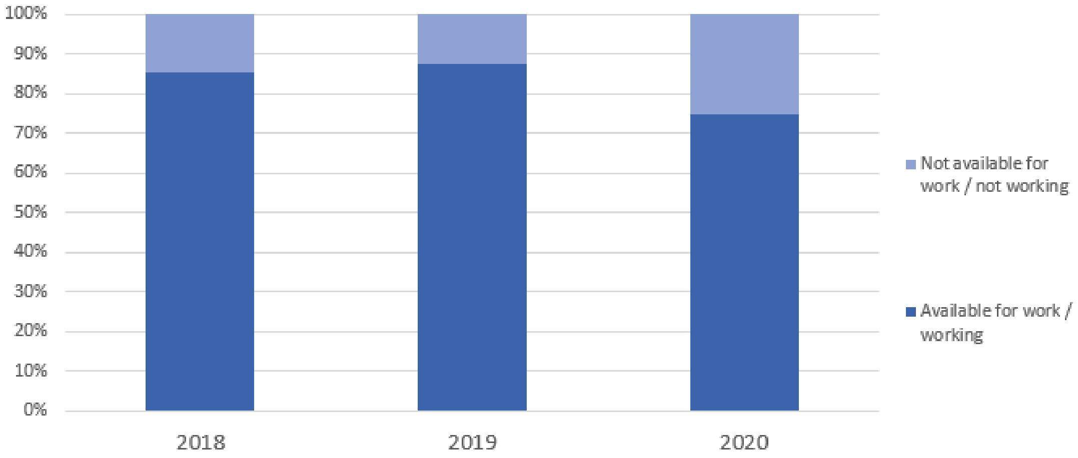
Considering the fuel consumption, the drilling vessels have an autonomy of 78 to 125 days, using the average operational fuel consumption per day. On average found transit speeds, the autonomy in transit amounts to 52 to 65 days. Looking at the port call data, the drilling vessels make a port call each 13 days.

3.5.4 Subsea

Last, a purpose-built Remotely Operated Vehicle (ROV) support vessel will be assessed in detail. Although belonging to the group of asset integrity vessels, the Fugro Aquarius is very versatile and can be deployed for various tasks Fugro is carrying out. This type of vessel has a displacement of 5400 m^3 and therefore falls between the survey and drilling vessels when considering size. It is equipped with five generator sets of 1118 kW totalling the power at 5590 kW. The vessel is propelled by two steerable thrusters and has two bow tunnel thrusters. Fugro Aquarius has a fuel capacity of 1059 m^3.

The fuel consumption of the Fugro Aquarius is also based on acquired information from the database as no information on fuel usage is specified in the commercial data sheet. As no 24-hour events of the Fugro Aquarius in DP out of operations were found, no fuel consumption in this mode is available. The other values are shown in table 3.3 again.

Looking at the operational profile, the Fugro Aquarius has the highest productivity of the assessed



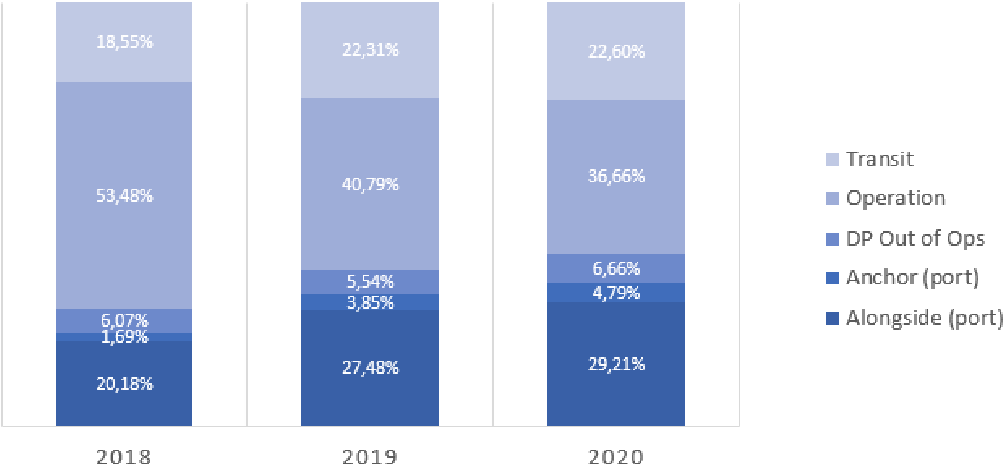


Figure 3.12: Drilling vessels operability and operational mode percentages

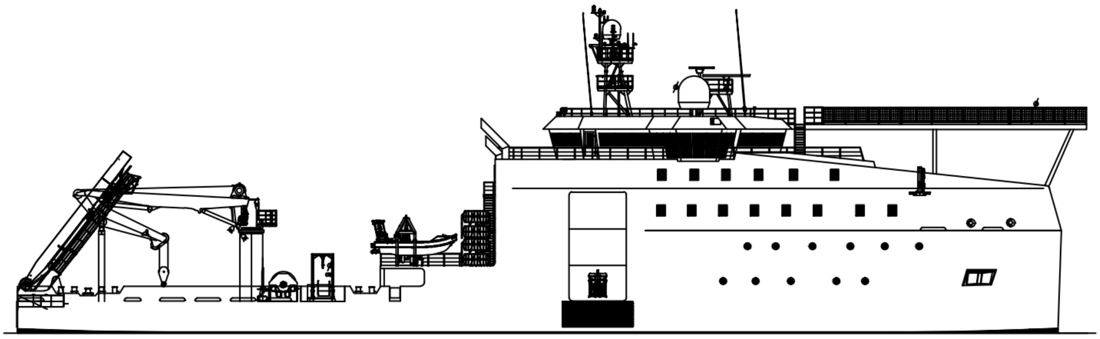


Figure 3.13: ROV support vessel ”Fugro Aquarius”

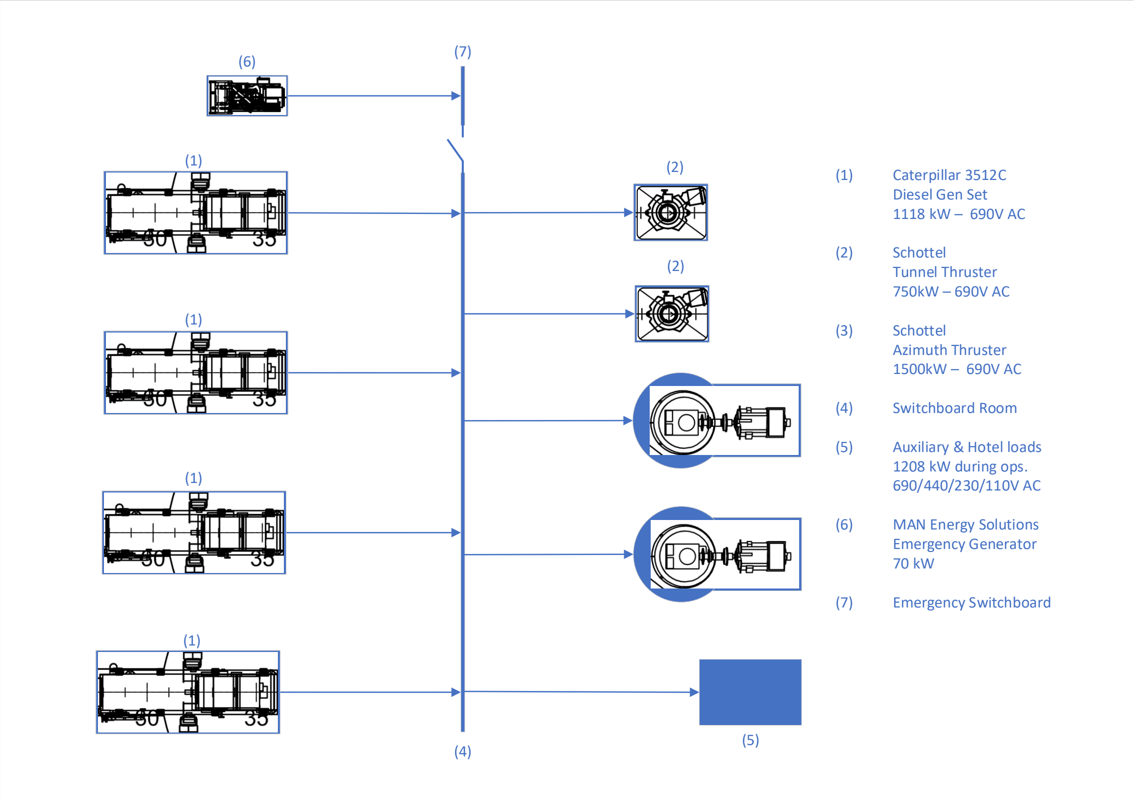


Figure 3.14: "Fugro Aquarius" propulsion arrangement

ships. This vessel is in operation mode approximately 72% of time. Dynamic Positioning out of operations almost never occurs. Some 18% of time, this vessel is in transit. The remaining time is spent in port, at anchor or alongside. The reason this vessel has such a high productivity is due to the fact that this vessel, opposite to other Fugro vessels, serves one client in Brazil the whole time. Probably weather in this seas is not that adverse and one permanent client makes that many operations can be carried out efficiently.

The Fugro Aquarius has the highest autonomy of the assessed vessels. The autonomy based on the average operational fuel consumption per day is 169 days. In transit, the calcualted autonomy based on fuel consumption is 101 days. However, it must be noted that this is based on a transit speed of five knots. This actually is the transit speed of the past 2.5 years, maybe due to client directions, but this could of course change when operating on another project. Therefore the actual autonomy based on fuel consumption will be somewhat lower normally. From the data acquired, this vessel makes a port call each thirteen days on average.

3.6 Conclusion

This chapter discussed the fleet that Fugro is operating, important in order to find a fuel alternative that is suitable for this case specific. The data made available by Fugro is discussed, then it is explained how this resulted in usable data for this study. It is motivated which vessels operated by Fugro are deemed most suitable to use as benchmark. For these vessels, the obtained values from the database as well as more common parameters were discussed. This chapter provides this study with a concise overview of the Fugro fleet, together with obtained parameters and a selection of usable vessels to test different alternative fuel cases later on in this study. As this

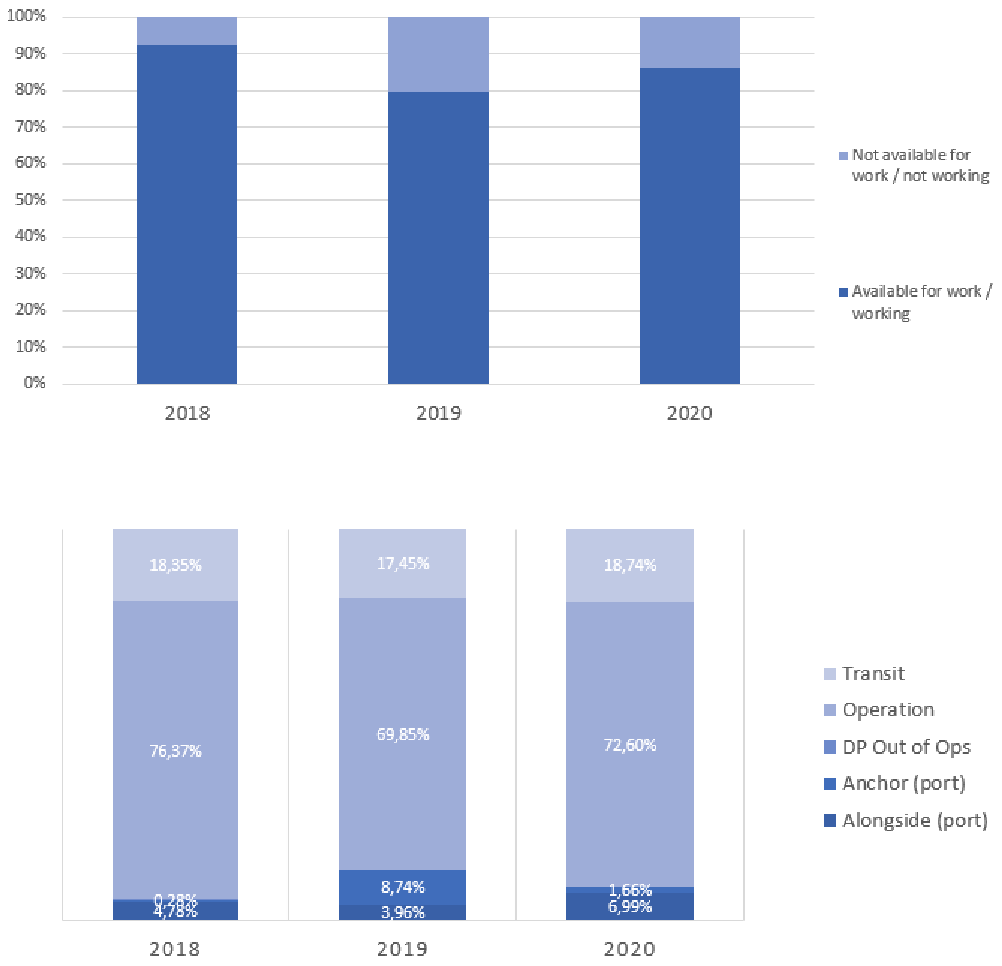


Figure 3.15: Subsea vessel operability and operational mode percentages

study investigates a solution to be applied in the long-term, the following chapter will discuss how the vessel parameters as presented in this chapter could change in the coming years.

4

Future Vessel Developments

The vessels deemed most representative for the Fugro fleet are discussed in the previous chapter. In the previous sections, parameters required to choose an alternative fuel were discussed and outlined. While these parameters provide an overview of the requirements of Fugro vessels nowadays, these aren't necessarily representative for the vessels to be built from 2030, which this thesis is aiming at. Therefore, this section will research developments on which vessel changes can be based. To make potential assumptions on how Fugro vessels could be different in ten years. This will be based on data trends obtained from Clarkson's research, consulted literature on legislation and CO_2-reduction measures and stakeholder interviews at Fugro.

4.1 Data trends

The four vessel classes as discussed previously, including similar sized Fugro vessels, do not provide a database extensive enough to make assumptions on data trends found in these vessel classes. Therefore, a database obtained via Clarkson's research was acquired to get more data points of similar vessels in the different classes. The vessel register of Clarkson's was filtered for similar vessel types. However, finding vessels similar to the specialist drilling vessels of Fugro didn't succeed. The filter class for drilling vessels didn't provide enough entries as these ships are often specified differently than *drilling vessel*. Comparing same-sized vessels to these drilling vessels wouldn't provide a good comparison due to the power-heavy and specialist equipment onboard. After the datasets for the three remaining classes were obtained, these entries were divided in different groups, based on a GT close to those of the Fugro vessel classes. Parameters of the different vessel entries were then plotted along time in order to find trends in the design and vessel specifics. Technical trends in size, deadweight, speed and engines can be assessed using methods as shown in Chen et al. (2010). The following paragraphs will analyze the observed trends of the different vessel classes and will assess if these indicate changes in future vessel parameters. The different data sets can be found in appendix **??**.

4.1.1 FOCSV

When looking at the trends of FOCSV-like vessels, the length and speed decreased the last few years, therefore the Froude number remained constant. While the length decreased, the breadth remained more or less constant, resulting in less slender hull designs. The installed power of this type of vessels shows no significant change in the last years.

4.1.2 FSSV65

The larger class of survey vessels and comparable fleet showed more or less the same results. The Froude number remained constant, with both length and speed decreasing. This trend showed no decreasing breadth however. The FSSV65 class is therefore not very slender, however, it has to be noted that the vessel's hull has a very low block coefficient. The trend shows larger installed power in this vessel class over recent years.

4.1.3 Subsea

Vessels comparable to the subsea class of Fugro were also plotted over the years. Significantly, there were no entries found between 1987 and 1997. While the length decreased, the speed and therefore Froude number increased in general. Modern ships are also less slender as their beam increased. Operating speeds became higher while the hull is less slender, therefore the installed power increased.

4.2 Literature

In order to assess expected vessel requirements in future, literature on legislation and CO_2 reduction measures was already assessed during the literature study of this thesis. This section will discuss the legislation and CO_2-reduction measures that could be of influence for future vessel designs. Later on in this thesis, in section 5.1, this subject together with additional regulations and measures will be discussed more extensively. Also elaborating on how regulation influences future scenarios that will be used in this thesis.

4.2.1 Legislation

As discussed in detail in section 5.1, literature on legislation is assessed in this thesis. In short, legislation influencing future vessel designs are mainly based on the already existing Energy Efficiency Design Index (EEDI) and Ship Energy Efficiency Management Plan (SEEMP). While SEEMP focuses on energy efficiency of currently sailing vessels, EEDI enforces more efficient design of newly built ships.(IMO, 2011) Where SEEMP doesn't provide stringent reduction potential to this research, it shows that vessel efficiency is a subject that is currently looked into by the IMO and therefore also ship owners. Moreover, stricter regulations on efficiency will change the operational profile of future vessels (N. Trivyza et al., 2016). The IMO is already looking into measures for ship operators to optimize and reduce speeds mandatory. Also, EEDI legislation is not yet applicable to the offshore-/work-vessels in Fugro's fleet. However, suitable efficiency legislation is expected to be developed for all vessel types. This new legislation will address the biggest emitters first, therefore EEDI could be applicable to the offshore fleet in the near future. For most cargo vessels, already existing EEDI legislation prescribes that vessels newly built around 2030 have to be up to 30% more efficient compared to the average efficiency of ships built between 2000 and 2010 (IMO, 2016). If these measures are mandated it is important to assess solutions that influence future vessel design most.

4.2.2 CO_2-reduction measures

Literature on CO_2 reduction measures outlined the most important solutions to optimize vessel efficiency. These reduction measures effect vessel parameters and can therefore be used to make assumptions on changing vessel parameters. Most of the existing efficiency measures are summarized in Bouman et al. (2017), a table of CO_2-reduction measures is presented that shows a range of measures and accompanying reduction potential. The studies referenced by Bouman state a reduction due to changing hull forms of between 2 and 30 percent for example. Of the reviewed studies, efficiency measures that entail the largest reduction are; ship size, hull shape, speed and capacity utilization. Also hull resistance measures are believed to yield a large efficiency win. This means that assumptions can be done on reduced resistance and therefore reduced installed power in future vessels.

Beşikçi et al. (2016) considers different fuel efficiency measures and applies AHP to choose the most desirable measure. This study concludes that Voyage Performance Management (VPM), Engine Maintenance Onboard (EMO) and Hull and Propeller Condition Management (HPCM) are most significant respectively. These findings can be used to make assumptions on the most applied ship efficiency measures and accompanying average reduction potential. Another aspect to take into account when considering the most applied efficiency measures is cost.

A study by Lindstad (2013) shows how bulkers can operate more efficient using different measures. To do so, cost and CO_2-emissions are compared against ship speed, slenderness and other factors. All while taking into account different oil prices. The study of Lindstad states that a significant emission reduction can be cost effective. Most promising measures are a more slender hull design, sailing at lower speeds and weather routing. However, Lindstad's study focuses on bulk carriers which differ from the vessels that are investigated in this thesis. While the proposed measures can be cost-effective for bulkers these measures are considered less suitable for appliance on the vessels Fugro is operating. Fugro vessels already sail at relatively low speeds, a more slender hull design is more difficult or not possible to apply and also weather routing can be difficult because the transits of Fugro vessels are not as long as those of bulkers.

The literature discussed above shows that it is likely that regulation will enforce more efficient ship designs. Besides, it is possible that the IMO will enforce rules concerning efficient transits, encouraging weather routing and slow steaming. How these two aspects could affect future vessel developments will be elaborated on in section 4.5.

4.3 Interviews

Fugro is the main stakeholder and for that reason relevant employees were interviewed on future operational scenarios. For instance, on changing vessel requirements due to new legislation or changing markets. This aids in the development of future operational scenarios to assess the best alternative based on different possible developments. To achieve this goal, questions on changing markets, legislation and technology in general were asked during these interviews. The first round of interviewed stakeholders were two global business line directors at Fugro. These stakeholders represent the marine site characterization and asset integrity *business lines* of the maritime branch of Fugro. This means they are responsible for the developments within these business lines and are therefore involved in future developments of the Fugro fleet. The largest part of the Fugro fleet has a DNV GL class. Therefore, an area business development manager at DNV GL was interviewed on the subject of Fugro fleet developments as well. During the interviews with the Fugro stakeholders it became clear that it could be valuable to also interview a chief scientist and director remote operations at Fugro. Why this was done will be elaborated on later in this section. Lastly, a vessel and technical superintendent were also interviewed because of their extensive operating experience with Fugro's fleet. The duration of the interviews varied between 30 and 45 minutes and were all carried out using Microsoft Teams as many were and are working at home during the COVID-19 pandemic. The interviews were recorded and transcripts were made to be able to reproduce for later use during this thesis. The following sections will discuss the key take-aways for the different question themes of each Fugro business line.

4.3.1 Market developments

Market developments are important to study as these influence what kind of vessels will most likely be added to the fleet in the time span this study focuses on. These developments are different for both business lines. In the first place, Fugro's operations in general will shift more towards offshore wind, coastal and infrastructure and away from oil and gas. The work carried out will not change significantly due to this shift and therefore this has no implications on future vessels. Also, Fugro will focus more on geodata in the future. This means that asset integrity will move towards inspection and pursue less work in construction-related businesses. This enables asset integrity to restrict the current fleet that is used for those operations and in future, these kind of vessels will not be built anymore. Marine site characterization is already focused on geodata so this will not have significant implications on the current fleet. Geophysical vessels will carry out the same sort of operations and also the geotechnical fleet will still rely on asset-heavy activities.

4.3.2 Technological developments

Considering payload or equipment, no large technological developments are expected. Except for Remotely Operated Vehicles (ROV) that will be electrically powered by their own batteries instead of using an umbillical to power the ROV. This could have minor implications for the installed power on Fugro vessels. However, something that was often mentioned by all participants is the fact that Fugro is very extensively researching the opportunity of operating their vessels remotely. This was mentioned by the business line directors that were interviewed. They therefore proposed to meet with two Fugro experts in this field to get a more detailed insight into these operations. Operating vessels remotely has the advantage that there is no need for crew on board, this makes that it is more safe, cheaper and more sustainable, as these vessels can be smaller and therefore more efficient. For those reasons, Fugro wants to expand remote operations as far as possible, what this means to the different business lines will be discussed below:

- **Site characterization, geotechnical** - This part of the fleet comprises of survey vessels, Fugro is looking at the utilization of ROVs as force multipliers. So called Unmanned Survey Vessels (USV). These are ROVs cruising along a mother survey vessel, enabling a larger spread to be surveyed at once. Fugro already has a handful of these vessels in operation as of today. Afterwards, especially in shallow waters, Fugro wants to deploy Beyond Line Of Sight (BLoS) remotely operated survey vessels.
- **Site characterization, geophysical** - Site characterization involves drilling and taking samples which makes it the most difficult branch to operate remotely. The expectation is that the drilling vessels will remain manned, as these process samples and are asset heavy. An opportunity would be however, to deploy USVs from the mother drilling vessels to survey for example.
- **Asset integrity** - As asset integrity is moving towards geodata by intensifying inspection operations, smaller ships are required than the current fleet. Therefore asset integrity is looking into replacing this fleet entirely by remotely operated vessels. This could be BLoS vessels operating from ports or even ROVs that are operating from a field residence.

4.3.3 Scenarios

As for scenarios from exogenous factors like regulatory bodies and governments, most of the participants agreed that a shift to more sustainable technologies is necessary. Large steps will be made in remote operations, making the fleet more efficient and thus more sustainable. Most expect that this could go relatively fast, making the Fugro fleet largely remotely operated in 2030.

At the same time, respondents also foresee that regulation, subsidies and taxes are likely to get extensified. ”There is a concern that the commitment to sustainability will waiver due to the low cost of oil. The crisis has really pushed new technology, the cost is a prohibitor, but you can sometimes work around it.” Another thing mentioned was that clients could choose differently, making the sustainability of a tender more important than cost. The general conclusion around these exogenous factors was that technology is changing, sometimes faster than deemed possible and that this will be the case as well for sustainable and remote technology.

4.4 Remotely Operated Vessels

During the interviews it became evident that the biggest change in vessel specifics will come forth out of remote operations. Fugro is planning to quickly intensify their remote operations which means that vessels that will be built around 2030 are probably remotely operated. Reducing the need for crew accommodation for example, making that these vessels will be smaller. Fugro already has two types of USVs in operation and one type under consideration. To motivate the choice for a fuel it is important to look at the vessel parameters for which this fuel is intended. For that reason, this section will discuss the specifics of the already existing examples of remotely operated Fugro vessels. This helps in getting to know the parameters and requirements for the alternative fuels that will be assessed during this thesis. These vessel types are the FAS900 USV and SEA KIT models.

4.4.1 FAS900

The FAS900 is a small USV built to operate remotely. Fugro is currently operating two of these vessels that were built from 2019 and onwards. These are survey vessels equipped to chart the sea floor. It can be used on its own from a port or as a force multiplier for a mother ship. This vessel has a displacement of 5,5 tons and is only 9 meters long, making it less energy consuming than conventional survey vessels. It is propelled by a regular direct-drive diesel engine and is capable of achieving speed of up to 8 knots. The fuel tank has a capacity of 1200 liters.

With this fuel capacity, the ship is said to have an autonomy of up to seven days. No operational data of these vessels is available as of yet, therefore less accurate numbers on fuel consumption can be calculated compared to the conventional vessel classes operated by Fugro. However, using the fuel capacity and autonomy, an average fuel usage of 7 liters an hour can be assumed.

4.4.2 SEA KIT

The SEA KIT USVs are vessels that are specifically built for asset integrity. Later on these vessels might also be used in the other Fugro branches. Equipped with a remotely launchable ROV and with other required survey equipment these vessels are quite versatile. Fugro ordered two of the 12 meter SEA KIT X and is looking at a larger variant of 24 meters, the SEA KIT Ω. These vessels weigh 11,2 and 85 tons respectively. Both SEA KITs have a hybrid propulsion. The Chi has a 36kW diesel generator set to power the installed batteries. SEA KIT hasn’t yet given any disclosure on the generator power of the Omega, it will be also hybrid however. Operating speeds are at about 6 knots.

Again, no operational data is available as of yet. The vessels are equipped with large fuel tanks giving them an autonomy between 100 and 150 days. As this autonomy is quite widely ranged and no vessels are operational as of yet, it is not yet possible to calculate fuel or energy consumption.

4.5 Conclusion

This section will elaborate on the findings of this chapter. In literature and based on data trends, assumptions can be made on developments regarding efficiency and energy savings. Interviews provide an insight of how Fugro stakeholders see the company's vessels change. The conclusions are separated in changes in ship design and changes in operation. While many indications of how ship designs could and will change in the coming ten years were found, no aspects were found that are so significant to assume that the found vessel parameters in chapter 3.1 need to be altered to remain representative. The only key take-away is that remotely operated vessels will play a larger role within Fugro, therefore these vessels will be taken along in the assessment in the remainder of this thesis. While none of the other findings in this chapter are deemed decisive enough to base assumptions about changing vessel parameters on, the most important findings to keep in mind are concluded in the paragraphs underneath. These are still deemed useful to take along when considering fuel alternatives and vessel newbuilds in future.

4.5.1 Changing ship design

The most effective measures influencing ship design found in literature are ship size, hull shape, and hull efficiency measures. When looking at the results found by Bouman et al. (2017), hull designs can be assumed to bring efficiency improvements of up to 40%. An important aspect influencing ship design are the hull form and hull resistance measures. This is a promising way to improve efficiency and likely to evolve in the coming years, especially when enforced and/or encouraged. However, it must be noted that Fugro vessels do already have a streamlined hull form with a very low block coefficient in order to prevent noise in the measurements when operational. As shown in section , Fugro vessels aren't specifically large. Fugro vessels are densely packed with all sorts of equipment. Therefore, looking at the conventional ship classes as discussed in this chapter, there are no reasons to expect that these vessels will become significantly smaller. This is, however, not the case when remotely operated vessels (ROVs) are looked into. These vessels do not require accommodation providing the opportunity to reduce ship size drastically. Multiple Fugro stakeholders pointed out that Fugro is looking to grow in this segment. Moreover, some stated that they mainly see ROV's to be built in 2030. Therefore this is the most important to account for in this research.

4.5.2 Operating efficiency

Sailing at lower speeds is recognized as efficiency-improving in shipping. Fugro vessels are already sailing at low speeds when in operation and data showed that transits are usually carried out at speeds around nine to ten knots. Therefore this efficiency measure is not believed to have a significant impact on energy consumption of future Fugro vessels. Hull and propulsor maintenance is another subject on which improvements can be made, but for this measure as well, it isn't assumed that this will have a significant impact on future vessel performance. Mainly because Fugro vessels are already maintained regularly.

5

Scenarios

Because this research focuses on the most feasible or suitable solution in ten years, a lot of uncertainties play a role. Whereas the previous chapter elaborated on changing vessel properties in future, also other factors around regulation, costs and technology advances play a role in choosing a suited alternative. This chapters will discuss these uncertainties. Also, multiple scenarios will be set up to deal with these uncertainties in later stages of this research. Different outcomes for a fuel choice can be acquired, influenced by the different scenarios. These scenarios are based on exogenous factors, developments which Fugro doesn't determine or influence. The most important exogenous factors are regulations and cost. Other factors are mostly technology-related. This includes technology readiness and infrastructure availability for example. This chapter will discuss the factors determining the scenarios and the scenarios themselves to be used in the method of this thesis later on, in order to take into account future developments and accompanying uncertainties.

5.1 Regulation

Considering regulation, the IMO plays the most significant role in international shipping. Besides the IMO, the European Union (EU) is also looking at ways to reduce shipping emissions by the provision of certain rules and legislation. For this thesis, some of these planned regulations are more relevant than others. In the first place, Fugro already stated that they want to focus this research on a zero-carbon alternative fuel, deployable from 2030 onwards. In the coming ten years, regulation on the uptake of alternative fuels will not advance to an extent beyond the ambitions of Fugro. The ambitions for the years after could however. Regulation for the coming years could accelerate the uptake of alternative fuels in general, therefore influencing costs and availability. Besides, some regulation could influence the design of vessels in 2030. The following section will discuss the IMO and EU regulation and the exogenous influence these regulations could have on a future fuel choice for Fugro.

5.1.1 IMO

To reduce GHG emissions of shipping, IMO already introduced regulation. In recent years resolutions were adopted to enforce the use of low sulphur fuel, NOx-emissions and the introduction of mandatory requirements for ships to record and report their fuel oil consumption. These regulations do not really impact Fugro as all vessels operate using MDO and are mostly smaller than 5000GT. Moreover, the Energy Efficiency Design Index (EEDI) and Ship Energy Efficiency Management Plan (SEEMP) were introduced. While SEEMP focuses on energy efficiency of currently sailing vessels, EEDI enforces more efficient design of newly built ships.(IMO, 2011) Where SEEMP doesn't provide stringent reduction potential to this research, it shows that vessel efficiency is a subject that is currently looked into by the IMO and therefore also ship owners should have this subject on their agenda. Moreover, stricter regulations on efficiency will change the operational profile of future vessels (N. Trivyza et al., 2016). EEDI legislation is not yet applicable to the offshore-/work-vessels in Fugro's fleet. However, suitable efficiency legislation is expected to be developed for all vessel types. This new legislation will address the biggest emitters first, therefore EEDI could be applicable to the offshore fleet in the near future. For most cargo vessels, already existing EEDI legislation prescribes that vessels newly built around 2030 have to be up to 30% more efficient compared to the average efficiency of ships built between 2000 and 2010 (IMO, 2016). The ambition to make EEDI regulation obligatory for more vessel types and other candidate measures are shown in a document published by the IMO (IMO, 2018b). These measures include short-, medium- and long-term ambitions and are not yet in effect. To get an impression of the different ambitions of the IMO, all measures are shown in table 5.1.

The candidate measures the IMO is proposing as shown in table 5.1 do not incur regulations on the uptake of alternative fuels that are more stringent than the ambitions as set by Fugro. As discussed in the previous chapter, some of these regulations influence the parameters of Fugro vessels in 2030. The proposed IMO measures that could influence the vessel parameters of Fugro vessels are shown below with a short description of the consequences.

- **Further improvement of the existing energy efficiency framework** with a focus on EEDI and SEEMP regulation - *If EEDI becomes applicable to Fugro vessels, this would influence the efficiency requirements of newly built Fugro vessels. These would have to meet requirements of a benchmark efficiency, which could lead to the adoption of more efficient designs.*
- **Speed optimization and speed reduction** - *A potential obligatory speed reduction could mean that Fugro vessels require less installed power in future designs.*

Besides above-mentioned proposals, a large part of the measures IMO intends to take encourage the uptake of alternative fuels. To obligate more shipping operators to assess alternative fuels, but also to require governments and ports to take measures against GHG emissions. For the middle- to long-term, market-based measures are mentioned to speed up the transition to other fuels for example. These kind of measures, like incentives and obligations, influence the future cost, availability and TRL of alternative fuels. To what different scenarios these aspects will lead is discussed in 5.4

Fourth IMO GHG study

Recently the Fourth IMO Greenhouse Gas Study was published. This study gives an estimate of historical emissions and presents the most recent projections of future emissions of shipping. With the current measures in place, the study foresees the emissions of shipping to be 90 to 130 percent of current emissions. A reduction is recognized but leveled out by the growing shipping industry. This study again emphasizes that climate change abatement is necessary and has to scale up relative to the efforts that are seen today. This doesn't add a scenario but shows that more extensive action is required and also more probable to be taken in the coming years. While incentives and some regulation seems far away, this report emphasizes that this kind of policy is very urgent and needs to be implemented quickly.

5.1.2 European Union

The European Union also set up a strategy to reduce GHG emissions from shipping. The IMO is sometimes perceived a slowly operating entity and for that reason the EU set up their own strategy

Type	**Period**	**Proposed measures**
Short-term	**2018-2023**	- Further improvement of the existing energy efficiency framework with a focus on EEDI and SEEMP regulations
		- Develop technical and operational energy efficiency measures for both new and existing ships
		- Establishment of an Existing Fleet Improvement Programme
		- Speed optimization and speed reduction
		- Consider and analyse measures to address emissions of methane and further enhance measures to address emissions of Volatile Organic Compounds
		- Encourage the development and update of national action plans to develop policies and strategies to address GHG emissions
		- Continue and enhance technical cooperation and capacity-building activities under the ITCP
		- Consider and analyse measures to encourage port developments and activities globally to facilitate reduction of GHG emissions from shipping
		- Initiate research and development activities addressing marine propulsion, alternative low-carbon and zero-carbon fuels, and innovative technologies to further enhance the energy efficiency of ships
		- Incentives for first movers to develop and take up new technologies
		- Develop robust lifecycle GHG/carbon intensity guidelines for all types of fuels
Mid-term	**2023-2030**	- Implementation programme for the effective uptake of alternative low-carbon and zero-carbon fuels
		- Operational energy efficiency measures for both new and existing ships
		- Market-based Measures (MBMs), to incentivize GHG emission reduction
		- Further continue and enhance technical cooperation and capacity-building activities
Long-term	**2030 and beyond**	- Pursue the development and provision of zero-carbon or fossil-free fuels to enable the shipping sector to assess and consider decarbonization in the second half of the century
		- Encourage and facilitate the general adoption of other possible new/innovative emission reduction mechanism(s)

Table 5.1: IMO candidate measures

as well (European Commission, 2020), besides supporting IMO guidelines. The strategy consists of three steps. These steps, on some points similiar to the IMO strategy, are:

- **Monitoring, reporting and verification of CO2 emissions from large ships using EU ports** - *Similar to IMO rules and not (yet) applicable to most Fugro vessels, due to GT smaller than 5000.*
- **Greenhouse gas reduction targets** for the maritime transport sector - *With the current uptake of zero-carbon fuels from 2030, Fugro already complies to goals as set by IMO and EU*
- **Further measures**, including market-based measures, in the medium to long term. - *Market-based measures or incentives could accelerate the uptake and availability of alternative fuels. Therefore influencing scenarios on cost, infrastructure etc.*

To speed up GHG emissions reduction policies, the EU set up above directives. Especially the third point, proposing market-based measures provides valuable information to the scenarios in this thesis. These could again influence the cost and uptake of alternative fuels. Proposals mentioned focus on carbon tax and Emission Trading Schemes (ETS).

5.2 Costs

One parameter heavily influencing the choice for an alternative fuel is cost. The cost of the relatively novel electro-fuels are not yet known, because these aren't mass produced yet. The cost for renewable energy also makes up a great deal of the fuel price for example. Therefore, the price of electro-fuels is uncertain and varies greatly (Brynolf et al., 2018). On top of that, fuel costs can be influenced by market-based measures or incentives as mentioned in the previous chapter. Also, both capital and operational costs concerning maintenance are not yet known. To deal with this uncertainty, scenarios can be set up in which different cost trajectories are assessed.

5.2.1 Fuel costs

Brynolf et al. (2018) made a comprehensive overview of the price for different alternative fuels in 2015 and 2030. Based on different scenarios and a reference scenario, the price build-up of different alternative fuels was assessed. These fuel price estimates still suggest costs over a broad range. Another important fuel price influencing the uptake of alternative fuels is the price of fossil fuels, MDO in this case. The future price of fossil fuels makes or breaks the feasibility of alternative fuels in most cases. Now that two cost factors influencing the problem are known, these have to be translated into a scenario. As stated in Schoemaker et al. (1995), it is not important to account for all the possible outcomes of each scenario, simplifying the outcomes can be sufficient. Leading to the first scenario outcomes that will be taken into account in this thesis. For both conventional and alternative fuels, varying fuel price values will be used in the scenarios. These different cost outcomes will be assessed together with the fuel price ranges found in Brynolf et al. (2018).

5.2.2 Technology costs

Another aspect is technology cost. These are both Capital Expenses (CAPEX) and Operational Expenses (OPEX). OPEX excluding the fuel costs, as these are already accounted for. The cost of conventional propulsion installations differs from those that could be used for alternative fuels. Also maintenance costs can differ for example. Therefore a technology cost scenario is introduced as well. Again, assessing varying price outcomes for different alternatives in the scenarios.

5.2.3 Cost incentives

Most cost outlooks, like that of Brynolf et al. (2018) for example, do not take tax benefits or market-based measures into account. Therefore, these developments are not yet included in the scenarios as proposed above. However, as discussed in the section on regulation, the IMO and EU plan on providing incentives to reduce GHG emissions. These are incentives for first movers to develop and take up new technologies. Lagouvardou et al. (2020) identifies the most probable scenarios as being carbon tax and Emission Trade Schemes (ETS). Balcombe et al. (2019) reviews several policy options to bring down costs of fuel alternatives; emission price controls, emission quantity controls and subsidies. These kind of measures are being proposed at the IMO and EU but aren't in effect as of now. As no examples or comprehensive proposals are in existence as of now, it is very difficult to include these in the scenarios. For that reason, this thesis will look at the feasibility of alternative fuels based on prices without taxes and/or incentives at first. If these alternatives turn out to be not viable, it could be derived what kind of incentives could be possible to increase the viability of application of alternative fuels. Moreover, this could give stakeholders an idea of which incentives are necessary in order to switch to alternative fuels.

5.3 Technology

Exogenous scenarios are considered to be mostly dependent on availability of fuel alternatives. Availability can be divided in two aspects, related to each other. Firstly the availability of the technology itself. Mostly expressed in TRL. Secondly, the availability of the fuel, highly dependent on production levels and port infrastructure.

5.3.1 TRL

The availability of a technology is largely dependent on it's maturity. An universal measure, introduced by NASA, is used to measure the maturity of a technology. This is the Technology Readiness level or TRL (Mankins, 1995). The scale is shown in the table beneath From TRL 7 onwards a technology is feasible to use in a commercial application. However, higher TRL levels mean that a technology is applied on bigger scale and therefore probably cheaper and more widely available. Because the TRL levels of different alternatives in 2030 are not known, these are suitable to assume under different scenarios. TRL levels have been used combined with the MCDA methods before. Conrow (2011) uses the TRL scale to set up a non-integer scale that can be used to score the different levels. This study will use a qualitative way of scoring the TRL levels, similar to the common TRL levels as shown in figure 5.1 below.

5.3.2 Fuel availability

The availability of a fuel is closely related to fuel cost and TRL. TRL influences the availability for a large part. This is not always the case however, therefore it is included as a seperate criterion in the analysis. Ammonia for example is not yet mature enough to propel a ship, however it is already used as agricultural and chemical commodity for a long time. Although not produced carbon neutral as of yet, this illustrates that there is a difference between the technology readiness and availability between the propulsion technology and fuel technology/availability. Another reason why fuel availability is a different scenario is the geographical nature of this problem. While the technology or fuel is already mature enough, the geographical location of a vessel on earth can influence if the fuel is available at that location. Due to lacking bunker and/or production infrastructure.

Figure 5.1: Technology Readiness Levels (TWI, 2020)

A score for availability can partly be assumed by the geographical boundaries and historical experience of the fuel types and will partly be influenced by the technological maturity and the fuel price.

5.4 Scenarios

The measures these regulators are considering that are relevant for this thesis are related and include cost incentives, market-based measures and/or an Emission Trading Scheme (ETS). These measures possibly result in cheaper fuels, an increased availability of alternative fuel (infrastructure) and a higher TRL because of accelerated development of new technologies. The plan to have zero-carbon fuels by 2030 is more ambitious than the restrictions regulators are planning. Thus, regulators mostly affect the cost and technology of alternative fuels in the case of the uptake of zero-carbon fuels around 2030.

With regards to cost, the following exogenous causes are believed to influence the fuel cost in different scenarios. First, Carbon Capture and Storage (CCS) and Renewable Energy (RE) can become cheaper in the near future. This influences the future price of carbon-based and (all) electro-fuels respectively. Another aspect is that CAPEX and OPEX can reduce due to larger production volumes of new technologies, Fuel Cells can become cheaper for example. Also, more experience with new technologies can reduce both CAPEX and OPEX. Lastly, regulators and governments can bring cost incentives in place, reducing the overall costs of all fuels, these will not be included in the scenarios but assessed later.

Also technological advances have influence on the choice for the best alternative fuel by 2030. An immature technology nowadays could be available by 2030 due to fast development. Possibly influenced by regulators that stimulate the development of new technologies by funding, cost incentives or tax benefits. TRL's of newer ICE technologies or FC technologies can be tested in different scenarios. Also the roll-out of new infrastructure and availability is very uncertain, therefore scenarios can test the impact of the development of infrastructures that are non-existent as of today.

The proposed scenarios to test in the decision tool are summarized below. These are based on the impacts of above-mentioned developments:

1. Cheaper CCS and RE
    - **Scenario I** Carbon-based fuels price changes due to reduced CCS price
    - **Scenario II** Electro-fuel price changes due to reduced RE price
    - (**Scenario III** All prices change due to reduced RE and CCS price, therefore no significant difference as everything becomes cheaper and the score between alternativives doesn't change relatively)
2. Fast uptake of new technologies
    - **Scenario IV** CAPEX H2/NH3-system lower, High TRL FCs, Hydrogen infrastructure available
    - **Scenario V** CAPEX H2/NH3-system lower, High TRL FCs, Ammonia infrastructure available
    - **Scenario VI** CAPEX LNG system lower, High TRL ICEs
    - **Scenario VII** High TRL ICEs, DME infrastructure available
    - **Scenario VIII** High TRL ICEs, Ammonia infrastructure available
    - **Scenario IX** High TRL ICEs, Methanol infrastructure available

5.5 Conclusion

This chapter discussed three subjects regarding exogenous factors that influence the choice for the most suitable fuel alternative. These are exogenous factors regarding regulations, cost reductions and fast evolving technologies. These exogenous factors are taken into account by setting up scenarios. This resulted in two groups of scenarios that are presented in the previous paragraph. These scenarios are proposed to cope with future uncertainties when assessing the fuel alternatives. The assessment method will be a MCDA method as motivated during the literature study. Which MCDA method specifically, is motivated now in chapter 6.

6

Multi-Criteria Decision Analysis

During the literature study it was identified that a MCDA method is suitable to be used for the problem of choosing an alternative fuel. The most important advantages of using one of these methods being that multiple stakeholders and criteria can be included in the choice for an alternative fuel. Moreover, it provides the possibility to include and weigh intangible criteria. Which of the different MCDA methods will be used was not yet decided on during the literature search however. The previous chapters provided a literature study and technical framework to carry out the method part of this thesis. Remaining to work out the method of this research now, is a choice for a suitable MCDA method. For that reason, this chapter will elaborate on different MCDA methods and motivate which is best to use during this research.

MCDA methods are widely used and many applications exist. A large number of methods exists and this chapter will outline the most common methods from different MCDA disciplines. Then, the state-of-the-art of MCDA is discussed. Afterwards, literature on MCDA in sustainability studies and fuel alternative studies specifically are discussed. The different criteria that are deemed most important to assess the research problem are also presented. In the end, a motivated choice is made which MCDA method is best to apply for this research.

6.1 MCDA methods

This section will elaborate on the different, most commonly used, MCDA methods that can be used to aid decision-making in this thesis. Besides from structuring the decision process, MCDA provides stakeholders a way to deal with decision-making while taking more than only economical aspects into account. MCDA involves stakeholders into making the decision, providing transparency in the decision process. Moreover, the inclusion of stakeholders could encourage collaboration between different stakeholder groups involved in the change to new alternative fuels.

6.1.1 SAW

The MCDA method considered most intuitive and simple is the Simple Additive Weighting (SAW) method. A linear additive function represents the preferences of decision makers without considering dependencies between criteria. The ratings of different alternatives are multiplied by the weights of each criterion to score the utility of different alternatives. This utility is then used to decide on the most suitable alternative. (Tzeng & Huang, 2011)

6.1.2 AHP

An often-used method of MCDA is the Analytic Hierarchy Process (AHP). The AHP method uses a priority scale to measure relative importance of different criteria, based on stakeholders judgements. These criteria are based on a hierarchic division of subcriteria. Using this priority scale and a score for each criteria, the most favoured alternative can be calculated. (Saaty, 2008)

6.1.3 ELECTRE

ELECTRE is an outranking method based on mutual relations between criteria. Using these relations, based on weight and rating of each criterion, a descending or ascendig order of alternatives can be made. The most commonly used methods are ELECTRE III and ELECTRE IV. (Roy, 1990)

6.1.4 PROMETHEE

PROMETHEE is a method that is quite similar to ELECTRE but uses fuzzy outranking for relations between criteria. It can be used for problems where the set of alternatives is continuous. Criteria weights can be determined with AHP and used in this method. As this method is an extension on AHP and this thesis will investigate a fixed amount of alternatives, this method is considered too extensive. (Greco et al., 2016)

6.1.5 MAUT

Multiple Attribute Utility Theory (MAUT) uses a function for Utility to carry out decision analysis. The expected Utility is calculated using a decision matrix and relative weight of all criteria. Using this expected Utility, the best decision of several alternatives can be determined. (Keeney, 1977)

6.2 MCDA State-of-the-Art

Multiple-Criteria Decision Analysis has been in use for decades. In recent times however, MCDA methods are more widely applied for sophisticated decision problems. MAUT and outranking methods like ELECTRE and PROMETHEE were already researched extensively halfway the 20th research. AHP has been first described in the seventies, introducing the relative importance of different criteria. Both above-mentioned methods are still being researched and developed. Fuzzy sets are being developed and used in AHP methods for example. On the evolution of MCDA, Greco et al. (2016) writes: ”We believe that in the last 10 years we have seen great progress of MCDA, from both a theoretical point of view and a real-life application point of view. We have seen the consolidation of the main “traditional” methodologies such as multiple attribute utility theory, outranking methods, interactive multiobjective optimization, as well as the growing success of new approaches such as Evolutionary Multiobjective Optimization (EMO).” The state-of-the-art of MCDA is in the development of new methods but also in the growing application of existing methods in real-world problems. (Tzeng & Huang, 2011) (N. Trivyza et al., 2016)

6.3 MCDA in sustainability studies

Wang et al. (2009) writes about MCDA in decision-making for sustainable energy. His study reviews criteria for MCDA and describes methods to select and quantify criteria. It concludes that multiple MCDA methods are necessary to evaluate and calculate sustainable decision-making. Moreover, he sees that AHP is the most used MCDA method in literature as of today.

Linkov and Moberg (2011) reviewed over 300 papers that applied MCDA in environmental studies. This review registrates a large growth in the application of MCDA in research papers. Moreover, more than 50% of the researches reviewed in sustainable energy used the Analytic Hierarchy Process. However, it must be noted that AHP has a share of almost 50% when more sustainibility topics are considered. Also MAUT, PROMETHEE and ELECTRE are often-used MCDA methods in the field of sustainable energy and strategy.

Recommendations on choosing a MCDA method are given in Greening and Bernow (2004). One of those is that weighting or scaling methods can be used when more information becomes available about alternative attributes and stakeholder preferences. This is applicable to this research as a lot of criteria will be quantifiable and stakeholders have certain preferences, for example based on the company profile of Fugro. Greening and Bernow (2004) also recommend to use more than one MCDA method to be able to verify and validate the outcome of a decision-analysis. Greening suggests certain useful considerations to use when developing a decision-framework. One of those, very applicable to this research is: ”A decision-support model that incorporates several different MCDM methods and that explicitly depicts the desired environmental and energy goals, the decision maker’s preferences towards those goals, and provides both technological detail (including the effects of learning) for the systems under analysis, and represents other economic activities.”

6.4 MCDA in fuel alternative studies

As mentioned above, many sustainability studies use a MCDA-method to consider different alternatives. Examples where MCDA was used to assess future alternative fuels specifically are also available. Saba (2019) researched the choice for an alternative fuel using MCDA. The research uses AHP to aid decision-making on alternative fuels for turbine peak power generation in the Port of Rotterdam. Another study that uses AHP to consider alternative fuels in shipping is Deniz and Zincir (2016). Alternative fuels and converters assessed in this study are not strictly valuable, but it shows a concise example of the use of an AHP for the assessment of alternative fuels. Ren and Lützen (2017) showcase a novel method of MCDA. This method uses fuzzy AHP to determine criteria weights. The results show that using this novel way of AHP has a slightly different outcome than conventional AHP. The study most comparable to this research is Hansson et al. (2019). This study includes seven different alternative fuels. It assesses technical, environmental, economical and social criteria to rank different alternative fuels using the Analytic Hierarchy Process. N. L. Trivyza et al. (2018) uses an unconventional method assessing environmental and economic performance by modelling different outcomes and showing these in a Pareto front. The fact that this study implements the operational profile of a case study is useful to this research, as this is also necessary for the case presented in this study.

6.5 MCDA criteria

As the name states, Multiple-Criteria Decision Analysis methods use criteria to consider different alternatives. For that reason, these criteria have to be set up for the problem posed. In MCDA applications found in literature a lot of criteria where used. In all these applications, the criteria have in common that they are subdivided in the same four main criteria groups; *technical*, *economic*, *environmental* and *other* criteria. All sub-criteria were listed in the four main criteria groups, to choose the most relevant criteria for this research. Special attention was given to the criteria posed in the studies described in section 6.4. This resulted in about 130 sub-criteria, including some similar or related, exact matches were deleted. From there, the most relevant criteria were determined and a shortlist was created. The chosen sub-criteria are elaborated on in the coming paragraphs. The criteria are also shown in the hierarchy tree in figure 6.1

Of the technical sub-criteria, gravimetric and volumetric density were deemed important as space

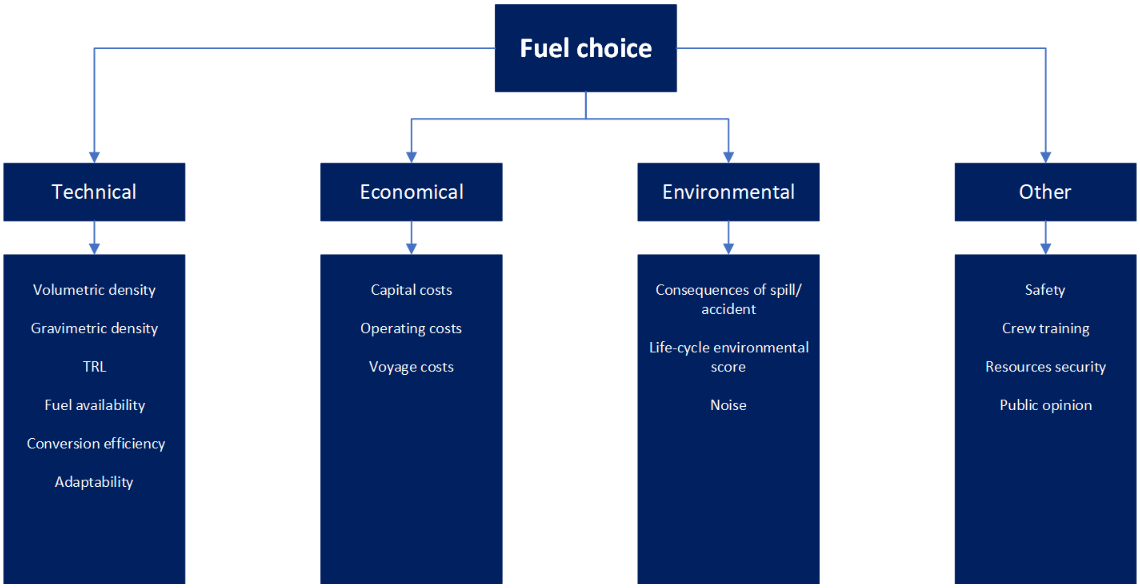


Figure 6.1: Decision hierarchy

and weight are often constrained on board of ships. Moreover, these two criteria vary over a wide range among alternatives. Another sub-criteria in this group is the Technology Readiness Level or TRL, how important is the technological development of an alternative when choosing a fuel. Also availability, in terms of the fuel production and bunkering infrastructure, is important and therefore chosen as a sub-criteria that influences the choice for an alternative fuel. Lastly, the efficiency and adaptability of different alternatives is included in the branch of technical criteria. Adaptability relates to the possibility of using different or drop-in fuels in the assessed alternatives.

The economical aspects deemed most important for the choice of an alternative fuel are Capital Expenses (CAPEX), Operational Expenses (OPEX) and fuel costs. These were most used in literature and also related to the three main costs of shipping as described by Stopford (2008); Capital cost, running costs and voyage costs. Therefore CAPEX, OPEX and fuel costs are chosen as the economic sub-criteria in this MCDA.

Environmental sub-criteria that are chosen include criteria on both emissions and pollution. The criterion taking emission into account is the life-cycle environmental score. Because all fuels are carbon-neutral when carbon capture during production is included, this criterion takes the whole life-cycle into account. Some fuels are carbon-neutral while others are zero carbon. Moreover, some fuels require after-treatment to prevent NOx emissions, this can be all included in this criterion. Then, the environmental consequences of a spill or accident are also included. This is an important aspect when looking at oil disasters of the previous years for example and differs for each fuel as well. Lastly noise is included, in ports but mostly on board of the vessels. Besides being important for the well-being of crew and local residents for example, this can be interesting for Fugro as noise could interfere with the used instruments on board of their vessels.

Lastly, *Other* criteria are also included. First, safety of different alternatives is assessed. Certain fuels bring or excluded certain hazards on board. Also crew training is included to assess whether personnel needs to be re-schooled in order to use an alternative fuel. Resources security is also included as a criterion, this takes into account the dependency of rare sources or the availability of a fuel with or without geopolitical instability for example. Lastly, public opinion is included as a criterion.

6.6 Conclusion

As described in this chapter, a large number of MCDA methods is being applied in different studies. The AHP method is the most often applied method of MCDA. Moreover, AHP is known for it's ability to easily work out different scenarios and the possibility to involve stakeholders in a transparent decision-making method. Which is important as this decision is based on incomplete and rapidly changing information due to future uncertainties and technological developments. Also, this chapter pointed out that literature describes that this method can be very suitable in order to compare different alternatives in a similar setting as the problem described in this thesis. For that reason, the AHP will be used as MCDA method in this research. Also, the criteria to be used are established. The AHP method for this research will be worked out in chapter 8. But first, now the criteria to be considered are known, a more thorough research and assessment of alternative fuels will be discussed in the next chapter, chapter 7. This is done to score and evaluate the different fuel alternatives on the criteria as posed in this chapter.

7

Alternative fuels

During the literature research of this graduation project, an initial examination of alternative fuels was carried out. The distinction between fossil-, bio- and electro-fuels was a key take-away from this study. Using the distinction between different alternative fuel types, the amount of considered fuels could be narrowed down for the first time. Fuels acquired from fossil feedstock, e.g. hydrogen or methanol from natural gas, can be zero-emission when tank-to-wake emissions are considered. When the well-to-tank emissions of these alternative fuels are considered however, these fuels sometimes emit more than MDO does. For that reason, in order to come up with a truly sustainable fuel alternative, it is important to consider the well-to-wake emissions of each fuel. Bio-fuels provide a more sustainable solution. However, studies considering bio-fuels all emphasize that the scalability of these fuels is difficult as these fuels need a feedstock that interferes with food production and forest conservation. Besides, most bio-fuels are not carbon-neutral when used as ship fuel. Fuel alternatives mentioned in literature that have the potential to be zero-carbon or at least carbon-neutral are so called electro-fuels. These fuels will be elaborated on in this chapter.

Thus, these electro-fuels are included in this research. These fuels are assessed in detail in this study. To gather knowledge on the different fuels and their properties, to provide stakeholders with a reference work of the considered electro-fuels but most importantly to use in the methodological part of this study. First, the properties and information on fuel alternatives are used to score the different alternatives in the AHP in chapter 8. For clarity, the information on fuels in this chapter is grouped per criterion as introduced in the previous chapter on MCDA methods. Moreover, the values and parameters that are found in this chapter are to be used in the case study in chapter 9. To make price or design estimations for example.

7.1 Hydrogen

Hydrogen is one of the potential zero-emission fuels considered in this literature study. It can be stored as a gas, cryogenic liquid or as a solid using Sodium Borohydride. Moreover, hydrogen can be used to produce other renewable fuels, as will be discussed in the following paragraphs. Energy converters running on this fuel are Fuel Cells (FC) and to a lesser extent, Internal Combustion Engines (ICE). Nowadays, 95% hydrogen is produced reforming natural gas, which incurs high production emissions. To be an attractive low-emission fuel in future, hydrogen has to be produced by electrolysis, using Renewable Energy (RE) to do so.

7.1.1 Technology

Storage

This thesis will look into hydrogen stored compressed at 700 bar and liquefied hydrogen stored at -252,8 °C or 20,3K. Hydrogen has a gravimetric density (120 MJ/kg) about three times higher than diesel. When the storage system to compress or liquefy hydrogen is included, this gravimetric density becomes approximately three times smaller than diesel. Meaning that the same amount of energy carried is three times heavier than the conventional diesel fuel and it's storage system. The volumetric density of hydrogen is about 10-15 times smaller than diesel when stored compressed and 7 times smaller when stored liquefied, including the storage system (DNV GL, 2019b). This is also where the main drawback of hydrogen lays, it's storage volume is very large and the conditions in which hydrogen has to be stored are difficult to maintain. Also, having boil-off gas is inevitable. The boil-off rate is 0,3 to 0,5 % per day, depending on the used storage technology and conditions (DNV GL, 2019a). Current liquid hydrogen tanks range from 400 to 6700 kilograms.

Converters

Hydrogen can be used in Fuel Cells (FC) as well as Internal Combustion Engines (ICE). When applied in an ICE hydrogen is mainly mixed in with another conventional fuel. The following paragraphs will discuss these options in detail.

The three fuel cell technologies considered most promising are the Protone Exchange Membrane Fuel Cell (PEMFC), it's High Temperature variant (HT-PEMFC) and the Solid Oxide Fuel Cell (SOFC). These are low-, medium- and high-temperature fuel cells respectively. All these technologies are still under development with the PEMFC being the most developed technology. Reported gravimetric and volumetric densities vary but are 250-1000 W/kg 300-1550 W/L for the (HT-)PEMFC, which needs reformers because it requires very pure hydrogen as fuel. Because of the higher temperatures HT-PEMFCs and SOFCs are able to use less pure hydrogen or hydrogen carriers as fuel. For example synthetic gases and methanol. This makes that HT-PEMFCs and SOFCs have a higher adaptability to different fuels. SOFCs have a gravimetric and volumetric density of 8-80 W/kg and 4-32 W/L respectively (Van Biert et al., 2016). PEMFC's are available up to 400 kW and have the highest technological maturity. HT-PEMFCs are applied as auxiliary power units and SOFCs are not yet deployed in the shipping industry. When they will be, SOFCs are suited for larger applications above 100 kW. (HT)-PEMFCs are therefore assumed to have a TRL level of 6 to 7. SOFC's TRL is assumed to be 5 (DNVGL, 2017). (HT)-PEMFCs have efficiencies ranging from 40 to 60 %, with higher efficiencies reached in a HT-PEMFC compared to the low temperature variant. The SOFC installations can reach efficiencies up to 60% possibly increasing to 70% in future. Fuel cells, especially the SOFC, need to be combined with battery technology to cope with peak power delivery and power fluctuations. Also known as peak-shaving.

Options to use hydrogen in an Internal Combustion Engine do exist, hydrogen can be used in gas engines as well as dual-fuel engines. In this case hydrogen is blended in together with the pilot fuel, not causing major technological challenges (DNV GL, 2019b). These engines have an efficiency of between 40 and 50 % and are therefore less efficient than the above-mentioned fuel cells. When hydrocarbon fuels are used however, ICEs can be more efficient as efficiency is lost using fuel cells due to reforming and leaking fuel (Van Biert et al., 2016). ICEs compared to the generator sets that Fugro is using now would be a pure-gas four stroke or dual-fuel four stroke engine. Technology readiness of these type of engines using hydrogen as fuel are assumed to be 5. (Lloyd's Register, 2020). Gravimetric density of these internal combustion engines vary from 45-70 W/kg and a volumetric density of 30-55 W/L (Van Biert et al., 2016). Most of these solutions would require dual-fuel systems, increasing these densities to the high side of this spectrum. These engines are capable of running on many different fuels with minor modifications making them suitable for other drop-in fuels.

Fuel availability

Electrolysis plants producing hydrogen using Renewable Energy are not yet in existence. In Germany, an electrolysis plant is being built and expected to be finished in the second half of 2020. This plant could produce up to 1300 tons of hydrogen each year but is not running on RE yet (Refhyne, 2020). Other projects considering the construction of large electrolysis plants running on RE are in the conceptual stage and likely to be carried out in the coming years. Hydrogen from electrolysis is also very suitable for local production as it only requires a source of water and Renewable Energy. All other electro-fuels that are considered in this thesis require hydrogen to be produced making that this has to be the most commonly available fuel of fuels considered in this thesis.

Infrastructure to compress or liquefy hydrogen is available, however not in large numbers and not for shipping specifically. Moreover, hydrogen fuel would require a whole different bunkering- and ship-infrastructure, which also has safety concerns tied to it. This infrastructure is not yet in existence and the uptake of LNG in recent years showed that this is a difficult task. The coming years will show how extensively this infrastructure will develop.

7.1.2 Costs

This section will consider the costs of hydrogen technology. Capital, operational and voyage costs will be discussed.

Capital costs

Today hydrogen technology is a lot more expensive than conventional energy converters (Van Biert et al., 2016) (DNV GL, 2019b) (Lloyd's Register, 2020). Fuel cells are more costly as well as the storage systems that hydrogen requires. Prices for a hydrogen fuel cell system range from 2000 USD/kW to 6000 USD/kW (DNV GL, 2019b) (Brynolf, 2014).In this price range, PEMFCs are at the low end, HT-PEMFC are priced mediocre and SOFC is the most expensive fuel cell technology. Prices of these fuel cells are expected to drop in future however. DNV GL expects PEMFC technology for heavy-duty road transport to be competitively priced by 2030 for example.

Internal Combustion Engines suitable for hydrogen are expected to be 15 to 20% more expensive than conventional engines (DNV GL, 2019b). Brynolf (2014) expects the price of ICE technology to be 870 USD/kW.

The additional costs of the storage system and the revenue loss due to the large volume of the installation (mainly for cargo carrying ships) make hydrogen an expensive option. Not a lot of experience with maritime appliances makes it difficult to assess. Brynolf (2014) uses 225 USD/GJ for the price of fuel storage systems. Lloyd's Register (2020) expects prices of the storage system to be higher than that of a LNG-system, without stating any prices.

Operational costs

Operational expenses are not yet known as these require experience in a maritime environment. Fuel cells are known to have less moving parts than an engine, however the fuel cell stacks have to be replaced quite often relative to other technologies. This makes operational expenses using hydrogen relatively high (Van Biert et al., 2016). ICEs running on hydrogen are expected to have comparable operational expenses to technology in use as of today (DNV GL, 2019a).

Voyage/fuel costs

Prices of hydrogen fuel are also varying. Renewable hydrogen is expected to cost 1000 to 2000 USD per toe according to DNV GL (2019a). Lloyd's Register (2020) expects the price to be in the range of 44 to 79 USD/GJ.

7.1.3 Environmental

Consequences of spills/accidents

Hydrogen is a colourless, odorless, non-toxic gas, bringing the consequences of spills to a minimum. More than that, hydrogen does always leak when being stored onboard. So called boil-off gas is inevitable and not harming the environment. Please note that this means that spills/accidents have a minor impact on the environment, safety could be highly jeopardized as accidents can very well occur using hydrogen, more on this in the section about safety below.

Life-cycle environmental score

The life-cycle environmental score of hydrogen as fuel is very good because the emissions during production and operation are very limited. Hydrogen and all other electro-fuels have a high cumulative energy demand must be noted however. Mestemaker et al. (2020) shows that even with upstream emissions caused by the development of Renewable Energy, building an offshore wind farm for example, hydrogen still only emits a fraction of the emissions of a conventional installation. Impact on the life-cycle environmental score from acifidication, eurotrophication and aerosol formation are negligible.

Fuel cell catalysts are often produced from rare earth and scarce materials. This is important to consider, however the effect on the life-cyle environmental score is difficult to evaluate. When using dual-fuel engines, depending on the fuel, hydrogen could still emit greenhouse-gasses. For that reason, this solution is therefore not aimed for in this thesis. When used in a Spark Ignition (SI) ICE, hydrogen again has very low emissions.

Noise

Fuel Cells are more quiet than conventional Internal Combustion Engines. Department of Energy (n.d.) reports a 50% reduction in produced sound of a PEMFC compared to an ICE. HT-PEMFC and SOFC could be more noisy due to coolers and other auxiliaries. The reduction in moving parts in fuel cell technology makes that this technology is considered less noisy than an ICE.

When hydrogen is used in an spark-ignition engine, sound levels are assumed to be comparable to current sound levels.

7.1.4 Other

Safety

An overview of safety relevant considerations of hydrogen systems are provided in the ISO/TR 15961 code (DNV GL, 2019a). The IMO also provides a code for the carriage of hydrogen in bulk in MSC.420(97). The fact that hydrogen has to be stored at very low temperatures or high pressures incurs safety hazards. The most important safety considerations recognized are:

- Low temperatures
- Low ignition energy
- High permeability, low viscosity

- Wide flammability limit
- Low visibility of flames in case of fire
- High flame velocity resulting in detonation with shockwave
- Liquefaction/solidification of inert gas and constituents of air (oxygen-enriched atmosphere)
- Hydrogen embrittlement including weld metals.

These considerations make that hydrogen brings serious safety concerns when installed on a ship. The shipping industry isn't experienced using hydrogen. Therefore, ISO and IMO codes and resolutions have to be expanded in order to safely operate hydrogen systems.

Crew training

As mentioned in the previous paragraph, the inexperience with hydrogen systems on board of ships is very limited. Hydrogen brings certain hazards for which ISO and IMO codes have to be established. The safe handling and operation of hydrogen systems is therefore considered complex and procedures are required, for this reason crew has to be (re)schooled intensively in order to operate a hydrogen fuelled ship.

Resources security

Hydrogen is produced sustainable using electrolysis. This process requires an electrolysis plant, Renewable Energy (RE) and water. This makes hydrogen an emission-free alternative that is relatively easy to produce without a lot of resources. The electrolyzer plants are very suited to set up locally. However, less developed regions could have difficulties setting up the required infrastructure and supply of Renewable Energy. Also, countries in which water is scarce could have difficulties producing hydrogen without imported resources, in these countries Renewable Energy could be available abundantly in the form of solar energy . The other way around, countries in which water is abundantly available could depend on these countries for a part of the Renewable energy.

Public opinion

In the car industry, batteries seem to have won the preliminary battle on alternative technologies when compared to hydrogen. Also some are sceptical about the safety hazards that hydrogen brings. Other than that, hydrogen doesn't suffer from a significant negative public opinion.

7.2 Ammonia

Another sustainable fuel considered is ammonia. Using renewably produced hydrogen and nitrogen, ammonia can be produced as clean alternative ship fuel. Ammonia can be used in both Fuel Cells and Internal Combustion Engines. Ammonia is an industrial commodity that is already produced at a large scale, however not without carbon emissions. To be carbon-neutral, ammonia can be produced using the Haber-Bosch principle powered by Renewable Energy. Because this molecule only contains nitrogen and hydrogen, no carbon is emitted when used as shipping fuel.

7.2.1 Technology

Storage

The largest disadvantage of hydrogen, it's volume when stored, is taken away by ammonia. It can be stored as a liquid at about ten bars and ambient temperature or at -33 °C. Ammonia, including storage, has a volumetric density of 11 MJ/L and a gravimetric density of 17,5 MJ/kg. Still, this is approximately 3,5 times more voluminous and 2,5 times more heavy for each carried MJ compared to conventional diesel (DNV GL, 2014). However compared to hydrogen, ammonia requires approximately half the weight and volume required to carry one MJ of energy. The storage of ammonia doesn't require unprecedented technology requirements, however corrosion in storage tanks can provide problems and has to be prevented (Royal Academy of Engineers, 2013).

Converters

Ammonia can be used in both Fuel Cells (FC) as Internal Combustion Engines (ICE). To use ammonia in an ICE, it has to be mixed with other fuels that have more suitable combustion properties.

When used in Fuel Cells (FC), ammonia has to be reformed at high temperatures. Especially PEMFCs require very pure hydrogen, this low temperature fuel cell would require a lot of additional energy to reform the ammonia sufficiently. Therefore it is not considered efficient to use this fuel in a PEMFC. However, the *Viking Lady*, an offshore vessel, will be retrofitted with a 2-MW fuel cell running on ammonia. This vessel is planned to be in operation around 2024. Ammonia is also suitable to be used in a SOFC which operates at higher temperatures however. The SOFC has very advantageous properties to run on ammonia but has difficulties to cope with peak shaving. The technology readiness level of SOFC solutions is still very low at approximately 4-5, these are expected to be commercially available in about 20 years (Mestemaker et al., 2020).

Ammonia has a very high resistance to auto-ignition and narrow flammability limits. For this reason it is difficult to apply in both compression- and spark-ignition engines and needs a pilot fuel (Transport Environment, 2018). However, MAN is planning to have an ICE running on ammonia within the next four years (MAN, 2019). When applying ammonia as fuel for Combustion Ignition (CI) engines it is important to prevent NOx emissions due to high temperature and pressure. MAN and Wartsila are researching ammonia-fueled Internal Combustion Engines (De Jong, 2020). Wartsila is setting up a project testing an ICE running on ammonia intensively over a long time. Therefore the TRL is assumed to be 5-6.

Gravimetric and volumetric density of the converters are similar to those mentioned in subsection 7.1.1.

Fuel availability

No ammonia is produced without GHG-emissions as of today. The Haber-Bosch process has provided large-scale production of ammonia for over 100 years. Therefore, this fuel can be produced on a large scale with available technology. To be sustainable however, this process requires renewable hydrogen as described in the previous paragraph. A company, funded by the government of Australia, is in the design phase of a plant to demonstrate the production of green ammonia. Just like hydrogen production, which is required for the Haber Bosch process, ammonia production is possible with current technology, but requires a large supply of Renewable Energy. This technology is available and the coming years need to point out how the production sets off.

7.2.2 Costs

Capital costs

The investments costs for ammonia Fuel Cells are high and comparable to those mentioned in the previous section considering hydrogen. When looking at ammonia ICE installations, the price is estimated to be 1.2 times higher than the CAPEX of a conventional diesel installation (Korean Register, 2020). Mostly because of the storage system and advanced ICE technology that are slightly more expensive. This is expected to be lower than the CAPEX of a LNG plant for reference.

Operational costs

No practical experience is available up to date, but it is expected that the operational expenses of an ammonia installation are comparable to those of a vessel operating a conventional installation without scrubber (DNV GL, 2019a). When applying ammonia in FC technology, the same considerations as described in 7.1.2 apply.

Voyage/fuel costs

1800-2300 usd/toe (DNV GL, 2019a). Lloyd's Register (2020) assesses two pathways for ammonia production. First pathway totals at 47 to 82 USD/GJ while the other pathway reports a price of 26 to 43 USD/GJ in 2030. The price decreases further with time, up to approximately 30 to 40 USD/GJ by 2050. Korean Register (2020) expects ammonia to be cheaper than hydrogen and synthetic methanol at a price of 4,5 $/Gasoline Gallon Equivalent (GGE). The reason ammonia can be cheaper than hydrogen lays in the fact that ammonia transportation and storage is less expensive compared to that of hydrogen.

7.2.3 Environmental

Consequences of spills/accidents

Ammonia is a poisonous gas, very toxic to both humans and animals. It has the ability to dissolve quickly but during a spill large harm to the environment can be done.

Life-cycle environmental score

Ammonia used in a dual fuel engine can easily generate significant emission reductions. The cumulative energy demand of ammonia production is even higher than that of hydrogen, but when Renewable Energy is used, the fuel is very environmentally friendly. When used without pilot fuel, it has a very good environmental score when nitrogen can be contained, for example when using an SOFC (ITF/OECD, 2018).

Noise

Again, when used in fuel cells, the installation will probably be more quiet. Depending on the installation, when a SOFC uses heat recovery, it could be that these auxiliaries have significant sound levels. When used in an ICE, sound levels are probably comparable to those measured nowadays.

7.2.4 Other

Safety

Ammonia is a very poisonous gas, human exposure could bring serious harm. Leakages could occur, spilling anhydrous ammonia gas. The limited flammability of ammonia gives it an advantage over some other fuels like hydrogen. Besides the hazards to the environment when being spilled, ammonia vapours are also toxic to humans. Therefore far-reaching safety measures have to be taken when bunkering or working on ammonia machinery. For example when maintenance is carried out on the prime mover. On the opposite, extensive experience on ammonia handling and usage is present because of its application in fertilizers for example.

Crew training

The safety concerns require that the crew has to be re-schooled to be familiar with ammonia and it's properties. Ammonia requires a sensing system, measures to dissolve it and safety manuals to be mastered by the crew sailing an ammonia-propelled vessel (Korean Register, 2020). When using ammonia in an ICE, technology isn't very different from the technology used nowadays, making the transition for a crew more easy.

Resources security

The resources security is comparable to that of hydrogen. A lot of Renewable Energy is required as well as hydrogen and nitrogen. Using these, the fuel can be produced using the Haber-Bosch principle.

Public opinion

Ammonia is already widely used in agricultural applications without severe complaints. While it could sound weird for some to hear that a vessel could sail on ammonia, the public opinion on ammonia is not good or bad.

7.3 Methane (e-LNG)

Another alternative considered is synthetic methane. Synthetic methane is also referred to as electro-methane, e-methane or e-LNG. Methane (CH_4) is the main component of conventional LNG and can be produced (without emissions) synthetically combining hydrogen from electrolysis with captured carbon dioxide. The resulting synthetic methane can be a direct substitute for compressed or liquefied natural gas. For this reason the technology required onboard is similar to the already existing components found in a LNG-installation.

7.3.1 Technology

Storage

The boiling point of (e-)LNG is at -163 °C and is therefore stored in insulated tanks. Including storage installation, LNG has a volumetric density of approximately 13 MJ/L, which equals a volume three times larger compared to diesel. The gravimetric density of LNG including storage system is 22 MJ/kg. Approximately double the mass of a conventional diesel fuel system (DNV GL, 2014). Without the storage system included, the energy density per mass is approximately 18 per cent higher than that of HFO, but the volumetric density is approximately 65 per cent of HFO (kg/m^3).

Compared to hydrogen and ammonia, LNG requires less volume and mass for the same amount of engine carried. When storing LNG, boil-off is inevitable and has to be dealt with.

Converters

When natural gas or LNG is used in fuel cells it has to be reformed first. Again, this requires extensive reformation, especially for PEMFCs which need external reformers, therefore this application is not considered very efficient. SOFCs can internally reform the LNG due to the high operating temperatures. The same pros and cons as stated in the converter section of ammonia are the case when using LNG as SOFC fuel. Again, this installation has a TRL of 4-5, which a slight advantage over ammonia due to the more extensive shipping experience with LNG.

Low cetane fuels like LNG require an external ignition source to start the combustion process. Therefore LNG can be used in Spark Ignition (SI) and Dual Fuel (DF) combustion engines. When burned in combustion engine, incomplete combustion, causing so called *methane slip* needs to be prevented. When used in a DF engine with diesel, the emission of NOx due to high combustion temperatures is an important aspect to avoid. LNG is already applied in both SI and DF combustion engines of existing ship applications. These LNG ICE installations are therefore already in an advanced stage, the accompanying TRL level is 9 (Lloyd's Register, 2020).

Fuel availability

The production of LNG as liquefied form of natural gas is already significant (DNV GL, 2014). Probably increasing in the coming years. Also, the infrastructure to bunker LNG is growing rapidly worldwide. The sort of LNG this thesis assesses has to be produced using hydrogen from electrolysis and captured or stored carbon. Both of these processes are not yet in existence on a large-scale. TRL levels of these technologies are at 5 to 6 at this moment and are expected to be around 8 or 9 in 2030 according to Bergsma, 't Hart, Pruyn, Verbeek (2020). A big advantage is that when synthetic methane is produced on a large-scale, the bunker infrastructure for this fuel is already available from the use of fossil LNG as shipping fuel. Moreover, synthetic methane can be mixed with conventional LNG when there is no availability of renewable LNG.

7.3.2 Costs

Capital costs

The capital expenses of a LNG installation are believed to be 1.3 the expenses of a conventional diesel installation (Korean Register, 2020). According to DNV GL (2014) CAPEX will decrease as applications increase and competition between suppliers intensifies. However, LNG installations will stay more expensive than a MDO or HFO system with scrubber. Mainly because of the more complex fuel system.

Operational costs

Operational costs for a LNG fuelled system are comparable to those of a conventional oil fuelled system. The maintenance costs for a high pressure gas system on board of these vessels needs to be considered however (DNV GL, 2014).

Voyage/fuel costs

Lloyd's Register (2020) expects the price of e-LNG to be between 59,7 and 98,5 USD/GJ by 2030, with the price decreasing another 30% in the 20 years thereafter. The reference scenario of Brynolf et al. (2018) expects the price of e-LNG to be between 100 and 290 EU/MWh.

7.3.3 Environmental

Consequences of spills/accidents

According to LiquefiedGasCarrier.com (n.d.), liquefied gases are non-polluting, products and create no danger to the marine environment. If however LNG spills on to the sea one should consider the following consequences:

- Creation of large quantities of vapour, sea water rapidly vapourises and the liquid gas may cause a fire or explosion or health hazard
- Generate toxic vapours, which could drift over a sometimes considerable distance
- Dissolving of LNG in sea-water causing local pollution

Life-cycle environmental score

Synthetic methane produced using renewable hydrogen, captured carbon and renewable electricity has a net negative emission because of the carbon that is captured and used to produce the fuel. When used as vessel fuel, this vessel will emit CO_2. When combining the net negative upstream emissions with the operational emissions of the vessel, these emissions level each other out. In other words, this fuel delivers a net zero emission solution for ship propulsion. *Methane slip* could significantly jeopardize this environmental score as the release of this gas has a very high Greenhouse Gas potential.

Noise

Again, less noise is expected when applied in a Fuel Cell system. When applied in an ICE, LNG installations have comparable properties as conventional installations.

7.3.4 Other

Safety

Mokhatab et al. (2013) mentions that the main hazards of handling LNG are fire and explosion, cryogenic freeze burns, embrittlement of metals and plastics, and confined spaces hazards. All these safety issues are well understood and can be mitigated when the potential hazards are carefully considered. Moreover, the IMO IGF code for LNG and CNG came into force in January 2017. The design and construction of LNG-fuelled ships is established in this document (DNV GL, 2019a).

Crew training

LNG applied in combustion engines relies on some technology that is different from conventional systems, but the main propulsor is mostly the same. Therefore crew has to be (re)schooled to be aware of the handling and safety concerns of this fuel.

Resources security

As recent times point out, natural gas is subject to some geopolitical tension and not widely available everywhere. When produced using renewable technologies, the fuel isn't necessarily relying on geopolitical aspects. Still a country that wants to produce synthetic methane requires sufficient funding and renewable energy in order to establish a synthetic methane production chain. Thus, less developed countries could have difficulties setting up production.

Public opinion

LNG is already applied as of today, no specific public opinion is known.

7.4 Methanol/ethanol

Methanol and ethanol are alcohols with a low carbon content and high hydrogen content. These are liquids which can also be used as ship fuel. Methanol is already used as a building block for a wide variance of chemical commodities. Nowadays the largest part of methanol is produced reforming natural gas or coal, which is not environmentally friendly (ITF/OECD, 2018). The methanol/ethanol considered in this thesis is formed from the renewable resources hydrogen and CO_2. Both can be used as shipping fuel and have quite similar characteristics. Because methanol is more often described in literature and used in existing applications this chapter will go into methanol specifically. Methanol can also be converted to DiMethyl Ether (DME), which can be used as a fuel for diesel engines and is described in the following section.

7.4.1 Technology

Storage

Methanol is a liquid between -93 °C to +65 °C at atmospheric pressure, for that reason it is relatively easy to store. Moreover, methanol is allowed to be stored in void spaces, which is considered a safety concern with conventional fuels (ITF/OECD, 2018). Methanol has a gravimetric density of 19.5 MJ/kg and is therefore twice as heavy as diesel for the same amount of engine carried. The volumetric density of methanol is approximately 17 MJ/L, meaning methanol fuel tanks have a size approximately 2 to 2.5 times larger than oil tanks for the same energy content (DNV GL, 2014). Methanol has a flashpoint of 11°C to 12°C and is considered a low-flashpoint fuel.

Converters

Alcohols like methanol have a high auto-ignition temperature, which makes them suitable for Spark Ignition (SI) engines. Compression Ignition (CI) is also possible when a pilot fuel is used (Bergsma, ’t Hart, Pruyn, Verbeek, 2020). Moreover, Dual-Fuel (DF) engines can combust methanol and ethanol. This requires a similar engine conversion as when using dual-fuel LNG in an engine. An advantage of this configuration is that it can also switch back to running on diesel solely. Lloyd’s Register (2020) places the TRL level of these technologies at 6 to 7. However, a ferry running on methanol is already active for a few years, this makes that the TRL is scored slightly higher for methanol ICE technology.

The HT-PEMFC may be used to operate on methanol because methanol is relatively easy to reform. The Direct Methanol Fuel Cell is not considered in this thesis as this converter emits CO_2 and isn’t efficient. It is also possible to use methanol in a SOFC application. While the utilisation of methanol is theoretically possible, few studies have investigated this solution to use methanol in HT-PEMFCs and SOFCs (Van Biert et al., 2016). Natural gasses are assessed more often for application in high temperature fuel cells. The SOFC running on methanol is assumed to have a TRL of 4.

Fuel availability

Methanol is already produced as chemical commodity on a large scale, using natural gas or coal reformation. Especially China reforms a lot of coal into methanol. From the bunkering of for example supply vessels, relevant experience concerning this process is present. This is mostly for methanol loaded as cargo however. Of course, bunkering fuel is different than loading cargo however (DNV GL, 2019b). Bergsma, 't Hart, Pruyn, Verbeek (2020) expects the production of renewable methanol to have a TRL level of 6 to 8 by 2030.

7.4.2 Costs

It should be mentioned that the extra capital cost for the storage of e-LNG is higher than the one required for e-methanol, but the TCO for a ZEV using e-LNG will still be less than e-methanol under the assumptions of the scenarios covered in this paper. (Lloyd's Register, 2020)

Capital costs

Due to the lack of special equipment and material that is able to handle cryogenic temperatures or pressurized fuel tanks, the investment for a methanol installation is relatively low. The additional CAPEX for a methanol installation are expected to be about one third of the expenses necessary for a LNG installation for example (Lloyd's Register, 2020) (DNV GL, 2019a). Bergsma, 't Hart, Pruyn, Verbeek (2020) expects a methanol engine to cost 655 EU/kW, the storage installation is estimated to cost 45 EU/GJ.

Operational costs

It is difficult to make an estimation of running costs of a methanol installation as only a few methanol fuelled ships are in operation as of today. It is expected that the operational costs are cmparable t those for oil-fuelled vessels without scrubber technology (DNV GL, 2019a).

Voyage/fuel costs

Many different fuel prices are mentioned in literature. Synthetic methanol is expected to cost between 73 and 118 USD/GJ in 2030 according to Lloyd's Register (2020), while Brynolf et al. (2018) estimates a fuel price of 100 to 260 EU/MWh. Lastly, DNV GL (2019a) estimates the synthetic methanol price to be between 1700 and 2500 USD per toe.

7.4.3 Environmental

Consequences of spills/accidents

Methanol is moderately toxic, especially to humans. However it is currently not classed as being toxic. This may change in the revised IBC code (International Code for the Construction and Equipment of Ships carrying Dangerous Chemicals in Bulk) however. Methanol will leak as a liquid and might partly evaporate. The fact that methanol may be carried in hull voids show that methanol is relatively harmless to the environment.

Life-cycle environmental score

Methanol combustion emits CO_2, the negative upstream emissions caused by captured carbon for production counter this emission however. Therefore using methanol produced from renewable hydrogen and captured carbon is a net zero carbon fuel alternative. The dual fuel engines combusting methanol do not yet achieve zero NOx emissions, for that reason additional measures are necessary.

Noise

Less noise is expected when applied in a Fuel Cell system. When applied in an ICE, installations using methanol have comparable properties as conventional installations.

7.4.4 Other

Safety

Methanol is generally more safe than conventional fuels and LNG (ITF/OECD, 2018). Therefore regulation is less constraining, however methanol is toxic to humans. Although not formally classed toxic yet, the revised IBC code might change this. Inhalation and exposure to skin need to be prevented. Moreover, methanol can catch fire in a mixture with water and air, this is dangerous considering the low ignition temperature (DNV GL, 2019b).

Crew training

Methanol applied in combustion engines relies on some technology that is different from conventional systems, but the main propulsor is mostly the same. Therefore crew has to be (re)schooled to be aware of the handling and safety concerns of this fuel. When fuel cells are applied this is different as an entirely different technology is used.

Resources security

For this high energy demand fuel, a very large Renewable Energy (RE) supply is required. Moreover, extensive Carbon Capture & Storage has to be available. However, the use of this fuel is not dependent on oil reserves like today.

Public opinion

Methanol isn't subject to a good or bad public opinion.

7.5 DiMethyl Ether (DME)

By dehydrating methanol or directly using syn gas, DiMethyl Ether (DME) can be produced. DME has properties very similar to those of diesel and this fuel can be used as a liquid fuel in an Internal Combustion Engine (ICE). DME is non-toxic and somewhat more energy dense than methanol. When burned in an ICE, no soot is formed as DME doesn't contain carbon bonds (Van Biert et al., 2016).

7.5.1 Technology

DiMethyl Ether (DME), is very similar to methanol with regard to fuel production, however in engine application it is completely different. DME has a low auto-ignition temperature which makes is very suitable for diesel combustion. The injection system is however different from diesel engines (higher volume, lower pressure, lower lubricity). Some demo truck engines on DME have been build, but not (yet) ship engines. Although for the engine DME has some advantage over methanol, the fuel tank would be more expensive and require much more volume, since DME is a liquid gas similar to LPG (Bergsma, 't Hart, Pruyn, Verbeek, 2020)

Storage

The handling and storage of DME is relatively easy as it can be stored as a liquid at pressures around 5 Bar, similar to Liquefied Petroleum Gas. However, methanol is still considered to be more practical in use than DME. DME tanks would require a larger storage volume as well as more expansive pressurized tanks (Bergsma, 't Hart, Pruyn, Verbeek, 2020). The volumetric density of DME is 19 MJ/L, the gravimetric density is 28 MJ/kg. Therefore, the energy density per mass and volume is lower compared to diesel. The storage volume of DME is therefore considered to be twice as large compared, to diesel. Another difficulty when handling DME is that it's viscosity is 20 times lower, more easily causing leakages and lubrication issues (Semelsberger et al., 2006).

Converters

With regards to fuel production DME is very similar to methanol, the engine application differs however. It's low auto-ignition temperature makes that it is very suitable for diesel combustion. It can be used as fuel in Combustion Ignition engine. However, modifications to the diesel ICE are necessary as the injection system is different from the one found in conventional diesel engines (Royal Academy of Engineers, 2013).

To acquire larger efficiencies, DME can also be used in SOFCs instead of natural gas (Mestemaker et al., 2020). Reforming DME would require significant amounts of energy making this fuel less suited for application in (HT)-PEMFCs.

Fuel availability

DME is made in almost the same process as methanol. It is also used as chemical commodity, as propellant gas in spraycans for example. Up til now it is not made using renewable hydrogen and captured carbon however. Bergsma, 't Hart, Pruyn, Verbeek (2020) expects the TRL of renewable DME to be 6 to 8 by 2030. Infrastructure to bunker vessels is different from the conventional infrastructure and is not yet available for DME.

7.5.2 Costs

Capital costs

The capital costs of DME will be similar to those of diesel-related costs but with a more expensive supply and storage system.

Operational costs

Also operational costs are expected to be comparable to those related with a diesel engine system. However, the difficulties concerning lubrication and leakages could drive the operational costs higher. No operational experience with DME as ship fuel is known to exist.

Voyage/fuel costs

DNV GL (2014) expects the fuel price of renewable DME to be 1,700 to 2,700 USD per toe. The reference scenario by Brynolf et al. (2018) epxects the price to lay between 100 and 310 EU/MWh in 2030. Non-renewable DME, as used in the checmical industry is cheaper and could be mixed together with renewable DME.

7.5.3 Environmental

Consequences of spills/accidents

DME has the advantage that it is non-toxic, non-mutagenic and noncarcinogenic. Therefore spills will have no severe environmental consequences.

Life-cycle environmental score

When combusted, DME doesn't produce soot. It still emits CO_2, but the same amount of CO_2 is captured from the atmosphere during production, therefore this fuel is carbon neutral. The production requires a lot of energy which has to be generated renewable.

Noise

Less noise is expected when applied in a Fuel Cell system. When applied in an ICE, installations using DME have comparable properties as conventional installations.

7.5.4 Other

Safety

As described in the paragraph about spills/accidents, DME has properties that make it a relatively safe fuel. It has to be stored in pressurized containers however, this could incur some safety concerns.

Crew training

DME requires crew to be schooled to use the supply and storage systems, the other technique is comparable to conventional propulsion systems. Therefore it doesn't require extensive crew training.

Resources security

Again, a very large Renewable Energy (RE) supply is required. Moreover, extensive Carbon Capture & Storage has to be available. However, the use of this fuel is not dependent on oil reserves like today.

Public opinion

DME isn't subject to a good or bad public opinion.

7.6 e-Diesel

Similar to the other fuels mentioned in this chapter, diesel can also be synthetically produced using renewable hydrogen from electrolysis and CO2 capture from air. The resulting fuel is still carbon-based, hence its combustion emits CO2 (and NOx); but since the CO2 is originally captured from the atmosphere, such a synthetic diesel fuel would be carbon neutral on a full life cycle basis. Electro-diesel fuels would have similar physical and combustion properties as fossil diesel, so could be used with existing on-board ship machinery and bunkering infrastructure (Transport Environment, 2018).

7.6.1 Technology

Storage

The energy density of diesel, LSHFO, bio-diesel and e-diesel are very similar. For that reason, the required storage remains the same as in conventional applications. Synthetic or e-diesel has a slightly lower volumetric and gravimetric energy density as fossil diesel. 34 MJ/L and 45 MJ/kg respectively. Synthetic diesel is the only e-fuel that doesn't require a significantly larger volume compared to conventional fuel (Lloyd's Register, 2020).

Converters

Synthetic diesel fuel can be used in conventional ICE technology without significant adjustments (Bergsma, 't Hart, Pruyn, Verbeek, 2020).

To acquire higher efficiencies, diesel can also be used as fuel for fuel cells, with reforming however. The SchIBZ project is using diesel fuel for highly efficient electricity generation with an SOFC (Van Biert et al., 2016).

Fuel availability

Diesel fuels can be produced synthetically from Fischer Tropsch synthesis (DNV GL, 2019a). The technologies to produce synthetic diesel is still in development (Lloyd's Register, 2020). Bergsma, 't Hart, Pruyn, Verbeek (2020) expects the TRL to 6 to 8 in 2030.

7.6.2 Costs

Capital costs

Extra capital costs required are expected to be negligible or zero, as this fuel can be used as drop-in for conventional fuels. Engine costs of an MGO installation are assumed to be 636 EU/kW with storage costs at 27 EU/GJ Bergsma, 't Hart, Pruyn, Verbeek (2020).

Operational costs

No practical experience is available of engines running on synthetic diesel fuels. Operational costs are expected to be the same for that reason.

Voyage/fuel costs

Where capital and operational costs are comparable to the costs of conventional propulsion systems, fuel costs of synthetic diesel are expected to be very high. This is the main drawback of this fuel type. DNV GL (2019a) expects the fuel price to be between 1700 and 2700 USD per toe. Other fuel costs mentioned are 114 to 182 USD/GJ (Lloyd's Register, 2020), 25 to 39 EU/GJ (Bergsma, 't Hart, Pruyn, Verbeek, 2020) and 110-340 EU/MWh (Brynolf et al., 2018).

7.6.3 Environmental

Consequences of spills/accidents

As with conventional diesel fuel, spills have large environmental consequences. When spilled, the oil spill needs to be restricted of further expansion and cleaned in order to prevent environmental damage.

Life-cycle environmental score

Synthetic diesel will emit CO_2 when burned as ship fuel, however this CO_2 is also captured from the atmosphere in order to produce the fuel. Therefore, this is a carbon fuel as well. NOx has to be abated as well when burning synthetic diesel. Producing synthetic diesel has the highest energy demand of all mentioned e-fuels. The primary energy demand requires 53% additional energy demand due to high inefficiencies of the production pathways (Transport Environment, 2018).

Noise

This will be the same as the technology used nowadays will not significantly change due to the utilization of synthetic diesel.
When applied in a SOFC it could be that less noise is generated, but also depending on the auxiliaries that are used.

7.6.4 Other

Safety

Diesel doesn't ignite easily, however it is a hazardous liquid. It is combustible, can cause skin irritation and can be fatal when swallowed or breathed in. Contrary to that, a lot of experience handling and using diesel fuel is present to date. This makes that the safety hazards are very well known and abated already.

Crew training

No additional crew training is required and a lot of experience is present due to the long track record of ships using diesel fuel.

Resources security

Like the other fuels, a large renewable energy industry is required. Also, especially for this high energy demand fuel, a very large Renewable Energy (RE) supply is required. However, the use of this fuel is not dependent on oil reserves like today.

Public opinion

It could be that synthetic diesel doesn't sound eco-friendly to the large public, other than that no bad or good public opinion is known for diesel.

7.7 Conclusion

This chapter presented information for each alternative fuel on the criteria that were introduced in chapter 6 about MCDA methods. Besides being a useful reference work on alternative fuels for Fugro stakeholders or others interested, this information is used to score the different alternatives on the different criteria. This score is required to set up the AHP method which is introduced in chapter 8. Also, found parameters and values on alternative fuels are to be used in the case comparison in chapter 9.

8

Alternative Fuel Stakeholder Scoring (AHP)

In this thesis, a method is used to score fuel alternatives including and based on stakeholder preferences. The method used to assess the best fuel alternative in this way is the Analytic Hierarchy Process (AHP). The motivation for this method is elaborated on in chapter 6. This chapter will continue on this method and will describe the steps taken in order to come to a concise result. The Analytic Hierarchy Process uses pairwise comparisons to prioritize, sometimes intangible, criteria (Linkov & Moberg, 2011). This kind of assessment of the different alternatives is conducted for several reasons. Because scoring and weighting to compare different types of criteria, such as costs and environmental impacts are difficult to do purely relying on intuition. Furthermore, because a method using solely economic criteria or thresholds is difficult to use in this case, as many conditions of the different alternatives are not yet predictable or known. Also, this method provides a relative comparison to predict important criteria and potential outcomes under incomplete information or uncertain developments. Lastly, the AHP is easily worked out for multiple future scenarios. Scenarios that are used are as presented in chapter 5.

In this chapter the method is explained first, after which the stakeholder weighting is discussed. Then, the criteria score is elaborated on, using the information on alternative fuels from chapter 7. Lastly, the results of this method are presented under different scenarios. This results in the first findings on the best alternative fuel for Fugro.

8.1 Method

The AHP method uses a priority scale to measure relative importance of different criteria, based on stakeholders judgements. These criteria are based on a hierarchic division of sub-criteria. Using this priority scale and a score for each criterion, the most favoured alternative can be calculated (Saaty, 2008)

The priority scale is obtained by letting stakeholders fill in pairwise comparison matrices. How each alternative scores on the criteria is based on an individual assessment derived from found parameters of the different alternatives. This is deemed less subjective than asking stakeholders for their judgements. Especially because not all participating stakeholders are aware of all parameters of different alternative fuels.

According to Saaty (2008), the AHP method is dependent on four steps in order to make a decision in an organised way:

1. Define the problem and determine the kind of knowledge sought.
2. Structure the decision hierarchy from the top with the goal of the decision, then the objectives from a broad perspective, through the intermediate levels (criteria on which subsequent elements depend) to the lowest level (which usually is a set of the alternatives).

3. Construct a set of pairwise comparison matrices. Each element in an upper level is used to compare the elements in the level immediately below with respect to it.
4. Use the priorities obtained from the comparisons to weigh the priorities in the level immediately below. Do this for every element. Then for each element in the level below add its weighed values and obtain its overall or global priority. Continue this process of weighing and adding until the final priorities of the alternatives in the bottom most level are obtained.

The first step is thoroughly discussed in the background and goal of this thesis. In short, it is to find a suitable alternative fuel for future Fugro vessels. Step three and four are discussed in sections 8.2 and 8.3 respectively. Step two, to structure the decision hierarchy is shown in figure 8.1 below. The choice and establishment of the different criteria is motivated in section 6.5. Below shows how the hierarchy is set up using these criteria when using the method as described by Saaty (2008). It shows the goal up top, followed by the main criteria groups, which are subdivided in other criteria below.

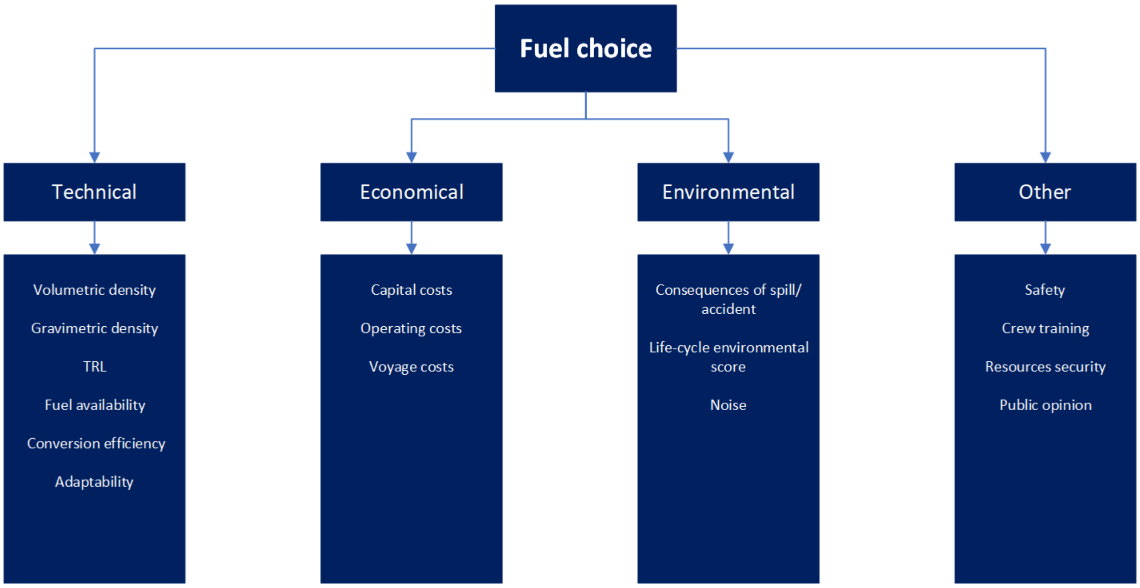


Figure 8.1: Decision hierarchy

8.2 Criteria weighting

In order to obtain the relative priorities of the criteria, stakeholders filled in pairwise comparison matrices. To clarify, when the economic sub-criteria are compared for example, the stakeholder fills in a 3x3-matrix. In this matrix, the diagonal is always comprised of ones, as this diagonal compares the same two sub-criteria. The entries in the top right part are submitted by the stakeholder, the entries in the opposed side of the matrix are then automatically the reciprocal of the given weights in the top right part. Saaty (2008) introduced a fundamental scale of absolute numbers to compare the criteria. This scale ranges from 1 to 9, with 1 being equally important and 9 being extremely more important than another criterion. To express unimportance, the reciprocals of these numbers are used. i.e. 1/3, 1/5, 1/7 and 1/9. For example, when an activity is judged as *strongly more important* over another, the stakeholder submits the number 5 in the relevant matrix entry. However, in order to make the judgements more comprehensive, linguistic expressions are used as also proposed by Saaty (2008). Therefore, the stakeholder will fill in *strongly more important*, which will then be processed to a 5 in the specific matrix entry. The fundamental scale as used by the stakeholders is shown in table 8.1 below.

Intensity of importance	Linguistic intensity	Explanation
1	Equally important	Two criteria contribute equally to the objective
3	Moderately more imporant	Experience and judgement slightly favour one criterion over another
5	Strongly more important	Experience and judgement strongly favour one criterion over another
7	Very strongly/ demonstrated more important	One criterion is favoured very strongly or is demonstrated more important
9	Extremely more important	The evidence favouring one activity over another is of the highest possible order of affirmation
Reciprocals of above numbers	” ” *less* important	If activity *i* has one of the above non-zero numbers assigned to it when compared with activity *j*, then *j* has the reciprocal value when compared with *i*

Table 8.1: Fundamental scale by Saaty (2008)

8.2.1 Stakeholder questionnaire

There are different options to acquire the necessary stakeholder opinions for the AHP method. Methods described in literature are to acquire the stakeholder comparisons by interviewing, organizing a workshop or by sending a questionnaire. To have the opportunity to include as many opinions as possible, interviewing is deemed too time-consuming, moreover the repetitive nature of the questions isn't believed to be suitable for an interview. A workshop where stakeholders fill in the comparison matrices in groups, dependent on a role-play or their reference group, could be very suitable. In such a situation, a clear explanation of the method is possible. Besides, the interaction and discussion between stakeholders could add to the consistency and provide a more thoroughly considered outcome. Unfortunately, due to the COVID-19 pandemic, such a workshop couldn't take place during this thesis. Therefore, an online questionnaire is chosen to gather stakeholder opinions. This gives the possibility to include a stakeholder group as large as possible but also requires to be made as comprehensive as possible, because explanation opportunity is limited.

To set up the stakeholder poll as clearly and comprehensive as possible, a few potential difficulties were considered upfront. The AHP method requires the participants to fill in a pairwise comparison matrix. A possibility would be to send out the questionnaire containing the empty matrices that have to be filled in by stakeholders. This is perceived to be more prone to mistakes because of the relatively complex form. Moreover, this would require the fundamental scale to be filled in as numbers, which is less comprehensive than the linguistic scale. The fundamental scale put in as a Likert scale would require 9 fields, which is also difficult to comprehend because of the abundance of choices. Another consideration was the way of distributing the questionnaires. To be able to easily aggregate and calculate the priority values, an online questionnaire is used. The questions itself are each comparing two stated criteria. The first question asks which criterion is more important to the stakeholder, then depending on the answer in the first question, a second question asks how much more important the stakeholder considers this criterion. All in a linguistic form of the fundamental scale by Saaty (2008) and dividing the questions to ensure the comprehensibility of the scale by reducing the amount of options in each question. Appendix **??** shows an example by means of the first page of the questionnaire, rating the main criteria.

8.2.2 Questionnaire aggregation

The online questionnaire tool used, Microsoft Forms, provides that CSV-files of the questionnaire results can be downloaded. A script is written in Matlab to aggregate the results and convert the linguistic input to the pairwise comparison matrices. This results in pairwise comparison matrices for all criteria and each stakeholder.

An important issue of this way of group decision making is how to aggregate the judgements of all the different stakeholders. As the questionnaire doesn't provide the opportunity of cooperation between stakeholders, the individual judgements need to be combined. The reciprocal values in the comparison matrices play a key-role in this aggregation. When taking the mean of different stakeholder opinions, it is proved that only the geometric mean, not the frequently used arithmetic mean, is the only way to do so (Saaty, 2008). For example, if one stakeholder chooses one matrix entry to be 1/5 and another stakeholder chooses 5, the mean score of these judgements should be in the middle, at 1. When taking the geometric mean of 1/5 and 5, 1 is correctly obtained. When one would use the arithmetic mean, a value of 2.6 would be obtained, which is incorrectly in favor of the stakeholder that filled in 5. Using the geometric mean method, the pairwise comparison matrix for the group of all stakeholders combined can be aggregated. Besides the combined group, the pairwise comparison matrices of different reference groups are also aggregated. The different reference groups are discussed in section 8.2.3.

Now that the comparison matrices are aggregated, these can be used to calculate the priority weights that the stakeholders give to the different criteria. These are also computed for the whole group of stakeholders as well as smaller reference groups. The eigenvalue method by Saaty will be applied in a Matlab script to do so. This method not only provides a consistent way of acquiring the criteria weights from the matrix, it also provides a way to test consistency, which will be discussed in subsection 8.2.4. The computations required to come to the priority weights are briefly explained using the steps below:

1. Compute eigenvalues of the pairwise comparison matrix.
2. Divide the found eigenvector by it's sum to obtain principal eigenvector.
3. The principal eigenvector is the priority vector containing the weight of the different criteria.

8.2.3 Stakeholders

This section will go into the different stakeholders that were asked to participate in the questionnaire as introduced in this chapter. To start with, all stakeholders that were interviewed on vessel developments in section 4.3 were asked to participate. These are stakeholders working at Fugro as well as DNV GL. Because it is interesting to research how different reference groups prioritize the criteria for the choice of an alternative fuel, it was attempted to find stakeholders from four different reference groups. These were stakeholders from Fugro itself (operators), stakeholders at class societies, stakeholders from propulsion system manufacturers (suppliers) and lastly stakeholders active in science and research.

The first group of Fugro stakeholders was extended by adding engineering and technical superintendents as well as fleet and technical managers. Also DNV GL was successfully contacted again to acquire more participants from the class reference group. Unfortunately, the inclusion of other class societies in this research wasn't successful. Several engine manufacturers were invited to participate as well, resulting in a few stakeholders active in that specific reference group. Participants active in science and research participated the questionnaire as well. They are active at Delft University of Technology, TNO and CE Delft. This resulted in a group of in total 27 participants, of which 13 employed by Fugro, 6 from the scientific (research) community, 6 from class societies and 2 from propulsion system manufacturers.

8.2.4 Consistency check

A drawback of the AHP method is that it allows for subjectivity and inconsistency. Inconsistency can be caused by stakeholders weighting a certain priority that isn't consistent with another weighting that they give. For that reason, Saaty (2008) provides a way to deal with this inconsistency by introducing a consistency ratio. This ratio is calculated using the eigenvalues that are computed during synthesis of the priority vector as discussed in subsection 8.2.2. Below is summarized how the consistency ratio is calculated.

The maximum eigenvalue in the eigenvector, λ_{max} is used together with the amount of rows/-columns n to calculate the Consistency Index:

$$CI = \frac{\lambda_{max} - n}{n - 1} \tag{8.1}$$

Then, this Consistency Index (CI) is used together with the Random consistency Index (RI), as introduced by Saaty (2008), to calculate the Consistency Ratio (CR):

$$CR = \frac{CI}{RI} \tag{8.2}$$

n	1	2	3	4	5	6	7	8	9	10
RI	0.00	0.00	0.52	0.89	1.11	1.25	1.35	1.40	1.45	1.49

Table 8.2: Random consistency Index (RI) by Saaty

Saaty (2008) states that Consistency Ratios lower than 10% or 0.1 indicate the stakeholder input to be inconsistent or too random to take into account during score synthesis. A consistency check for each matrix of each individual stakeholder is computed. This resulted in a small reduction in input as some matrices came out to be inconsistent. For the pairwise comparison matrices considering the six technical criteria, an exception was made to have enough input. The consistency threshold for this matrix was increased to 0.12.

8.2.5 Results

The results of the criteria weighting are computed and plotted in bar graphs. The stakeholders prioritized the four main criteria and the different sub-criteria within the four main-criteria groups.

Using these two weightings, the relative priority of all criteria can be calculated. These results are also plotted in a bar graph.

Besides looking at the whole group using the geometric mean method, the results were also analyzed by taking the geometric mean of one reference group. This was done to see how and if stakeholders from the reference groups prioritize the criteria differently. Because the involvement of the group working in propulsion system manufacturing was low at 2 participants, it was unclear if this would result in enough input to analyze as a separate group. Especially after the consistency check, enough matrices would have to be still valid. Unfortunately, this wasn't the case. For that reason this group was left out as a separate reference group when analyzing results of the stakeholder poll.

When looking at the prioritization of the four main-criteria, there is quite some spread between priorities given by different stakeholder groups. Overall, environmental criteria are deemed most important, closely followed by technical criteria. Then economical criteria are prioritized third and lastly the least priority is given to other criteria. Class stakeholders give the highest priority to environmental criteria by far but follow the same priority ranking as the overall score, this is also valid for Fugro stakeholders. It is remarkable that Fugro stakeholders give such a high priority to environmental criteria compared to economical criteria. From the different stakeholder groups, only science voted for another priority. They put technical criteria up top, closely followed by economical criteria. Then, environmental criteria are prioritized third. Other criteria are also put last by this group.

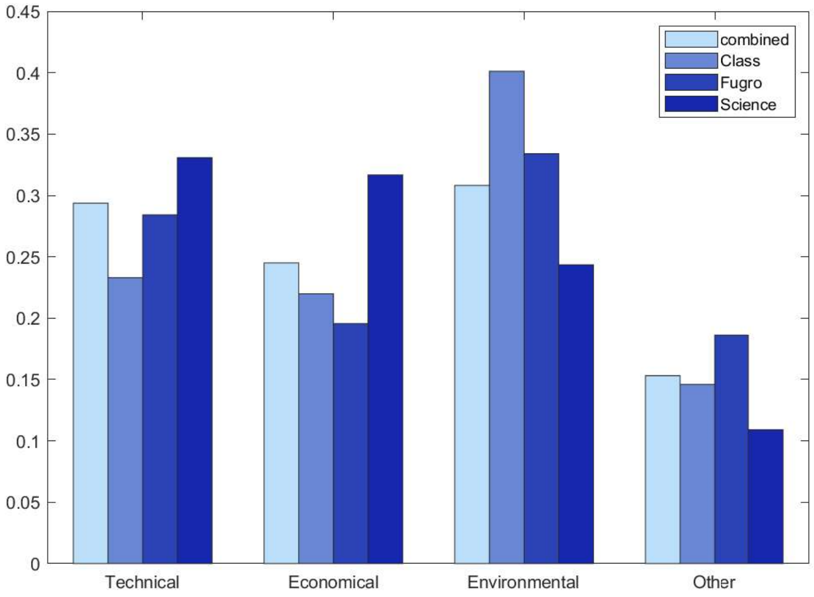


Figure 8.2: Priority weighting main-criteria

Now the priorities for the main-criteria are presented, the priority for the sub-criteria has to be analyzed to come to the relative priorities of each criterion later on. The priorities given to the different sub-criteria overall and for each stakeholder group can be found in figure 8.3.

The technical sub-criteria are also prioritized by the stakeholders. Overall, availability is deemed most important, followed by TRL and efficiency. Fourth most important is adaptability of an alternative fuel technology and last come gravimetric- and volumetric density respectively. Stakeholders from the class reference group gave all sub-criteria more or less even priority. Fugro stakeholders prioritized availability and TRL most important, followed by efficiency and adaptability. Remarkably, Fugro stakeholders weigh gravimetric- and volumetric density as relatively unimportant. Science stakeholders prioritize availability most, followed by efficiency, gravimetric density. Gravimetric density strikes out, as science is the only stakeholder group that prioritizes this criterion relatively high.

The economic sub-criteria are prioritized as follows: OPEX, voyage costs, CAPEX. Stakeholder groups weigh relatively the same on the different criteria. Fugro prioritizes the same as the overall weighting. Class prioritizes not one criterion specifically, with all weightings being equivalent. Science weighs voyage costs most important, the others are prioritized identical to the overall weightings.

For evironmental sub-criteria, the life-cycle environmental score is weighted most important, followed by the consequences of a spill and noise. Fugro stakeholders weighted the consequences of a spill more important than all the other criteria. Science prioritizes consequences of a spill last, after life-cycle evironmental score and noise.

For the other sub-criteria, safety has the highest priority for the choice of a fuel alternative. Priorities differ between stakeholder groups for resources security and crew training but are more or less even overall. Public opinion is deemed least important by all stakeholder groups.

As all weightings are now known, the relative weight for each criterion can be calculated. This relative weight will be used to come to the score synthesis of the different alternatives. The value for the relative weight is obtained by multiplying the weight of the main-criterion with the relevant sub-criteria. The outcome is shown in figure 8.4.

From figure 8.4 it can be seen that the environmental criteria have a high relative importance, because this is deemed the most important main-criterion. Overall, the life-cycle environmental score has the highest relative importance. As this study is researching an alternative fuel to reduce the carbon footprint of a shipping company, it is as expected that this sub-criterion has the highest importance. Moreover, it shows to an extent that the stakeholders that participated, recognized and confirmed the importance and goal of this study into a more sustainable alternative fuel. Due to the high score of the environmental main-criterion, the two other sub-criteria of this environmental criteria group score relatively high. Therefore, spills and noise are considered to be of importance for the choice of a sustainable fuel alternative. It is worth mentioning that this graph seems to show that technical criteria are less important in the choice for an alternative fuel. However, these are more criteria, meaning that these automatically have a high impact on the score synthesis while still maintaining the same relative weight as was discussed in the previous paragraphs.

8.3 Criteria scoring

Unlike the criteria weighting, criteria scoring isn't done by means of stakeholder consultation. However, the method is again dependent on the use of pairwise comparison matrices. This time, the matrices do not compare different criteria however, the entries compare how the alternatives perform relative to each other on a certain criterion. So for each criterion a pairwise comparison matrix is set up in which the score of each alternative on this specific criterion is determined. The same fundamental scale as mentioned before is used to fill in the scoring matrices. The values are based on factual values this time however. These are based on the parameters of different

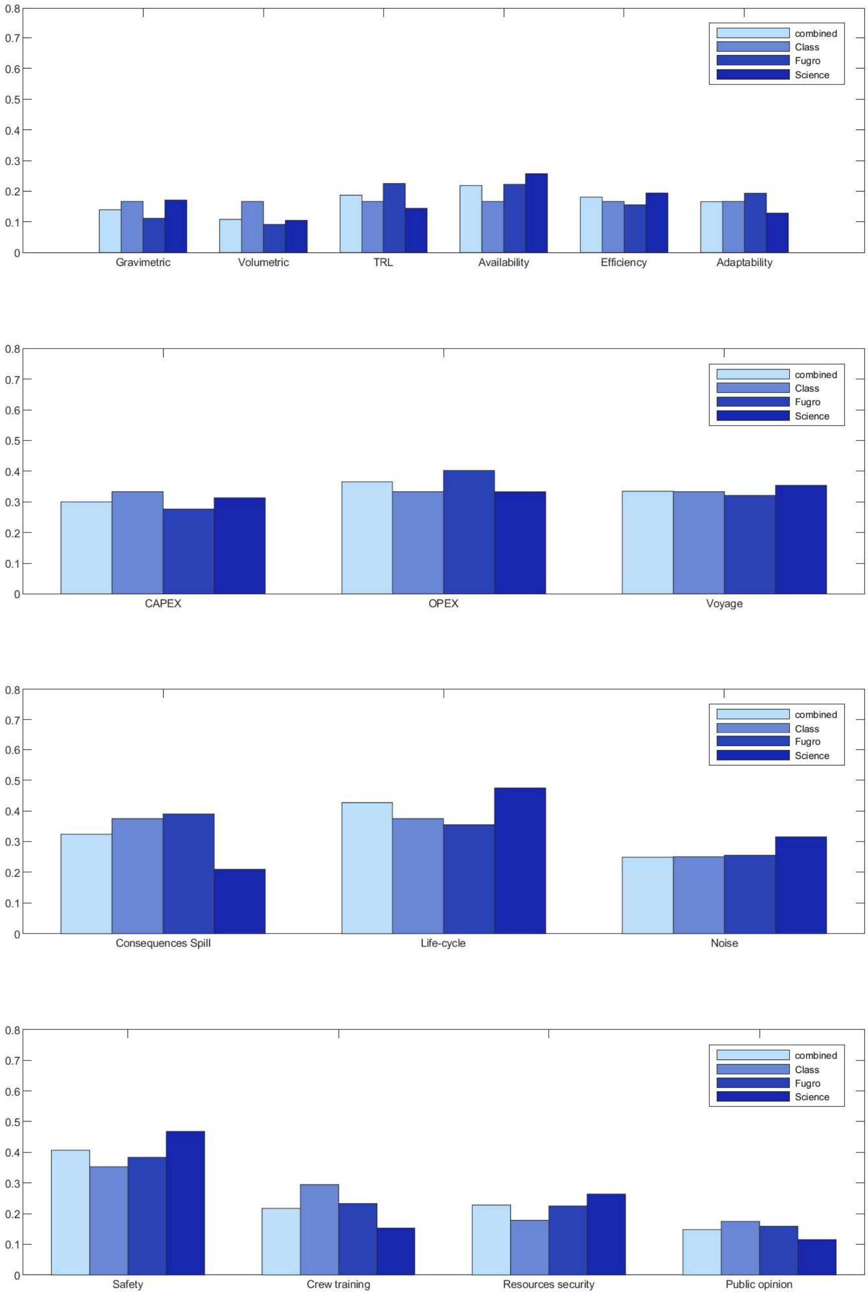


Figure 8.3: Priority weighting sub-criteria groups

fuels as described in chapter 7. All the pairwise comparison matrices to score the different alternatives can be found in the appendix. The relative score of each alternative on the different criteria.

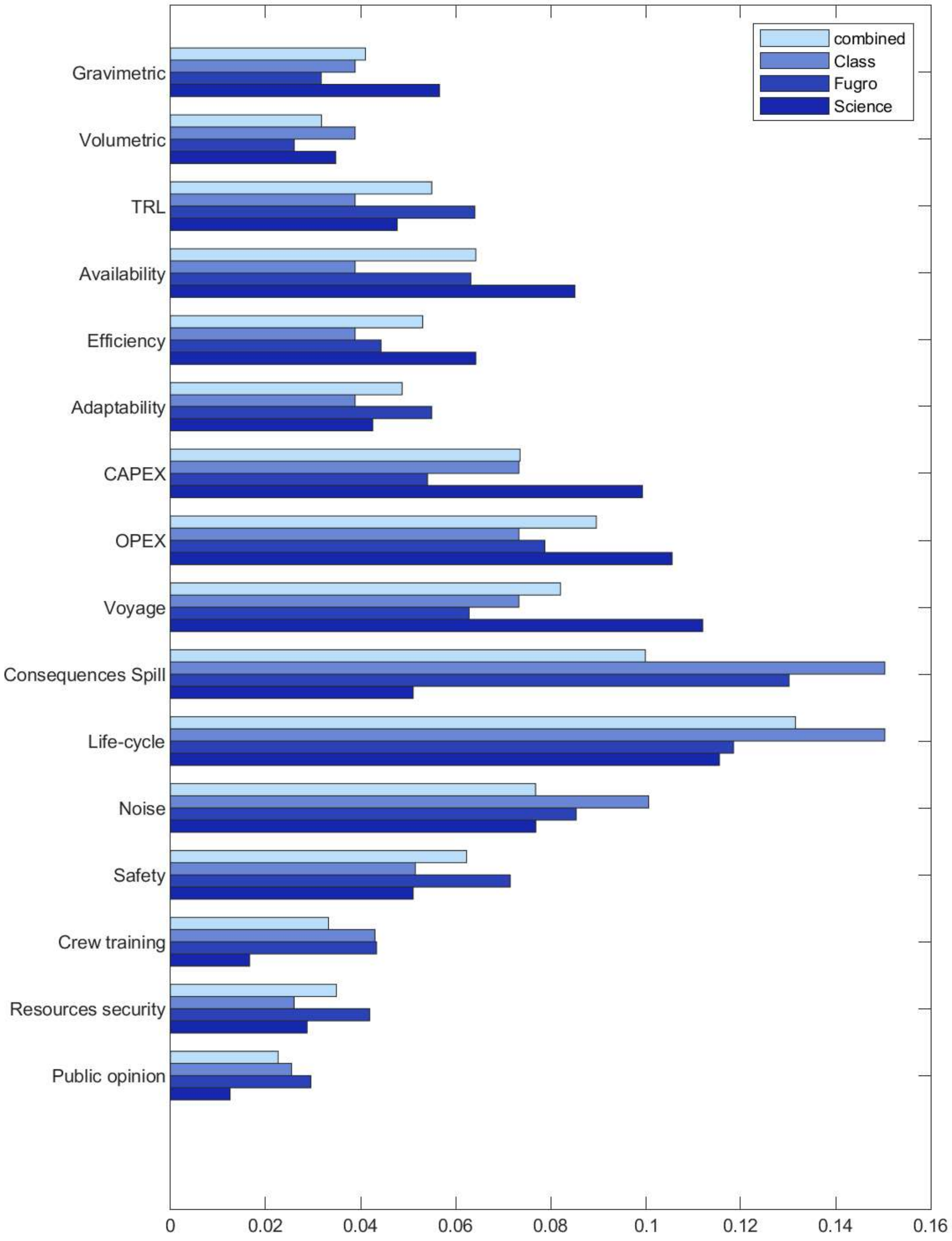


Figure 8.4: Relative weight for each sub-criterion

Graphs showing the relative scores under different scenarios are also found in appendix **??**. An example of the different scores in the base case scenario is shown underneath in figure 8.5

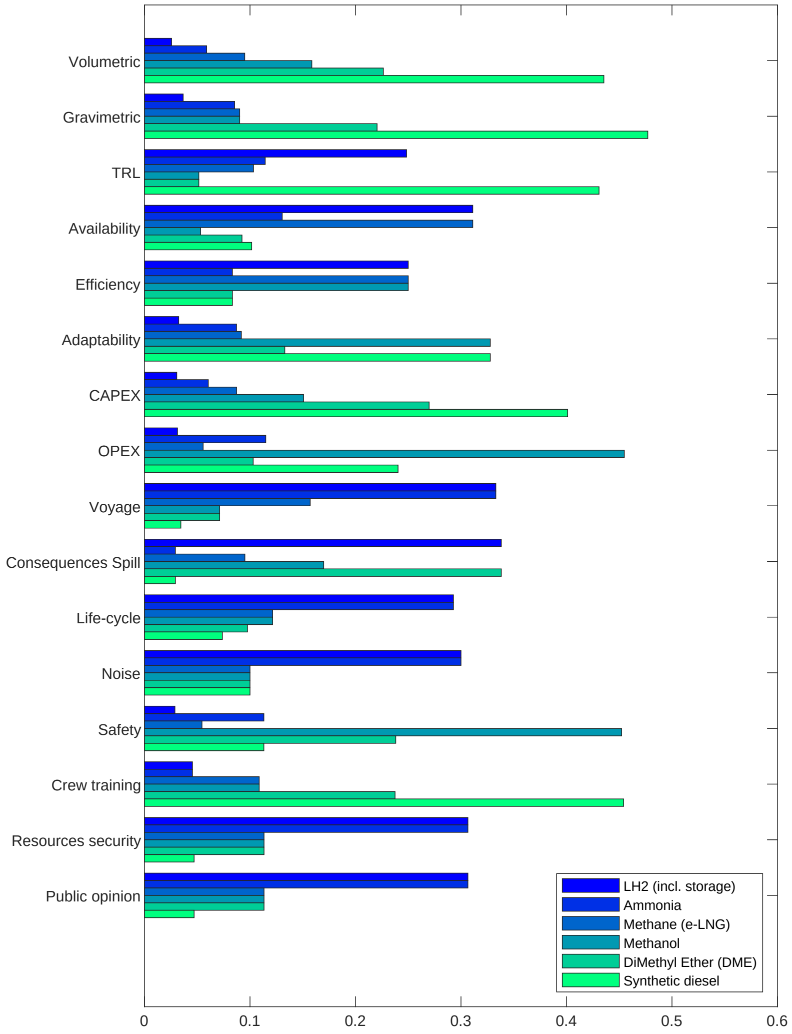


Figure 8.5: Relative scores of fuel alternatives on all criteria - Base case

8.4 Sensitivity analysis / Scenarios

To test the robustness of this method, a sensitivity analysis is performed. This shows how the results of the model are influenced by changes to input. If the results follow to the changed input in a proportional way, this shows that the model is working properly and the results can be used. Both the input of the relative weight and the score were changed to investigate the impact on the results.

The sensitivity analysis on weighting was done by leaving out the environmental criteria in the synthesis. Because all considered alternatives are carbon-neutral and therefore cleaner alternatives, it is interesting to see how the alternatives score when these criteria are left out. Also some stakeholders voted environmental criteria as very important. For example, Fugro stakeholders voted environmental criteria more important than participants from the scientific/research community. This is interesting to see and to investigate the effects of these preferences further. These reasons, together with the fact that this is a clear way to test how the results change when making changes to input makes that this method is suitable to use in a sensitivity analysis. When leaving out this criteria group, the remaining criteria weights still have to add up to 1, this is the case. Therefore this check is the first indication that the model is working. Moreover, the outcome of the scoring model has to change due to the exclusion of environmental criteria. The fuel alternatives that are not necessarily scoring well on environmental criteria should gain in in score, more environmentally friendly fuels should have decreasing scores. This is the case as will be pointed out in section 8.5.2. Therefore this first part of the sensitivity analysis indicates that the model is working properly.

The other part of the sensitivity analysis that was carried out entailed adaptations to the score of alternatives on different criteria. This means changing how alternatives score on certain criteria and analyzing how the results change. The scenarios discussed before, are used to carry out this analysis. Not only this is providing insight to the score of different alternatives under different scenarios, it also functions as sensitivity analysis. How these score changes worked out is discussed in section 8.5. The adaptations show the expected results. When for example the availability of a certain fuel is scored better under a certain scenario, this is reflected in the scores that the AHP provides. For that reason also this part of the sensitivity analysis show the desired results and a proper working model.

8.5 Results

In this section the results of the AHP method will be discussed in order to come to a conclusion regarding the most promising alternative fuels to work out in this research. The results of the different scenarios will be discussed, also analyzing how these came about, identifying decisive reasons in the different criteria weightings and scores. These can be used to do recommendations and aid in concluding which alternative fuel is a suitable alternative for conventional fuels. The results will be discussed per scenario in the coming section.

8.5.1 Base case

For the base case scenario, hydrogen is listed as most preferred fuel alternative when looking at the preferences of all stakeholders. Followed by methanol and synthetic diesel of which the small required changes to current installations cause this high score. For diesel specifically, the advantageous gravimetric- and volumetric-density also make diesel a desired alternative. Methanol stands out in safety and Operational Expenses. Then, ammonia follows as fourth preferred alternative. Compared to hydrogen, ammonia only scores slightly higher on criteria like densities, adaptability and safety but is more often scoring less. Fugro stakeholders follow the overall distribution. Class places the other alternatives, except for methane, close to each other behind hydrogen. For class stakeholders, methanol scores relatively high because environmental criteria are highly prioritized and methanol has good scores on these criteria. Hydrogen scores lower than average when looking at science stakeholder preferences. Technology and cost criteria are prioritized higher than average, on which other fuels often score higher than hydrogen.

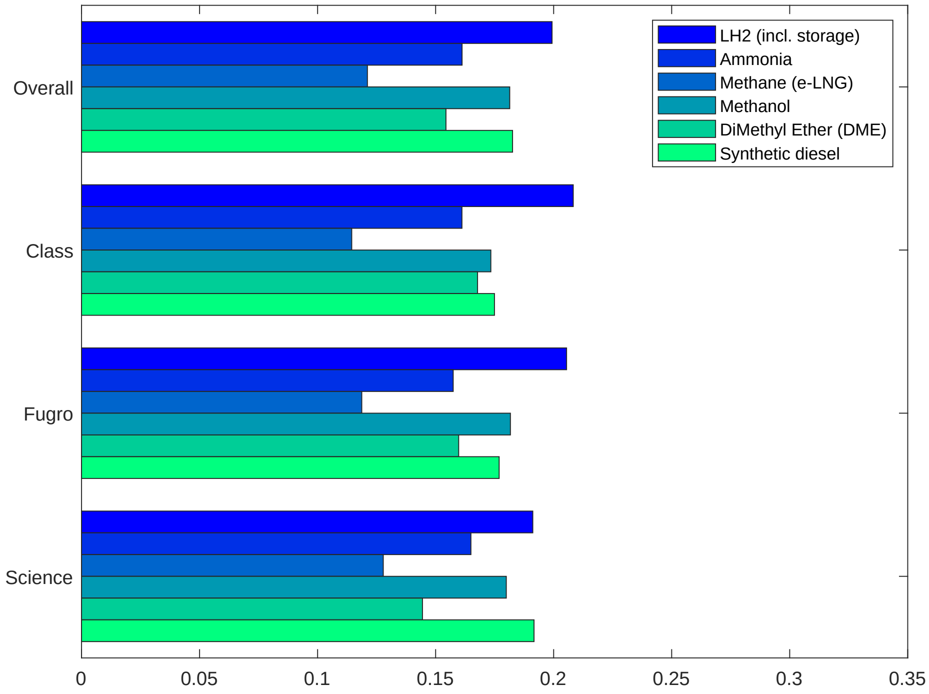


Figure 8.6: Score for different fuel alternatives: Base case

8.5.2 Scenario 1

This first scenario stands alone from the other scenarios presented in section 5.4. These scenarios are annotated using roman numerals. This scenario was added to expand the sensitivity analysis and to investigate how decisive the role of environmental criteria was in the score aggregation. This first scenario leaves the environmental criteria out of scope to see what the best fuels would be in that case. As all fuels considered are carbon-neutral at least, this doesn't jeopardize the goal of researching a zero-emission alternative fuel. However, the results do differ significantly. Hydrogen and ammonia are not carbon-based and score high on the life-cycle environmental score for that reason. Now that this criterion, as well as the other environmental sub-criteria, is not included, hydrogen doesn't remain the best alternative anymore. Overall, diesel and methanol become the most preferred alternatives. Synthetic diesel takes over the second place of most preferred alternative. The other fuels follow in the same order for each stakeholder group. Depending on the stakeholder group, the differences between fuel score are larger or smaller. When environmental criteria are left out, technical criteria are deemed most important for all stakeholder groups. Of all stakeholder groups, Fugro weighs other criteria more important than others, while economic criteria are weighed relatively less important compared to the different stakeholder groups. For that reason synthetic diesel scores less good and hydrogen is slightly more favoured relative to others stakeholder groups.

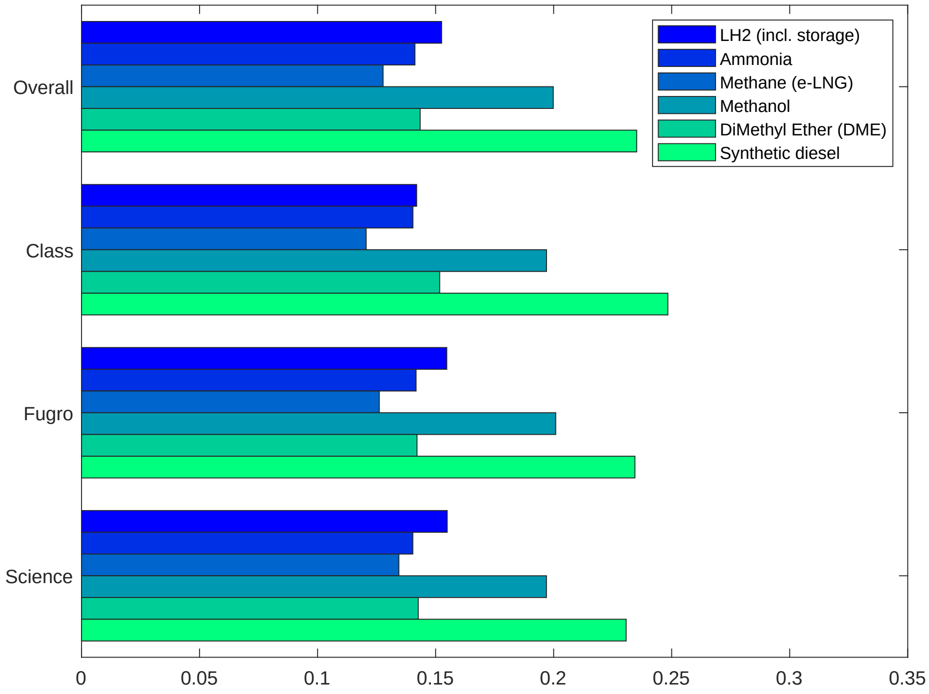


Figure 8.7: Score for different fuel alternatives: Scenario 1

8.5.3 Scenario I

For scenario I, the price for carbon-capture is set to decrease. This results in a lower fuel price for fuels that rely on carbon capture and storage for their production. Therefore these fuels score better on voyage costs in this scenario. This results in a lower overall score for hydrogen and ammonia. Overall, hydrogen remains the most preferred alternative fuel in this scenario. When only looking at the input of science stakeholders, who prioritize environmental criteria lower than average, both synthetic diesel and methanol overtake hydrogen as most preferred alternative fuel.

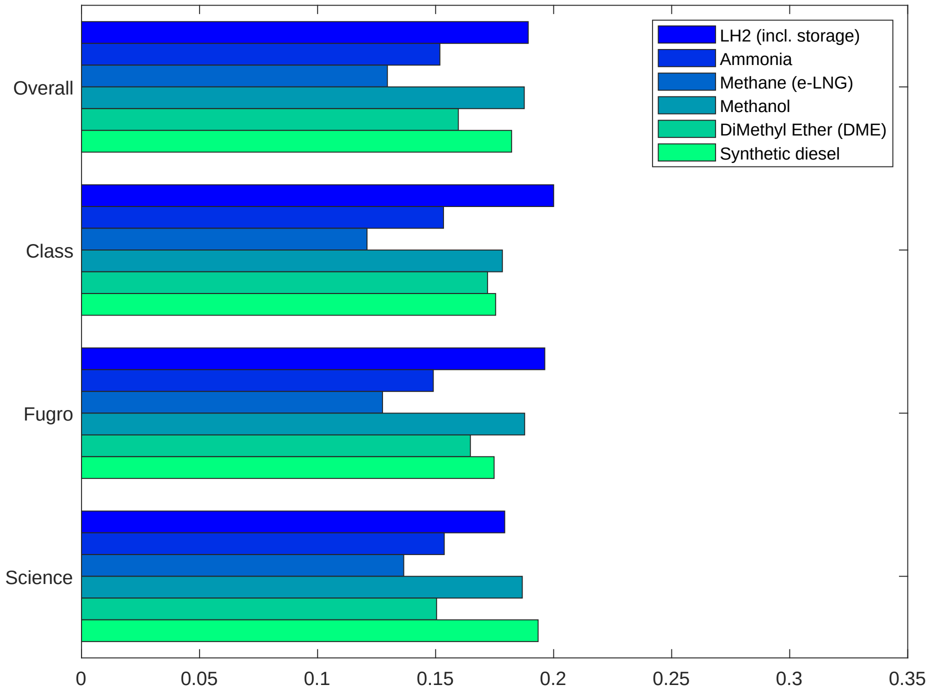


Figure 8.8: Score for different fuel alternatives: Scenario I

8.5.4 Scenario II

When the scores are calculated for a reduced Renewable Energy price, the fuels that use relatively much energy for production become cheaper compared to the other fuels. This means that hydrogen, ammonia and methane score relatively worse on voyage costs. This results in a slight decrease in the score for hydrogen and ammonia and increase for the other synthetic fuels. However, this change doesn't result in a different ranking than the base case. Hydrogen would still be the most preferred alternative. Only when looking at the scientific stakeholder group, hydrogen is again passed by methanol and synthetic diesel as most preferred alternative fuel.

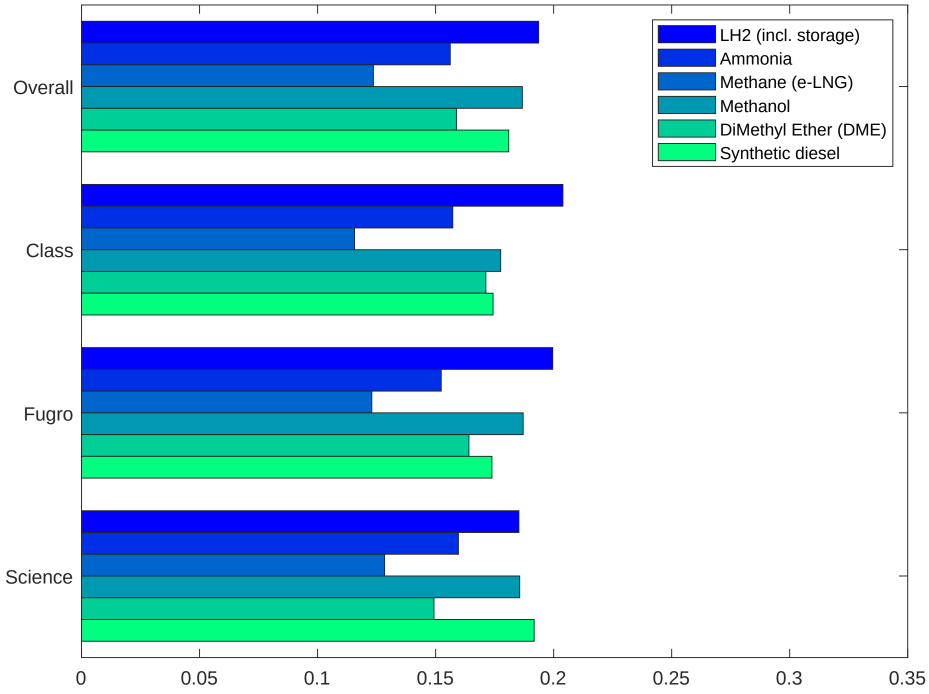


Figure 8.9: Score for different fuel alternatives: Scenario II

8.5.5 Scenario IV

The fourth scenario takes a fast uptake of hydrogen technology as foundation. This means reduced Capital Expenses for fuel cell systems, a higher TRL for technologies depending on fuel cell technology and availability of hydrogen infrastructure. This results in a higher score for especially hydrogen as alternative fuel. Overall, hydrogen strengthens its position as most preferred alternative fuel in this scenario. Moreover, hydrogen becomes the most preferred alternative for all stakeholder groups. Also, ammonia technology is catching up slightly for the science and class stakeholder groups.

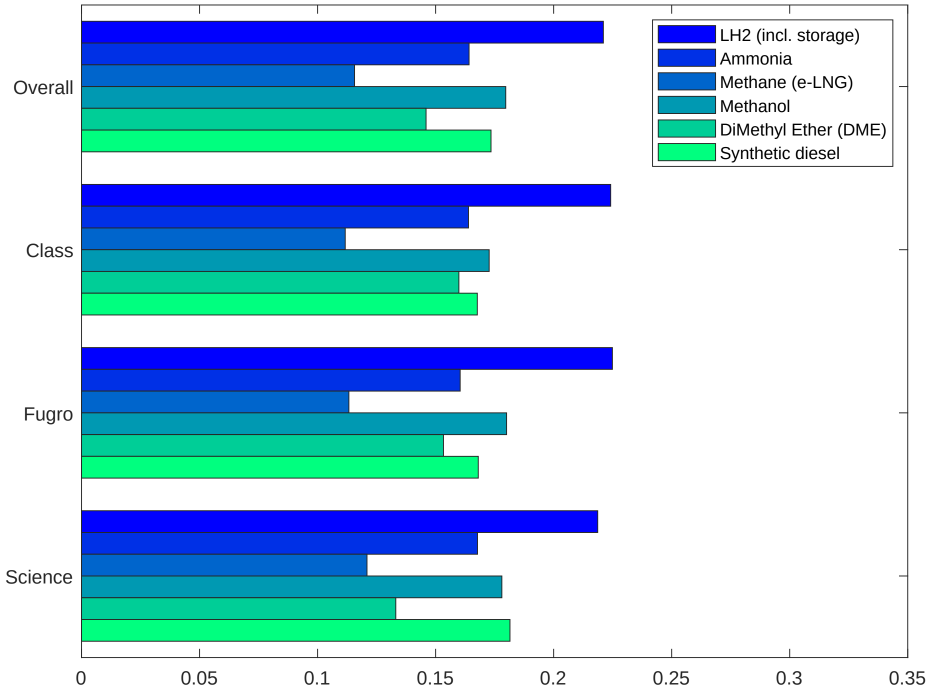


Figure 8.10: Score for different fuel alternatives: Scenario IV

8.5.6 Scenario V

Scenario V is comparable to scenario IV, except for the availability, which is now further developed for ammonia. Under this scenario, ammonia takes a leap in the ranking and becomes second when taking into account the overall stakeholder preferences. Behind hydrogen, which is still the most preferred alternative under this scenario. Ammonia is however closely followed by methanol and synthetic diesel. Overall, hydrogen still has an advantage over the other fuels. When looking at the preferences of scientific stakeholders however, ammonia and hydrogen almost have the same score. This again shows that the impact of environmental criteria is significant in the synthesis of the choice for an alternative fuel.

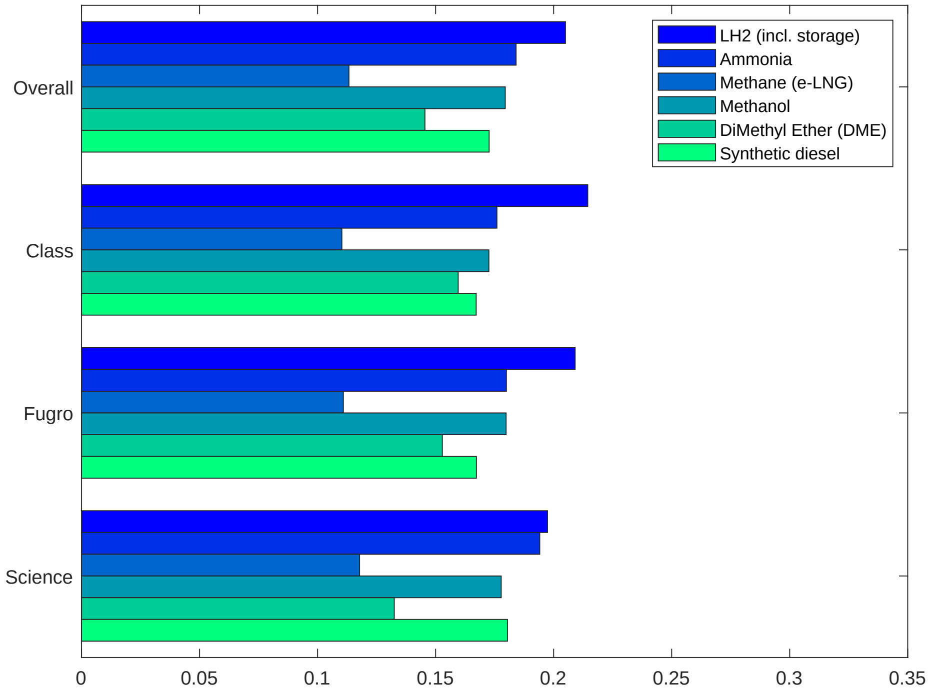


Figure 8.11: Score for different fuel alternatives: Scenario V

8.5.7 Scenario VI

In the past years, LNG propulsion systems in ships are increasing. To investigate the results when this uptake continues, a scenario is added. In this scenario the Capital Expenses of LNG (e-methane) systems are further reduced and the TRL of Internal Combustion Engines is increased in future. However the score for methane does increase, this is not significant. Overall and for all stakeholders groups seperately, methane stays the least preferred alternative fuel from this analysis.

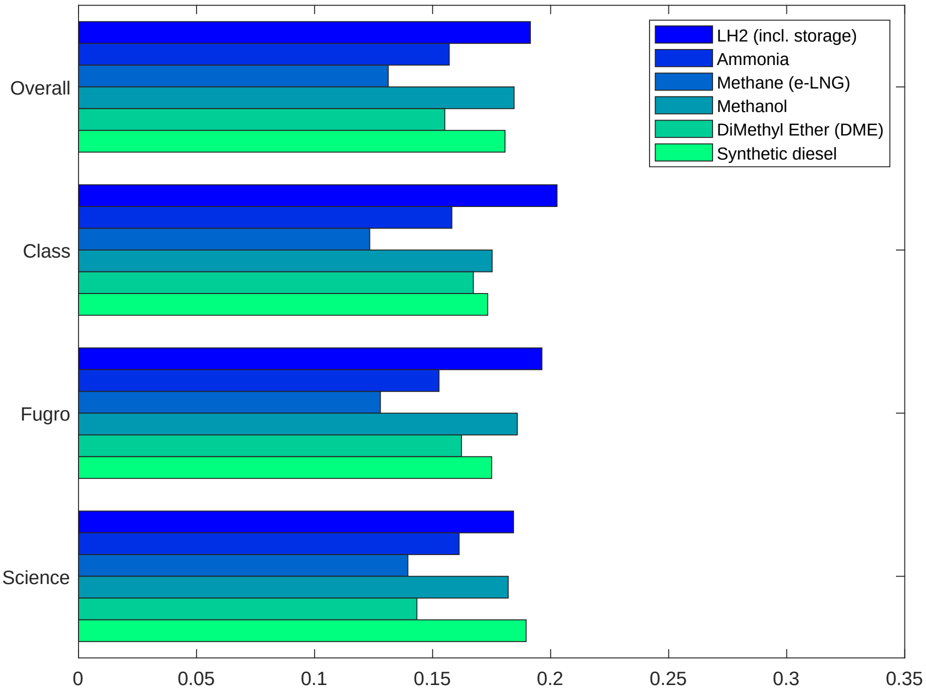


Figure 8.12: Score for different fuel alternatives: Scenario VI

8.5.8 Scenario VII

The seventh scenario investigates if a wider availability of DiMethylEther (DME) together with an increased TRL of Internal Combustion Engines significantly changes the results. Methanol, DME and syntetic diesel all come closer to hydrogen in this scenario. Overall, the uptake of new ICE technology results in methanol and synthetic diesel becoming about evenly preferred as hydrogen, DME preference increases but stays put at the fourth place in the ranking. For no stakeholder group specific, DME ends higher than fourth in the ranking. Because class prioritizes safety and consequences of a spill highly, DME ends close to methanol and synthetic diesel, but far behind hydrogen.

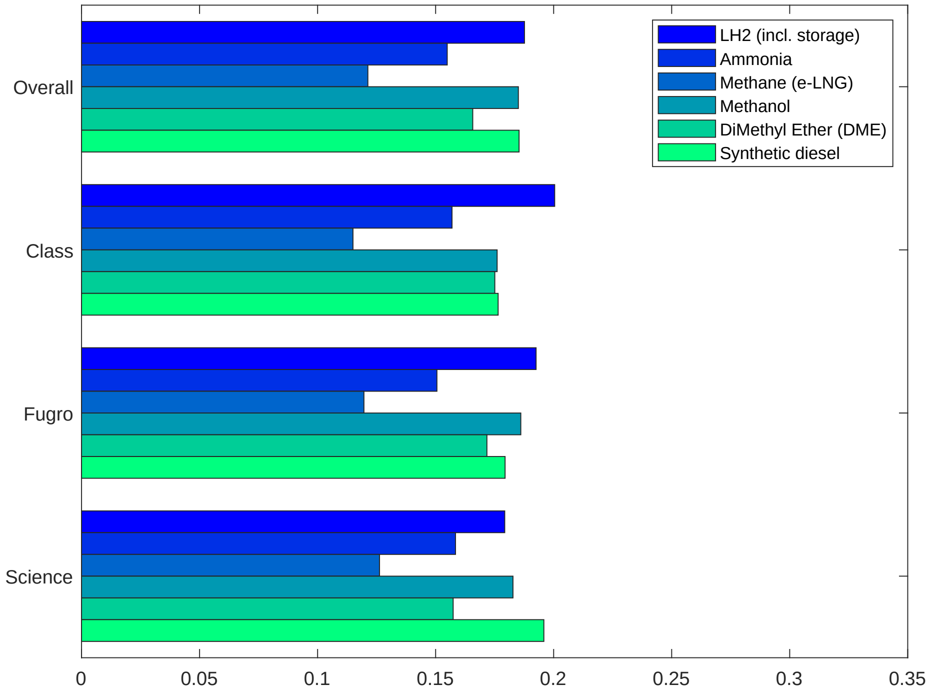


Figure 8.13: Score for different fuel alternatives: Scenario VII

8.5.9 Scenario VIII

Because ammonia is also considered to work in Internal Combustion Engines, this scenario is also tested. Therefore, the TRL of ICEs is increased. This is necessary for this technology to become viable. Also, the availability score of ammonia is increased in this scenario. Because the increase in TRL for ICE technology is also beneficial for the score of other alternative fuels, hydrogen is approached by all fuels relying on combustion technology. The increased availability of ammonia gives it a better overall score, however without the uptake of FC technology this alternative is not scoring high enough to enter the top three of alternatives. When looking at individual stakeholder groups, ammonia scores relatively good under this scenario. This is because the group of science stakeholders weighed the availability of a fuel above average. Using this prioritization and weighting, ammonia scores as a viable alternative.

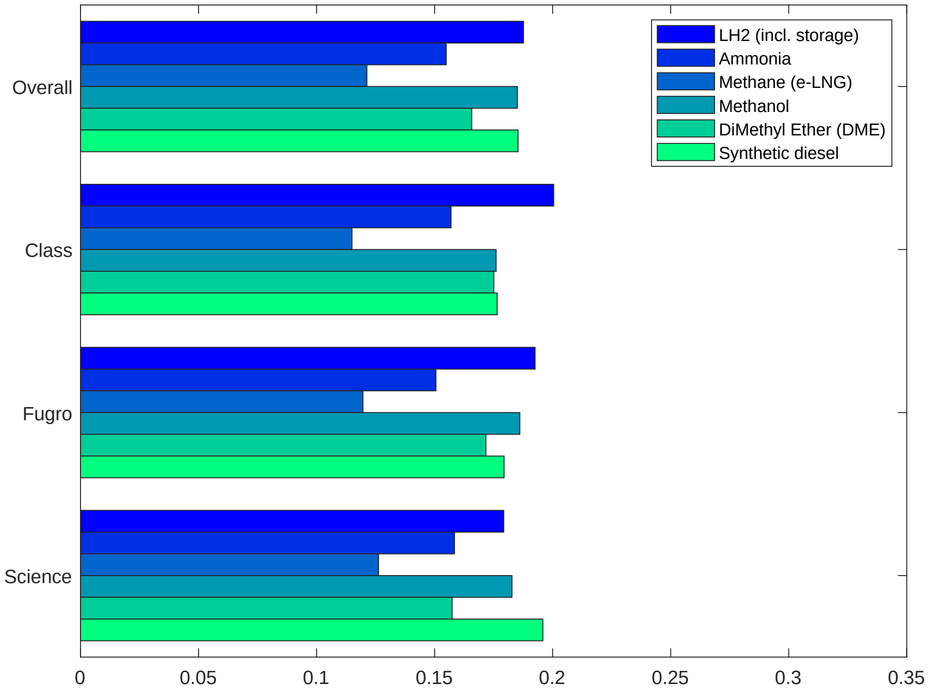


Figure 8.14: Score for different fuel alternatives: Scenario VIII

8.5.10 Scenario IX

The ninth and last scenario also tests a higher TRL for Internal Combustion Engines together with an uptake and therefore larger availability of methanol. In this scenario, methanol overtakes synthetic diesel and hydrogen and becomes the most preferred alternative fuel. This ranking differs between stakeholder groups. Class values the availability relatively low and the life-cycle environmental score high. For that reason, hydrogen remains the most preferred alternative fuel using their priority vectors.

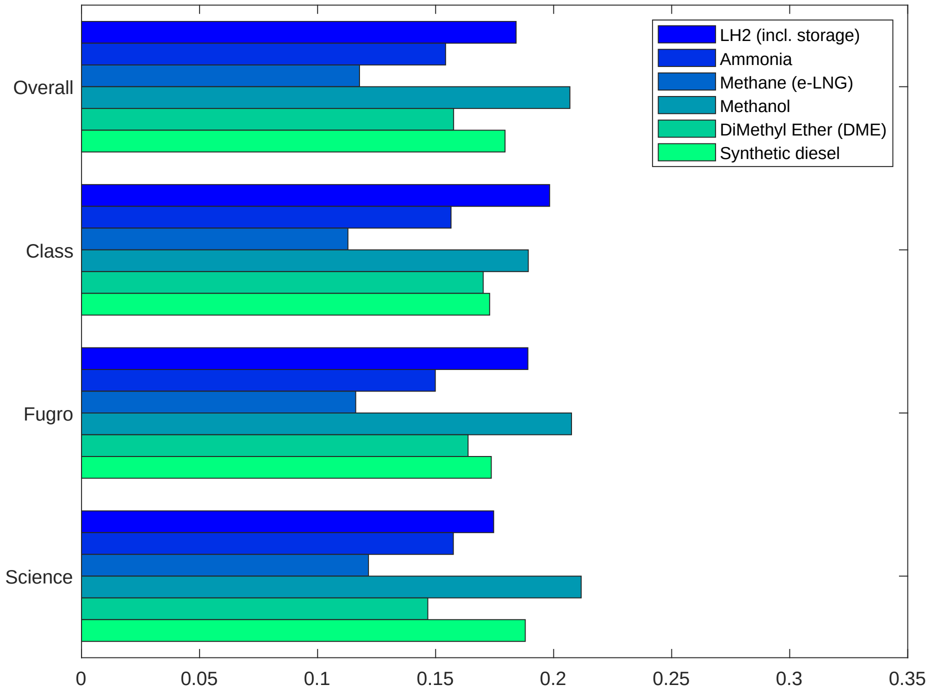


Figure 8.15: Score for different fuel alternatives: Scenario IX

8.6 Conclusion

This chapter described the implementation of the Analytic Hierarchy Process in order to motivate a suitable fuel alternative in the long-term. AHP provides a robust way of fuel score synthesis in a situation like this, including stakeholders and under highly uncertain conditions. However, it also proved to be a method subject to some flaws. It is the question whether some stakeholder results are intended to be as they are and subjectivity also stays a concern. In the previous chapter, the process of stakeholder inclusion is outlined and the results of their participation in this research are described. Overall, the differences in priorities between stakeholder groups are interesting to analyze. Environmental criteria are deemed more important than economical criteria by Fugro stakeholders for example. Also remarkable are the relative weights. Environmental criteria like spill consequences and noise obtain a high overall priority because of the high priority of the environmental criterion compared to the other main criteria. To investigate the effects of the high relative weight for environmental criteria, a scenario was added to the score synthesis. This scenario leaves the environmental criteria out of scope to analyze how the score synthesis changes. A point of discussion concerning the execution of this method could be the amount of criteria that were used. A lot of subcriteria under technical criteria were included for example. This could have been difficult or confusing for the stakeholders. Especially when considering that this method should also be accessible to stakeholders that are less experienced in this subject.

The main outcome of this chapter is in the results of the other part of the score synthesis however. The AHP provides the different scores of the considered alternatives. Based on the priorities given by stakeholders. This synthesis is carried out under different scenarios to cope with future uncertainties. These different scenarios also function as sensitivity analysis to see whether the method functions as expected. Mainly because of the high prioritization of environmental criteria, hydrogen scores best under almost all scenarios. Often with a smaller margin relative to other fuels in stakeholder groups that prioritize environmental criteria less. Where some scenarios and stakeholder groups give a different outcome than the overall base case outcome, it can be concluded that hydrogen, methanol and synthetic diesel scores are most favourable. Important exceptions are:

- Scenario 1, where methanol and especially synthetic diesel top hydrogen by far due to the exclusion of environmental criteria.
- Scenario I, in which methanol levels hydrogen as most favourable fuel due to cheaper CCS.
- Scenario V, as the only scenario in which ammonia becomes an interesting alternative due to the uptake and grow of ammonia availability.
- Scenario IX, where methanol becomes the most favourable fuel due to large availability and a good TRL level of the necessary ICE installation

Especially synthetic methane (e-LNG), DME and to some extent ammonia are lacking to compete with the other fuel alternatives. While these fuels score better in some scenarios with favourable external factors, they're not the best calculated option in any of the outcomes. The fuels that came out best from the AHP method are liquid hydrogen, methanol and synthetic diesel. Therefore, these are the first results that indicate the best alternative fuel for future Fugro vessels. Together with ammonia, these fuels will be assessed again in the last chapter of this thesis.

9

Alternative Fuel Application Fugro Fleet

To further work out and especially quantify the alternatives that came out most promising from the AHP method, this last chapter will work out a test case for the alternatives applied on different Fugro vessels. To do so, a model will be set up that applies the different fuel alternatives to the base-case vessels discussed in chapter 3. Using the acquired operational profile and vessel parameters, an assessment will be made of the autonomy, required power, fuel consumption, fuel tank size and ship size. Moreover, a cost estimate of the different alternatives will be set up using this model. This cost estimate will include capital expenses and fuel costs in detail, operational expenses are already assessed qualitatively in previous chapters and do not differ much between the different fuels. This is done to assess the feasibility of an alternative fuel application onboard of a Fugro vessel, especially the autonomy and cost factors are interesting to research as these are considered the most significant drawbacks of alternative fuels compared to MDO.

This method takes the current vessel parameters as a base point and assesses the vessels when other alternative fuels are applied. For instance, the achievable autonomy when hydrogen tanks are placed on one of the current vessels. At first, no vessel parameters will be redesigned. Later on in the chapter, different fuels are applied to one type of Fugro vessel to investigate how vessel dimensions can or need to be changed in order to facilitate the fuel alternatives.

By applying the found alternatives to the Fugro vessels specifically, it is expected that a better assessment or strategy advise of different alternatives can be given for Fugro specifically. Moreover, some points of attention or even drawbacks of certain fuels could come to light.

The model will also deliver a more tangible result for Fugro stakeholders. Different alternatives applied to different Fugro vessels, including a motivation, will result in a better understanding of the choice for a strategy than the results of the AHP solely. It provides an overview of necessary adjustments or things to consider when applying these fuel alternatives in the long-term.

Lastly, using the model, a cost estimation can be made of the different alternatives. Using this estimation, it not only becomes clear how different fuel costs compare, it can also give an idea of necessary taxes or cost incentives to move towards a more sustainable fuel alternative while remaining profitable as a company. As all the alternatives considered in this study are and will be more costly than the conventional diesel installation.

This chapter will work out applications of alternative fuels that were identified as most suitable from the Analytic Hierarchy Process. Hydrogen, methanol and synthetic diesel will be elaborated on for that reason. Moreover, the application of ammonia will be worked out. Ammonia came out *best of the rest* from the Analytic Hierarchy Process, performing significantly less well than the three previously stated alternatives. However, this alternative fuel is considered interesting to work out nonetheless. This is because of the relatively favourable properties of it’s application and the fact that this alternative is very often mentioned in literature as a good alternative. It also provides a comparison of the AHP and this last chapter. It can show how criteria that are difficult to quantify are included in the outcome of the AHP. On the other hand it could also provide insight on the level of subjectivity in the AHP method.

9.1 Considered alternatives

For the considered alternatives, the converters as discussed in chapter 7 will be used. For Fuel Cell technology this includes the PEMFC, (HT)-PEMFC and SOFC with suitable fuels. Internal Combustion Engine solution vary for the different fuels, the converters with subsequent fuels are shown in table 9.1. Besides the different fuels with matching converters, this table summarizes general parameters that are used in calculations elaborated on in this chapter.

Fuel	**Type**	**Gravimetric Density Low (W/kg)**	**Gravimetric Density High (W/kg)**	**Volumetric Density Low (W/L)**	**Volumetric Density High (W/L)**	**Low efficiency (%)**	**High efficiency (%)**	**CAPEX Brynolf ($/kW)**	**CAPEX Low vBiert ($/kW)**	**CAPEX High vBiert ($/kW)**
Liquid hydrogen (LH2)	PEMFC	250	1000	300	1550	40	60	4300	280	1000
	HT-PEMFC	250	1000	300	1550	40	60	4300	250	600
	SOFC	8	80	4	32	60	70	1500	2000	6000
	Spark-Ignition ICE	45	65	30	45	40	50	1240	875	1240
	Dual-Fuel ICE	45	71,5	32,5	55	40	45	1220	1170	1205
Ammonia	HT-PEMFC + R	300	1250	350	1665	35	45	4050	250	600
	SOFC	8	80	4	32	45	60	1500	2000	6000
	Dual-Fuel ICE	45	71,5	32,5	55	40	45	970	875	985
Methanol	HT-PEMFC + R	300	1250	350	1665	35	45	4050	250	600
	SOFC	8	80	4	32	45	60	1500	2000	6000
	Dual-Fuel ICE	45	71,5	32,5	55	40	45	970	875	985
	Spark-Ignition ICE	45	65	30	45	40	50	1065	840	1060
Synthetic diesel	SOFC	8	80	4	32	45	55	1500	2000	6000
	Compression-Ignition ICE	45	71,5	32,5	55	35	45	730	730	730
MDO	Compression-Ignition ICE	45	71,5	32,5	55	35	35	730	730	730

Table 9.1: Considered alternatives for application (Van Biert et al., 2016) (Brynolf, 2014)

9.2 Overall comparison

While the alternatives are assessed and discussed for all five vessel types mentioned in section 3.5. The graphs and figures are not shown for all five vessel types. To demonstrate the assessed graphs and figures in this chapter, all application examples are shown for one vessel type to avoid repetition. The values shown are for the Fugro Offshore Coastal Survey Vessel. These graphs are included to indicate and demonstrate the used method. All other graphs, for the different types of vessels, can be found in appendix **??** however.

9.2.1 Fuel consumption & autonomy

One of the aspects to consider when choosing an alternative fuel is autonomy. This section will outline how fuel consumption and autonomy will change when implementing a different fuel technology. Using the fuel consumption set out in the operational profile section and the energy density of MDO, the energy consumption of the different Fugro vessels is calculated. Assuming a current fuel efficiency of 35% for the current MDO compression-ignition generator set, approximately 90% generator efficiency and 40% diesel engine thermal efficiency (Klein Woud & Stapersma, 2003)

(ABB, 2003). Each considered alternative has another assumed fuel efficiency, for instance because fuel cells are more efficient in general. While fuel cells will be more efficient than the current MDO ICE, also other ICE technologies like spark-ignition and to a lesser extent dual-fuel engines are assumed to be more efficient around 2030. These assumed efficiencies are shown in table 9.1.

Using these efficiencies, the energy consumed for each alternative for the different Fugro vessels is calculated. Subsequently, the fuel consumption for the different alternatives can be calculated using the energy densities of the different fuels that are considered. Now that the fuel consumption is calculated, a lot of other aspects of each alternative can be calculated using these values. Starting with the achievable autonomy of all different alternatives. This comparison can be made in three ways.

First, it can be investigated how voluminous and heavy the fuel tanks have to be in order to attain the same autonomy as conventional MDO installations on the different Fugro vessels. Second, a comparison can be made by keeping the available volume constrained. This shows the possible autonomy for the different alternatives when the tank volume is kept equal to the current installation. Last the same as the previous step can be done, but with the tank weight constrained. The graphs 9.1 and 9.2 show the outcome of these calculations. First, a bar chart shows the different tank weights and achievable autonomy when the same volume of each alternative fuel is stored as possible in a MDO tank. Then, the tank volume and achievable autonomy is shown when the tank weight is the limiting factor. Later in this chapter, this comparison will be made again using these three steps. In that case however, vessel dimensions are modified.

9.2.2 Fuel cost

Related to the fuel consumption and autonomy and at least equally if not more important, is the fuel cost of the different alternatives. While the autonomy is decisive in reaching and carrying out operations, the fuel cost is crucial in doing this economically. Projected fuel costs vary over a wide range. Dependent on the assumed efficiency of the alternative and the consulted reference (DNV GL or Lloyd's Register). Both give a low and high price scenario. Figure 9.3 shows the range of fuel costs per day for a selected vessel, based on the calculated fuel consumption as an example. Graphs of fuel cost ranges for other vessels can be found in appendix **??**. As expected each of the alternatives is more costly than the current fuel MDO. How the different fuels compare to MDO will be explained in subsection 9.3.2. The MDO price to compare the alternatives to is relatively low at this moment in time. This study uses an estimated price of 350 to 400 $/ton which leads to the following cost estimation.

9.2.3 Installation weight and volume

Another aspect taken into account to compare the different alternatives is the weight and volume of the installation. This provides another assessment whether a fuel can be applied in a Fugro vessel or not. It could be that an installation is very voluminous or heavy and therefore difficult to be placed in a Fugro ship. This assessment is shown in the schematics in chapter3.1. All Fugro vessels have a diesel-electric lay-out. Therefore, the diesel generator sets can be compared to the alternative converters, without having to look at changing other parts of the propulsion installation. However, Fuel Cell systems are not capable of handling power transients and peaks very well, therefore these systems would require a battery pack together with this type of alternative converter. On the other hand, it could be that Fugro vessels could already be hybrid by 2030, because of efficiency advantages. For these reasons, only the converters themselves are compared.

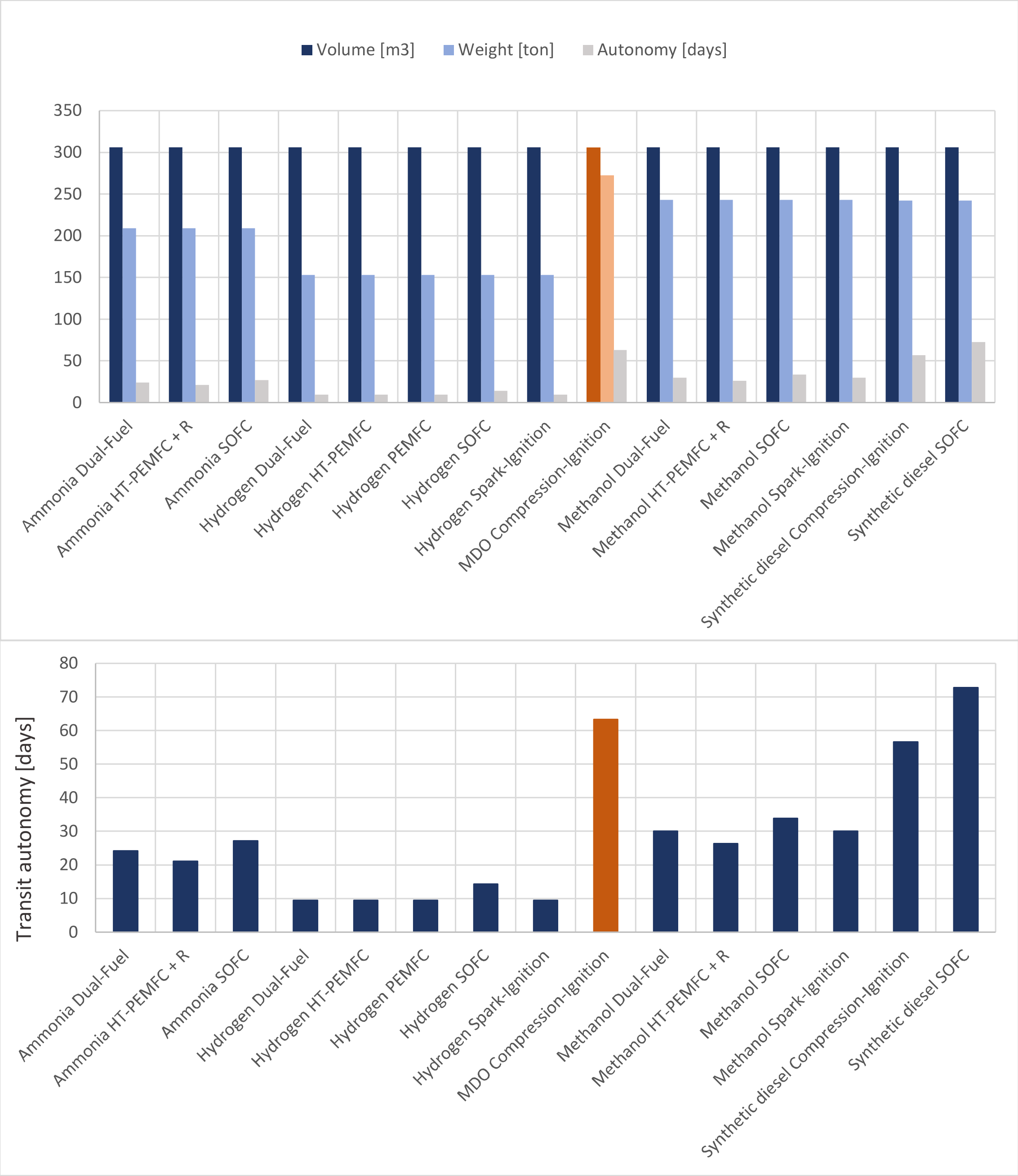


Figure 9.1: Volume constraint, autonomy and tank weight (FOCSV)

Alternative ICE installations are comparable to the installations used nowadays. SOFC systems are likely to be larger and possibly heavier, requiring different lay-outs. (HT)-PEMFCs are expected to be relatively compact. However, battery packs are to be included in the ship design, bringing the difference in weight and volume to a minimum. A reason for these minor differences in installation capacity can be partly found in the fact that Fugro vessels are and will be configured with a diesel-electric propulsion installation. This makes that these vessels and their machinery spaces are relatively versatile.

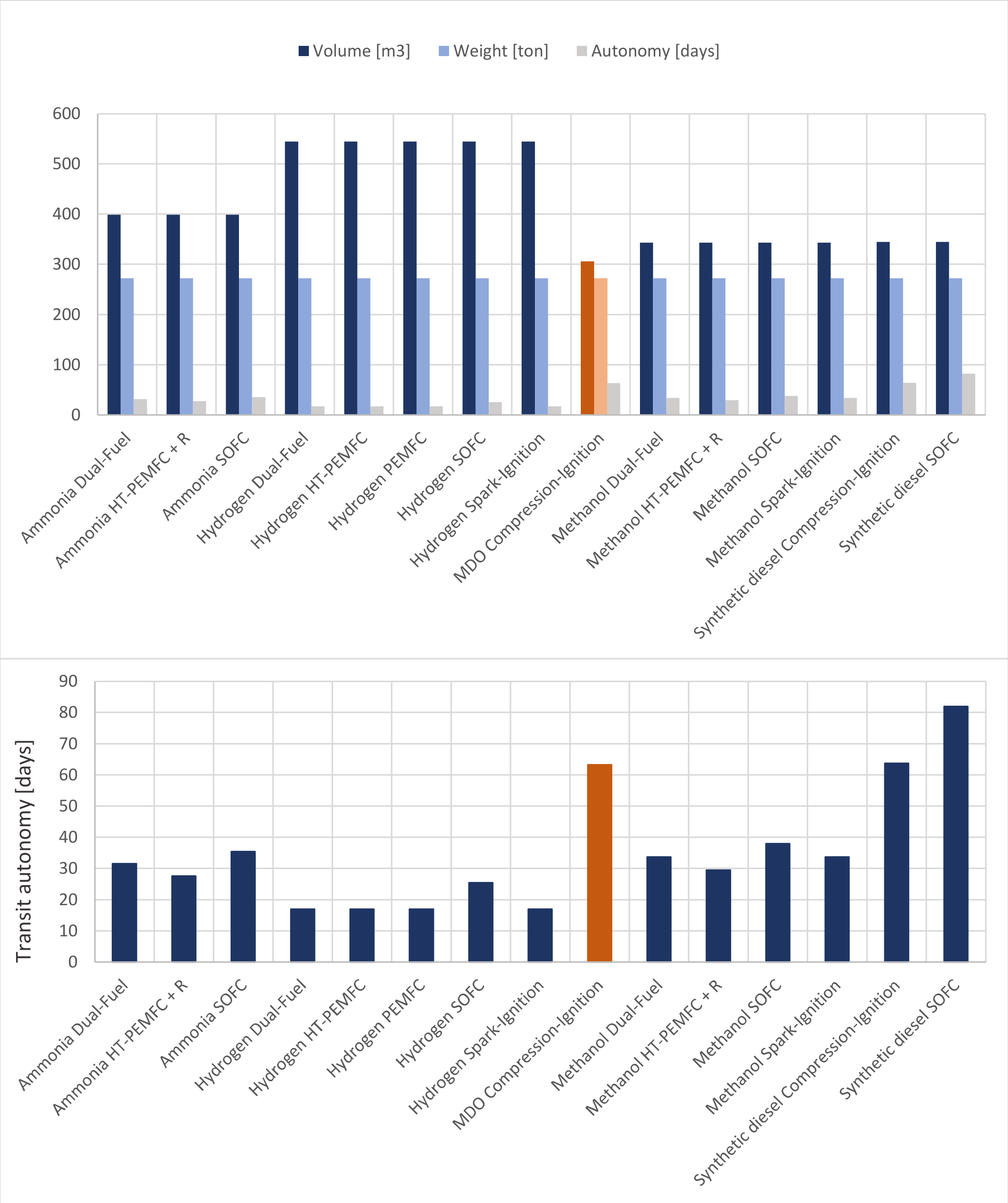


Figure 9.2: Weight constraint, autonomy and tank volume (FOCSV)

9.2.4 Installation cost

The found prices for an installation or power plant still vary. Especially for Fuel Cell technologies. Scaling up production in the coming years could drastically lower FC technology prices. However, if this upscale in production doesn't occur, Fuel Cell prices can remain very high. This explains the large range in installation costs as shown in figure 9.5. When production numbers do increase, (HT)-PEMFC technology could potentially become cheaper than conventional installations. However, in the case of hydrogen this is deemed unlikely as the required piping and insulated tanks incur high costs. This is also the reason why hydrogen ICE technology is slightly

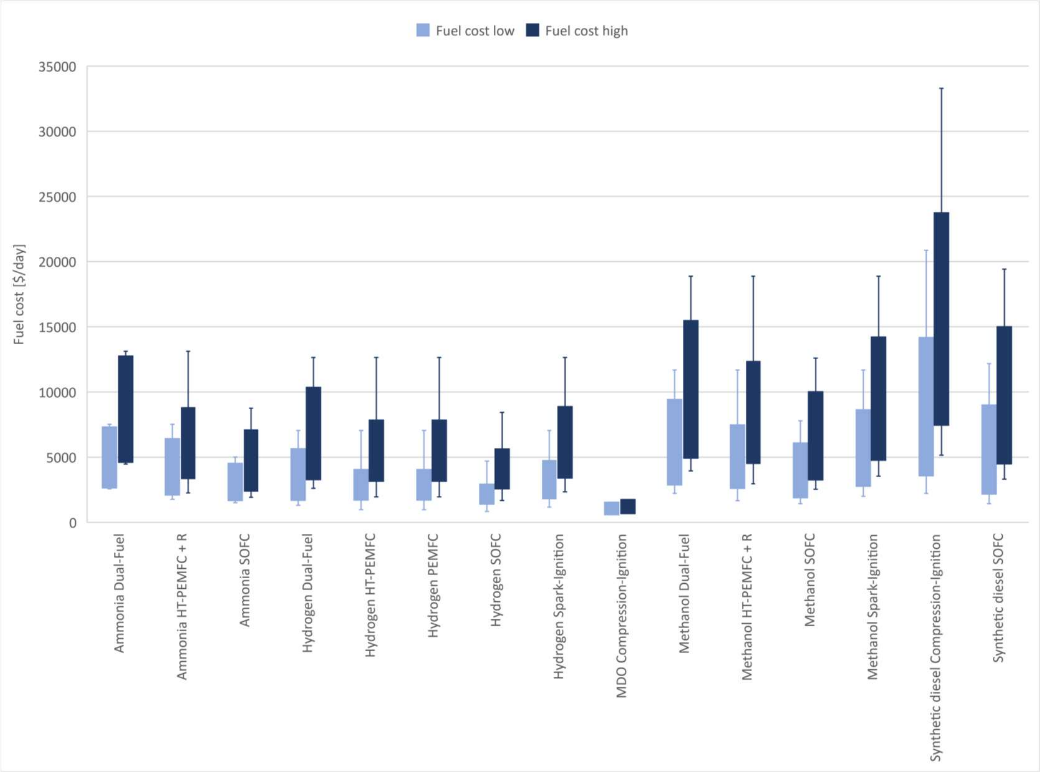


Figure 9.3: Fuel cost range (FOCSV)

more expensive than other ICE alternatives. In general, ICE alternatives are expected to have higher investment costs than the technology we see nowadays. Sometimes comparable to the investment cost increase of LNG installations, which is about 1.1 to 1.2 times higher than a normal compression-ignition engine. Moreover, spark-ignition technology is expected to be more costly than dual-fuel or compression-ignition technology.

9.3 Dashboard comparison

To acquire and summarize the exact values for the parameters of different fuel alternatives that were mentioned in this chapter, a model generating a dashboard was set up. A capture of this dashboard is shown in figure 9.6. Until now, prices are shown over a range for example. While this is valuable to assess the different alternatives at a glance, exact values for each alternative based on different dimensions like vessel type are deemed important as well. In this dashboard, the vessel type, together with different dimensions can be selected in order to generate output for a selected alternative. This tool provides a way to quickly analyze and compare different fuel alternatives. Even more, when more precise input values become available, these can be entered into the database, resulting in more definite output in this dashboard. The image underneath shows this dashboard. Different output is marked by the numbers in the image, this output is explained underneath.

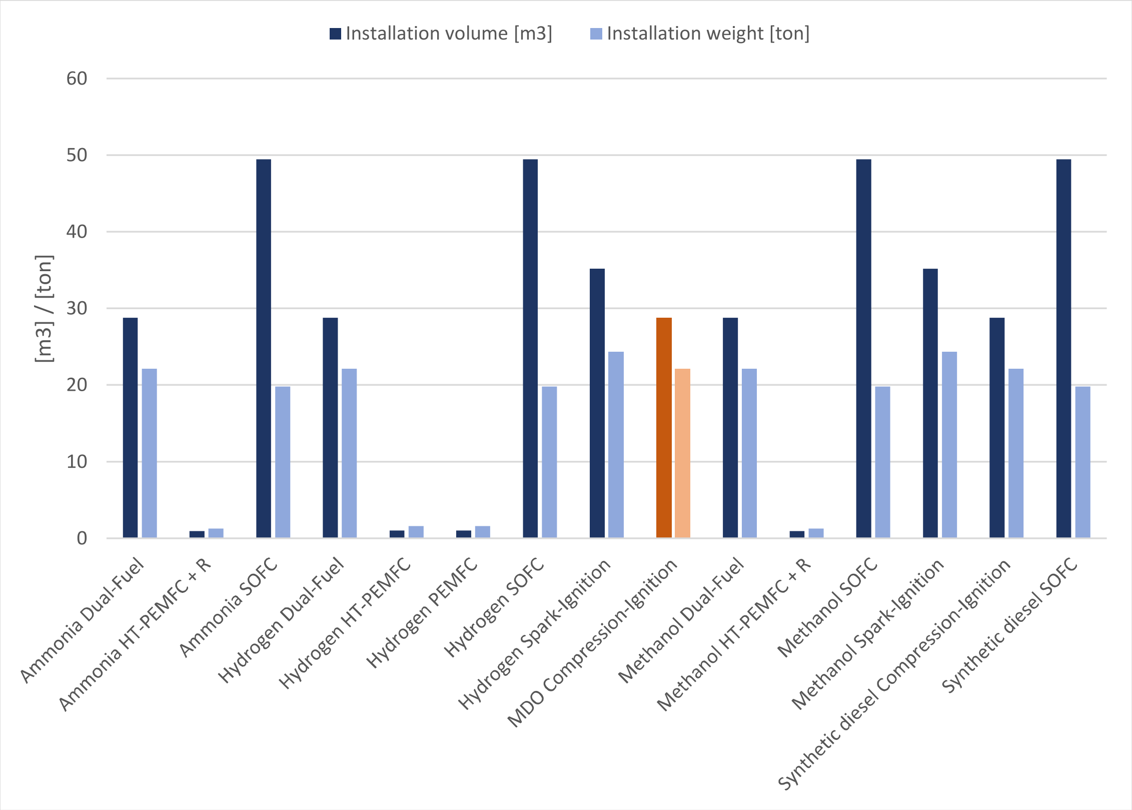


Figure 9.4: High density scenario converter size and volume (FOCSV)

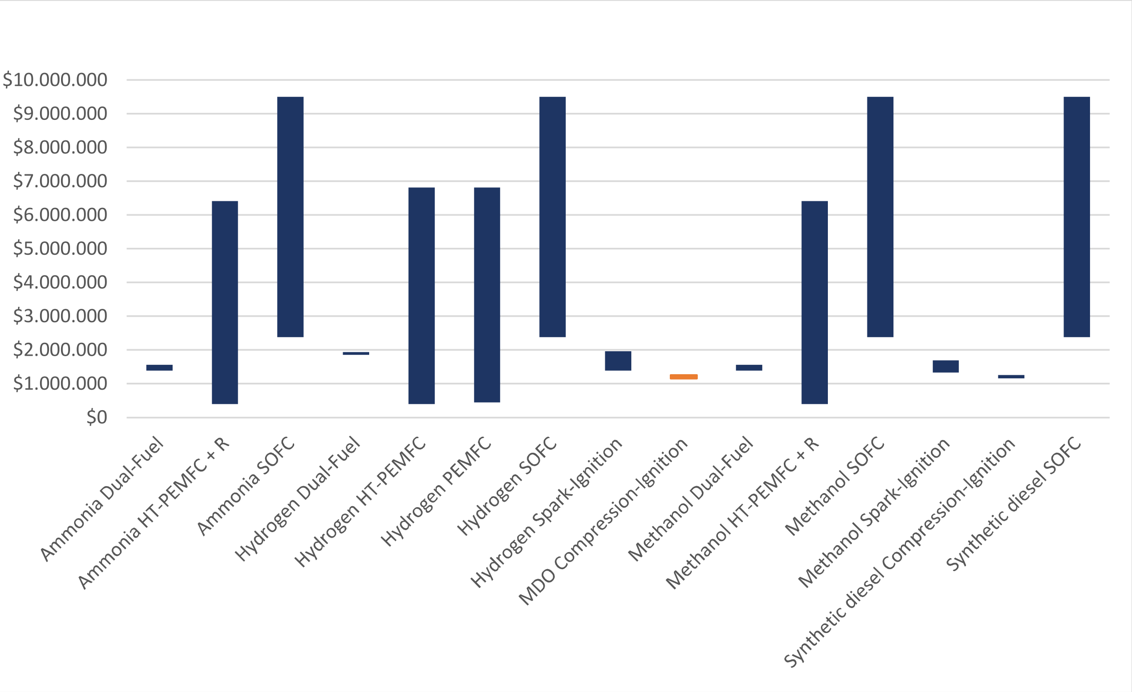
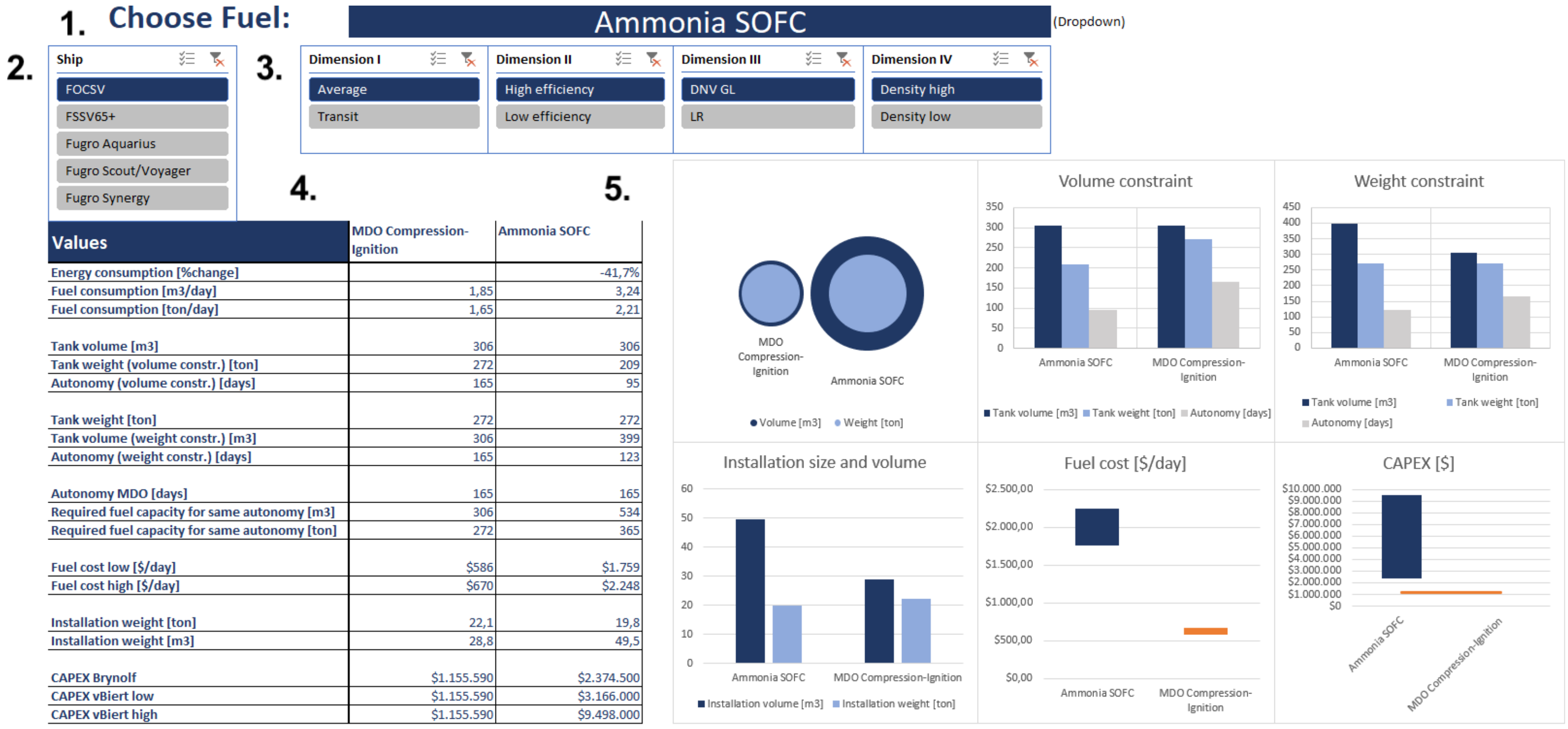


Figure 9.5: Range of installation CAPEX (FOCSV)



1. Choose Fuel: Ammonia SOFC (Dropdown)

2. Ship
- FOCSV
- FSSV65+
- Fugro Aquarius
- Fugro Scout/Voyager
- Fugro Synergy

3. Dimension I
- Average
- Transit

Dimension II
- High efficiency
- Low efficiency

Dimension III
- DNV GL
- LR

Dimension IV
- Density high
- Density low

4.

Values	MDO Compression-Ignition	Ammonia SOFC
Energy consumption [%change]		-41,7%
Fuel consumption [m3/day]	1,85	3,24
Fuel consumption [ton/day]	1,65	2,21
Tank volume [m3]	306	306
Tank weight (volume constr.) [ton]	272	209
Autonomy (volume constr.) [days]	165	95
Tank weight [ton]	272	272
Tank volume (weight constr.) [m3]	306	399
Autonomy (weight constr.) [days]	165	123
Autonomy MDO [days]	165	165
Required fuel capacity for same autonomy [m3]	306	534
Required fuel capacity for same autonomy [ton]	272	365
Fuel cost low [$/day]	$586	$1.759
Fuel cost high [$/day]	$670	$2.248
Installation weight [ton]	22,1	19,8
Installation weight [m3]	28,8	49,5
CAPEX Brynolf	$1.155.590	$2.374.500
CAPEX vBiert low	$1.155.590	$3.166.000
CAPEX vBiert high	$1.155.590	$9.498.000

5.

Figure 9.6: Dashboard capture (FOCSV)

1. **Fuel dropdown menu**: In the dropwdown menu, the fuel alternative that is to be compared can be chosen from a dropdown list. In this case, an ammonia SOFC is chosen, making that the sheet compares an ammonia SOFC intallation to the conventional diesel installation.
2. **Ship slicer**: In this slicer, a vessel can be selected as base case to assess the selected alternative. As for each selected ship the dimensions and operational profile are different. For each selected ship, the relevant output changes according to the chosen vessel parameters.
3. **Dimension slicers**: Values for different alternatives change for different selected dimensions. For example, fuel cost can be based on projected values from DNV GL or Lloyd's register. In the same way, the dashboard can show values for a fuel consumption in average or transit operations, an low or high assumed fuel efficiency and low or high gravimetric and volumetric densities of the converters that are assessed.
4. **Output table**: This table generates output for the selected options in the previous steps. Values for fuel or energy consumption, fuel capacity, autonomy, fuel and investment costs and converter size and weight are displayed. The left column shows the values for the original installation, the right column displays the values for the alternative that was selected under option 1.
5. **Output graphs**: The graphs to the right of number 5 visualize the output. Required volume and weight capacity for the same autonomy are shown scaled relative to each other. Possible autonomy for weight or volume constraint cases are shown. Again, also converter size and volume and fuel and investment costs are shown, relative to a MDO installation.

Using output from above dashboard, this section will discuss each of the different fuel alternatives in more detail.

9.3.1 Autonomy

This section will discuss the autonomy of the different alternatives seperately. Using the output of above dashboard. Again the distinction between fixed autonomy, fuel tank volume and fuel tank weight is used. From the table output, the new values compared to MDO are obtained. These are values based on the calculation as discussed in the previous section. Changes in vessel dimensions or installed power are neglected in this assessment.

Ammonia

Ammonia has lower energy densities (MJ/kg & MJ/m^3) and a lower density (kg/L) than MDO. For that reason, more ammonia is required in order to attain the same autonomy as compared to MDO. When the current tank volumes of the different vessels would be filled with ammonia instead of MDO, the autonomy of the vessels would decrease to around 40% of the current autonomy. When the weight is the constraint, a larger volume of ammonia can be taken in due to its lower density. In that case the autonomy decreases by 50%. For all considered vessels, the transit autonomy becomes around 30 days using ammonia. When SOFC technology would be installed, the autonomy could remain somewhat better, due to it's higher fuel efficiency. The Fugro Aquarius has a relatively good fuel economy, meaning that the autonomy remains slightly larger compared to the other vessels. While the decrease in autonomy is significant when using ammonia, it is considered to perform well enough. Large transits would still be in reach.

Hydrogen

The main drawback of hydrogen comes to light in this case application as well. While the fuel, including storage, is relatively lightweight, the large amount of required volume remains a significant disadvantage. In the most efficient case, when using hydrogen in a SOFC, the transit autonomy is decreased to around thirty days. This is when the weight is a constraint and a scenario that would require twice as much tank volume on board of Fugro vessels. Twice as much tank volume, at cryogenic conditions, is not deemed feasible on a Fugro vessel comparable to the vessel designs that are in service now. Thus, a different, larger design would be required. When current tank volumes are used, the autonomy would decrease to fourteen days transit autonomy. An Atlantic crossing from IJmuiden to Houston, Texas at nine knots takes around 28 days. This voyage would not be possible without bunkering en route, making hydrogen a less suitable alternative to be used on board of Fugro vessels, unless vessel dimensions are increased.

Methanol

Of the non-diesel alternatives, methanol comes closest to the density properties of MDO. While lighter and somewhat more voluminous for the same energy carried. The energy densities are relatively advantageous compared to other alternatives. The autonomy of this alternative is highly dependent on the converter type. Methanol is suitable to be used in a lot of different converter alternatives. In the best case, using a high-efficiency SOFC, methanol almost achieves the same autonomy as a MDO installation. In the worst case, using methanol in an ICE or low-efficiency HT-PEMFC, the autonomy remains thirty days in the same tank volume as present in current designs. However, methanol has a lower density than MDO. Because methanol is far less hazardous to the environment than conventional fuels like MDO, methanol can be stored in more ship spaces than MDO. Therefore, a larger volume of methanol can easily be carried in the vessels that were assessed in this case. Yielding an autonomy of a minimum of about 50% compared to MDO for the same vessel types. Enough for larger transits and providing the capability to carry out significant operational spans.

Synthetic diesel

Synthetic diesel is very comparable to MDO. It has a lower volumetric density however. For that reason, a slightly smaller amount of energy can be carried in the same tank volume. When the tank volume is kept equal, the autonomy is decreased by roughly 10% compared to MDO.

9.3.2 Fuel cost

Ammonia

The current forecast is that ammonia will be about six to eight times as expensive as the current price of MDO, dependent on the converter and it's efficiency. An advantage is that the price range is relatively small relative to the other fuels, resulting in less uncertainty on future price levels. While this fuel is also dependent on the price of renewable hydrogen, it isn't dependent on CCS prices. Exact values per day of operation or transit can be best found in the dashboard.

Hydrogen

As all the other considered fuels are products produced using renewable hydrogen, this alternative is least expensive, in all scenarios. However, also this fuel is significantly more expensive than MDO. Hydrogen is projected to be about five to eight times more expensive than MDO.

Methanol

The production of the last two considered fuels, methanol and synthetic diesel, requires captured carbon besides renewable hydrogen and renewable energy. For that reason these fuels are even more expensive. Because of the uncertainty in price of captured carbon, the price projection is also more uncertain than the two fuels discussed above. The currently projected methanol price is at least six times as high as the current price of MDO. This estimation can raise to up to eleven times more than the price of MDO for one day of vessel transit.

Synthetic diesel

Projected synthetic diesel prices are estimated to be thirteen to nineteen times more than the current MDO price.

Overall

Based on these prices, ammonia looks the most safe alternative price-wise, excluding hydrogen because of the insufficient autonomy. It is clear however that current fuel price projections are not economically viable and the future has to point out what actions will lower these prices. CO2-taxes, incentives on renewable fuels and or price reductions because of economy of scale can and must all play a role. Another alternative to reduce prices is by blending renewable fuels with fossil fuels during a transition period in which the renewable fuels are still expensive and relatively scarce. All fuels that are treated in this study are suitable for blending, however this is out of scope of this thesis as this study only looks at zero-carbon or carbon-neutral alternative fuels.

9.3.3 Installation weight and volume

The considered Internal Combustion Engine alternatives consist of the conventional Compression-Ignition engine, the Dual-Fuel engine and the Spark-Ignition engine. The weight and volume is more or less equal to the engines that are used today. Only the SI engines weigh more and are somewhat more voluminous. Regarding Fuel Cells (FC) this is different. The experimental SOFCs of today are very large and voluminous but it is expected that this will significantly drop when SOFCs are developed further. Eventually, these SOFC systems will be more voluminous but more lightweight than conventional installations. But this is when assuming a scenario with a large uptake of SOFC technology, resulting in a high power density. When power densities remain low, SOFC technology is not suitable for Fugro vessels yet. (HT)-PEMFCs have higher power densities compared to the conventional installation, with batteries included however, this would be different. Still it is expected that these installations would require less space and payload than the current installations.

When Fuel Cells are applied in future designs, this requires the inclusion of battery systems to cope with power peaks and transients. However, Fugro is already looking to convert some of their vessels to a hybrid configuration that use a conventional diesel-electric installation combined with battery packs. Therefore, it is likely that future vessel designs will already feature hybrid configurations of this type.

9.3.4 Installation cost

The investment costs for a conventional MDO system for the assessed Fugro vessels range from 1.2 million USD to 8.7 million USD. 1.2 million USD being the price for the smaller survey vessel and 8.7 million USD for the larger drilling vessels. For the smaller range of vessels, CAPEX for ICE alternatives will be higher than the current CAPEX. The prices are expected to remain under

2 million USD however. The investment costs of newer ICE technology for the larger vessels that are assessed, are expected to remain well under 15 million USD.

Fuel cell prices are more difficult to forecast. Both (HT)-PEMFC and SOFC prices have a wide range. SOFC technology for the smaller survey vessels could possibly be available for under 2.5 million USD. However, looking at the price range, this is unlikely. Based on the values presented in section 7.1.2, the following investment cost estimates are calculated. For the smaller survey vessels, CAPEX for a Fuel Cell alternative can raise to 6-9 million USD. For the larger drilling vessels, these prices can even increase to between 50 and 70 million USD. It is clear that these investment costs have to be reduced to be a viable solution to install on newly built Fugro vessels.

Again, the estimated prices under different dimensions can be looked up in the dashboard sheet. These installation costs solely assess the price of the installation itself, neglecting additional investment costs due to changing ship dimensions or different power requirements. This will be looked into more extensively in section 9.4.7.

9.4 FOCSV application comparison

The values obtained from the dashboard, show how the different fuels compare to each other by giving a conceptual overview of autonomy and cost. However these numbers don't point out some specific considerations of the application of the different fuels. Moreover, the values for autonomy show that larger vessels are required to approach an autonomy similar to that of today's vessels using alternative fuels. For those reasons this section will elaborate on these subjects by outlining a rough concept of the application of the different alternative fuels on a Fugro vessel. The Fugro Offshore Coastal Survey Vessel or FOCSV. This provides extra clarity on the application of the different alternative fuels on a Fugro vessel and gives a more in-depth comparison between achievable autonomy and costs.

9.4.1 Method

As pointed out in the introduction of this section, this case application will be done for the FOCSV specifically. This vessel type is chosen as it is considered a representative and versatile vessel type in Fugro's fleet. Moreover, detailed information and models of this vessel type are available. Besides the considerations mentioned previously, there are some specific conditions in applying different alternatives. These will be mentioned in the coming section. These considerations mostly cover the application possibilities of the different alternatives.

In this section, the different considered alternatives will be assessed in three ways. First the available autonomy with the same vessel dimensions are worked out, based on the acquired values from the dashboard and by modelling fuel tanks in a Delftship model of the FOCSV. Secondly, the necessary tank size to acquire the same autonomy will be reviewed. Again by using the values obtained from the dashboard in the previous section and by modelling the specific tank type. Lastly, using findings in the previous step, vessel dimensions will be changed to obtain the same autonomy as today's FOCSV using MDO. This last step is deemed most interesting as it gives insight into how vessels need to change in order to successfully adopt an alternative fuel. Moreover, it shows what these changes in vessel dimensions incur to both autonomy and costs. It also gives a more imaginable idea of the application of the fuel alternative.

When the vessel dimensions change, so does the fuel consumption and speed or installed power. Also investment costs change due to increased steel costs for example. This section will work out how these parameters change using Delftship software. In Delftship, the existing FOCSV model

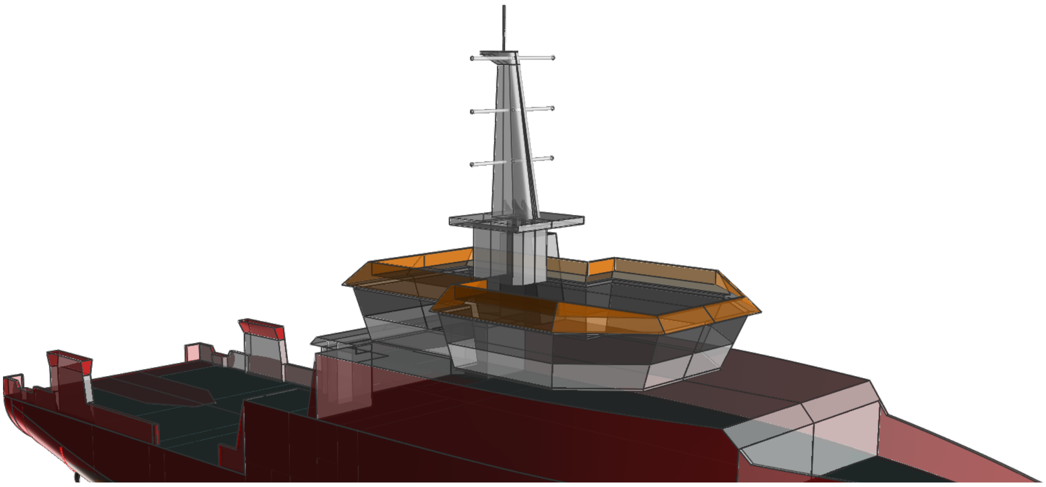


Figure 9.7: Original Delftship model FOCSV

can be assessed and altered to acquire the parameters necessary for the calculations in this part of the thesis. As an example, these parameters can be used in a resistance calculation using the method of Holtrop and Mennen (Holtrop & Mennen, 1982). The acquired parameters of the default and concept hulls, together with this method provide the resistance curves. With these resistance curves and the following equation (Klein Woud & Stapersma, 2003), the effective towing power for a range of ship speeds can be calculated:

$$P_E = R * v_s \tag{9.1}$$

From the load balance of the FOCSV that Fugro provided, the propeller power is obtained. Using the calculated value for the effective towing power and the propeller power, the propulsive efficiency is calculated. The propulsive efficiency is then assumed constant for all ship speeds to calculate the delivered power at different speeds. In reality this efficiency is not constant for all ship speeds, however this assumption is considered precise enough for the intended calculations in this thesis. Using this calculation, the propeller efficiency of the azimuth thrusters is assumed to be 0.32. This is a relatively low efficiency. Because the FOCSV has a shallow draft, the thrusters have small (D=1.4m) relatively highly loaded ducted propellers. For these calculations the following two equations are used (Klein Woud & Stapersma, 2003):

$$\eta_D = \frac{P_{E(9kts)}}{k_p * P_{P(9kts)}} = \frac{P_{E(9kts)}}{P_{D(9kts)}} \tag{9.2}$$

$$P_D = \frac{P_E}{\eta_D} \tag{9.3}$$

The transit speed under increased resistance, but with the same delivered power or the delivered power to sail nine knots under increased resistance can now be calculated. Using the following formulas:

$$P_E = c_1 * v_s^3 \tag{9.4}$$

$$P_D = \frac{c_1 * v_s^3}{\eta_D} = c_2 * v_s^3 \tag{9.5}$$

In the first case, the vessel becomes larger, thus resistance becomes larger, propulsion power and fuel consumption remain the same but transit speeds drop. If this reduction is small, it would have minor effect, if the transit speed drops significantly however, the extra required power needs to be calculated. In this other case, the transit speed is kept constant and the required increase in power is calculated. Due to this increase in delivered power, the fuel consumption is higher and so become the fuel costs. While the autonomy decreases. The fuel consumption is also calculated using efficiencies that are assumed constant over the whole range of ship speeds. The effective engine efficiencies as stated under dual-fuel ICE low efficiency in table 9.1 are used for this calculation. Note that engine efficiencies are not constant for different engine loads in real applications. Because the diesel-electric FOCSV is equipped with four generators, there is room to tune engine loads for optimal fuel efficiency however. The initial value for the efficiencies is calculated backwards from the reference point from operational fuel data. Using a electric conversion efficiency of 0.9, this reference point is matched. This electric conversion efficiency entails losses between the generator set and the actual power delivered to the propellers. It includes losses in cabling, switchboard and frequency drive for example. The equations then used to find values for fuel consumption at different ship speeds are shown below:

$$\eta_{trm} = 0,9 = \frac{P_D}{P_B} \tag{9.6}$$

$$P_B = \frac{P_D}{\eta_{trm}} \tag{9.7}$$

$$\eta_e = \frac{P_B}{\dot{Q}_f} \tag{9.8}$$

$$\dot{Q}_f = \frac{P_B}{\eta_e} \tag{9.9}$$

$$\dot{Q}_f = \dot{m}_f * h_f \tag{9.10}$$

$$\dot{m}_f = \frac{\dot{Q}_f}{h_f} \tag{9.11}$$

Above equations are used to calculate the desired values to assess the autonomy and fuel consumption of the different concept designs. The following sections will discuss the findings and results of these calculations for the different fuels.

9.4.2 Ammonia concepts

Liquid ammonia has to be stored in cylindrical, elliptical or spherical tanks, making it more difficult to find suitable storage space on board of Fugro vessels without having to increase the ship dimensions. To acquire the same autonomy as when using MDO, ammonia would need a fuel tank capacity of 801 m^3 and 547 tons, far beyond possible on a design similar to that of the FOCSV. Especially considering that the tanks are likely to be cylindrical. Therefore, a model with the maximum amount of ammonia in the current design and a model with changed parameters is evaluated.

When considering cylindrical tanks, a configuration as shown below in figure 9.8 could be used. In this configuration certain tanks and rooms are re-positioned to place the large cylindrical ammonia tanks. While no specific regulation for ammonia tanks is in place as of yet, this configuration

Fuel	Autonomy [days]	Concept	Lwl [m]	B [m]	T [m]	Cb	Displacement [ton]	Tank weight [ton]	Tank volume [m3]
MDO	63	Same dimensions	52,8	12,50	3,1	0,74	1449	272	306
Ammonia	63	Dimensions increased, LB constant	64,7	15,55	3,1	0,78	2366	438	807
Ammonia	63	L increased	71,1	12,50	3,1	0,80	2163	438	807
Ammonia	25	Same dimensions	52,8	12,50	3,1	0,74	1449	208	306
LH2	25	Dimensions increased, LB constant	64,7	15,55	3,1	0,78	2366	404	807
LH2	25	L increased	71,1	12,50	3,1	0,80	2163	404	807
Methanol	63	L increased	59,0	12,50	3,1	0,76	1688	511	644
Methanol	63	Dimensions increased, LB constant	56,3	13,40	3,1	0,75	1695	511	644
Methanol	63	T increased	52,8	12,50	3,8	0,73	1689	511	644
Methanol	34	Same dimensions	52,8	12,50	3,1	0,74	1449	272	343
Methanol	30	Same dimensions	52,8	12,50	3,1	0,74	1449	243	306

Table 9.2: Hull dimensions for assessed alternative fuel concepts

places the tanks well out of the sides and bottom of the hull, for safety in case of collision damage. However, the largest ammonia tank is placed underneath the accommodation, requiring extensive ventilation and fire precautions. In this configuration the current fuel tank volume can be fitted. Meaning that around 300 m^3 can be stored in this vessel without needing to change it's dimensions.

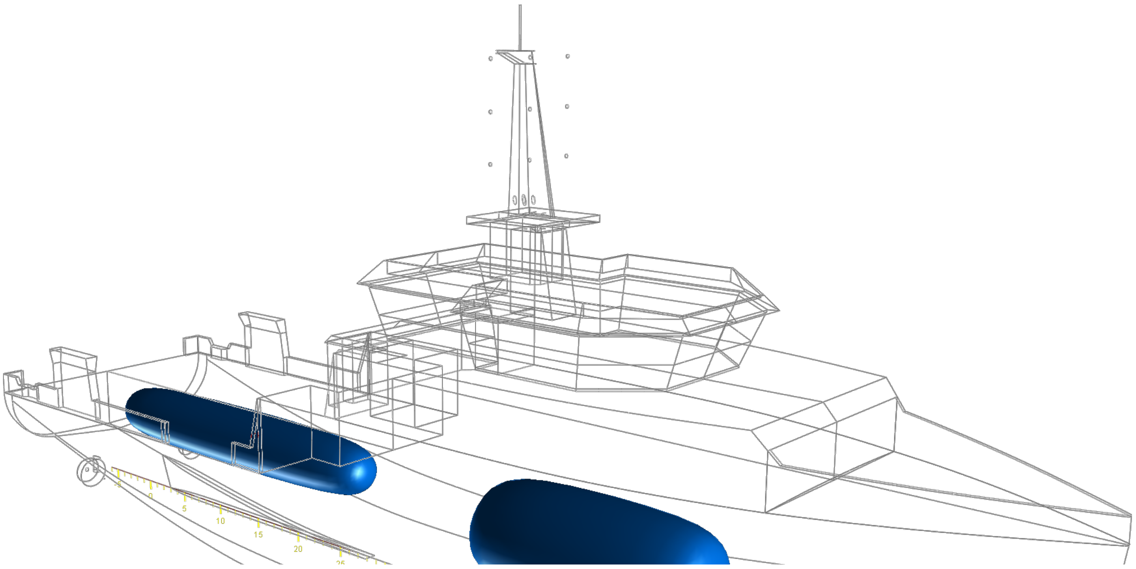


Figure 9.8: Delftship concept ammonia with same vessel dimensions

When a theoretical autonomy of 63 days using ammonia is required, the dimensions of the vessel need to be changed. In this case, a solution using on-deck storage is considered because of the available space and for safety reasons. This concept is also used in the application study into hydrogen. A storage tank consisting of approximately 800 m^3 can be placed on deck by solely increasing the length or by increasing length and width of the ship while keeping the L/B ratio constant. Important to state is that the available deck space is kept constant and that the tanks need to be placed $0.2 * B$ measured from both sides of the vessel ("IGF Code (MSC.391(95) Code of safety for ships using gases or other low-flashpoint fuels) - Netherlands Regulatory Framework (NeRF) – Maritime", n.d.). This results in a very long and a more lumpish design as shown in figures 9.9 and 9.10. The changed main dimensions are shown in table 9.2.

Using Holtrop and Mennen a new resistance for this hull is calculated. Then, with the same amount of delivered power as the conventional situation, the transit speed would decrease to 8,1 and 8,3 knots for the larger and lengthened hull respectively. The autonomy in days would be the same as that of MDO, however the distance travelled will reduce. The speed could remain nine knots when the delivered power would increase to 591 and 635 kW for the overall larger and lengthened concepts respectively. This however would mean more fuel consumption, and therefore a smaller autonomy in days. The possible distance to be travelled however would become 9460 nm for the overall larger design and 9978 nautical miles for the lengthened concept. Compared to 12220 and 12518 nm when sailing at lower speeds. Therefore, a lengthened concept would be able to travel longer distances and both concepts would easily be able to make long transits. However, this longer autonomy could incur a lower transit speed, this trade-off has to be considered during the design phase. Also when an autonomy comparable to the autonomy of MDO is desired, transit speeds have to be reduced when using ammonia.

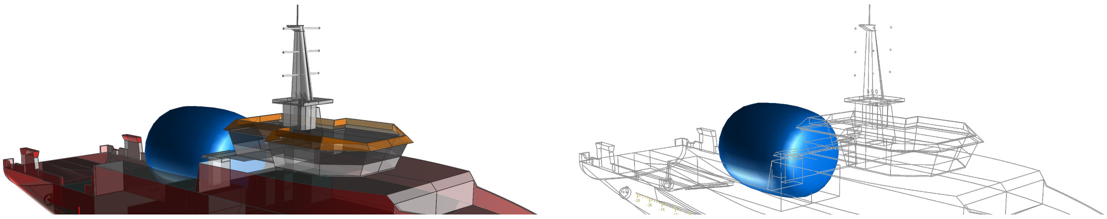


Figure 9.9: Delftship concept larger with constant LB ammonia/hydrogen

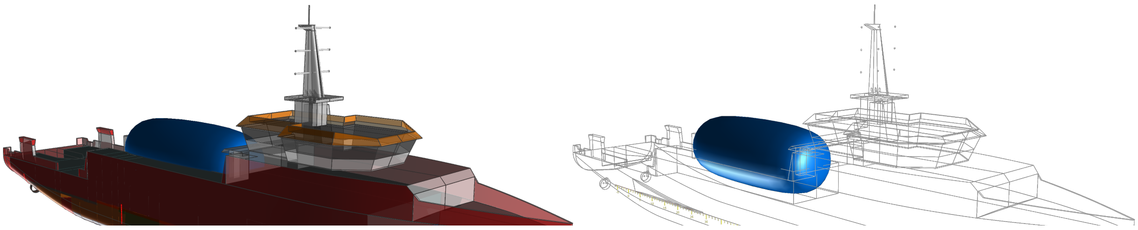


Figure 9.10: Delftship concept lengthened ammonia/hydrogen

9.4.3 Liquid hydrogen (LH2) concepts

When applying liquid hydrogen, an important aspect is the location of potential hydrogen tanks. While there is no specific regulation for the storage of liquid hydrogen as a fuel, the IGF code can be used to approve a hydrogen fuel installation. Besides a lot of other aspects, this code prescribes the location of hydrogen tanks. Using these prescriptions, hydrogen tanks were modelled into a model of an existing Fugro vessel to get an idea of the possibilities for hydrogen fuel in a similar design as existent today. The cryogenic circumstances under which hydrogen has to be stored, mean that hydrogen fuel tanks have to be cylindrical, elliptical or spherical in order to evenly distribute the pressure load on the thickly insulated tank walls. This together with the IGF regulations make it undesirable to place a significant amount of hydrogen on another place than on the deck of the vessel.

Liquid hydrogen would require 2035 m^3 of tank volume and 1017 tons of tank weight capacity in order to attain the same autonomy as a conventional FOCSV propelled using MDO. To place this volume in perspective, the render in figure 9.11 below shows a cylindrical tank of this size modelled on a FOCSV. Due to it's sheer size and weight, this quantity of liquid hydrogen is therefore deemed impossible to apply on a FOCSV. Moreover, it is deemed impossible to apply hydrogen fuel on a FOCSV without changing vessel dimensions as a whole. This is because the liquid hydrogen tanks are best placed on deck, meaning that the vessel has to be larger assuming that the current deck area is fully required for operations.

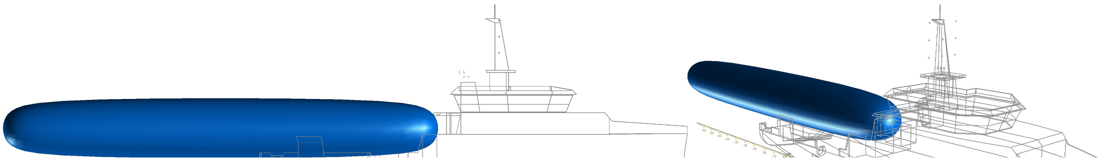


Figure 9.11: Required fuel tank to attain autonomy comparable to MDO autonomy

To test the application of liquid hydrogen when changing vessel parameters, the same tank capacity and design is used as for the application of ammonia. However, due to the lower energy density of hydrogen including the tank system, the autonomy is highly compromised. This volume is suited however because it entails a theoretical endurance of 25 days, enough for a large transit, like an Atlantic crossing for example. These designs are also relevant as they take the relevant IGF code into account as far as possible. Meaning a minimum distance to ship hull and a location on deck are both in place. These concepts are shown in figures 9.9 and 9.10. The main dimensions that are changing are shown in table 9.2. In the same way as with ammonia, the speed or actual autonomy in nautical miles is compromised due to the increasing vessel dimensions. Meaning that a trade-off has to be made between lower transit speeds and higher autonomy or the same transit speed but with a reduced autonomy in nautical miles. With a transit speed of 8,1 or 8,3 knots, autonomy is slightly better at approximately 4900 miles compared to 4200-4500 miles when sailing a nine knots. While these autonomies are relatively close compared to each other, both are not considered to provide enough autonomy capabilities. These concepts do not provide the capability of a transit from IJmuiden to Houston for example.

9.4.4 Methanol concepts

Opposite to the storage of hydrogen and ammonia, the storage of methanol is not difficult and can even bring advantages compared to MDO storage. Methanol can be stored liquid at ambient temperatures. Only a few modifications need to be assessed because methanol is a low-flashpoint fuel. The most significant advantage however, is in the options for tank locations. Methanol can be stored in the double hull of all Fugro ship types for example. Together with the fact that methanol has a lower density (kg/L), this means that a larger volume of methanol can be taken in when considering a similar to existent design. This makes that the autonomy loss compared to MDO becomes smaller when transitioning to methanol as alternative fuel.

To achieve the same autonomy as the conventional MDO installation, 644 m^3 or 511 tons of methanol is required in fuel tanks on the vessel. While voids and extra tank locations could be added to the concept design to add tank volume, the payload of the FOCSV isn't sufficient to store an extra 239 tons of fuel. For that reason, a similar vessel as the FOCSV isn't able to achieve the same autonomy as a MDO variant without increasing vessel dimensions.

When considering the amount of methanol that can be carried in the same vessel design as the current FOCSV, two concepts are assessed. First, by having the volume as a constraint, so by filling the current tanks with 306 m^3 methanol instead of MDO. This would result in an autonomy of 30 days. However, because of the above-mentioned advantage of different storage possibilities, also a design is made where more fuel tanks are placed in voids where MDO isn't allowed to be stored. In this case, the payload of the fuel is the constraint, resulting in the possibility to store 343 m^3 of methanol in the current vessel design. Enabling an autonomy of 34 days at nine knots. This means that the current vessel dimensions enable the storage of enough methanol to transit approximately 6500 to 7300 nautical miles. A quantity significantly less than conventional, but enough to make larger transits without a forced refuelling stop. Therefore it can be concluded that methanol would be a suitable alternative even without the need to enlarge Fugro vessels.

The third option to store an amount of methanol yielding an autonomy comparable to that of MDO, is by increasing vessel dimensions. Three options are considered. Lengthening the vessel, lengthening and widening the hull with a constant L/B and lastly increasing hull height and draft. All these concepts are intended to increase the displacement so that the increased amount of fuel payload can be accommodated. These concepts carry the methanol in conventional tanks inside the hull.

The first concept is shown the top right corner in figure 9.12. The top left corner of this figure shows the original design. How the vessel dimensions increased can be seen in table 9.2. This concept lengthened the hull to acquire required displacement to carry enough methanol for a theoretical autonomy of 63 days. Due to the lengthening of the hull, the resistance increases and with the same delivered power, the transit speed drops to 8,6 knots. The reach of the FOCSV becomes 13070 nautical miles in this case. When the transit speed should remain 9 knots, delivered power has to increase 58 kW. With increased fuel consumption, the autonomy becomes 10900 nautical miles in approximately 50 days.

A render of the second concept together with the new dimensions can be found in the bottom left corner in figure 9.12 and table 9.2. The resistance increase in this concept is slightly less than for the lengthened concept, the achievable speed with the same delivered power lowers to 8,7 knots. At this speed, the autonomy is 13100 nautical miles, hardly lower than the conventional distance that can be bridged by the FOCSV. To sail at nine knots, the delivered power has to be increased by 53 kW to 513 kW in total. While the speed and power increase is marginal, the distance that can be travelled drops to 11000 nautical miles, a significant decrease but still more than enough to cover larger distances.

The third concept covers an increase in displacement by having a higher hull and larger draft. As shown in figure 9.12. Table 9.2 shows how the dimensions change. This concept has the lowest increase in resistance at nine knots. However, at higher speeds, the resistance rapidly increases to undesirable values. Because of the minimal difference in resistance, the vessel would still sail at 8,9 knots when increasing the draft and displacement. Also the autonomy is hardly compromised in this case, to 13400 nautical miles instead of 13600 nautical miles. To sail nine knots, the power has to increase by 24 kW. Due to the increased fuel consumption the autonomy drops by ten days, resulting in a range of approximately 11400 nautical miles.

9.4.5 Synthetic diesel

Synthetic diesel doesn't require a different fuel tank lay-out. Only the volumetric energy density is slightly less than MDO, therefore the autonomy will be somewhat compromised or a small extra diesel tank could be included in the design. No different concept for synthetic diesel is made for that reason. The resistance, effective towing power and autonomy are all assumed to be the same as for MDO. The autonomy and transit costs are assessed in the following subsection.

9.4.6 Transit range and speed

As the previous assessments on alternative fuels pointed out, there are differences in range (nm) depending on the dimensions and speed of the vessel. On the one hand, it is possible to transit at low speeds, meaning longer transit times and a lower fuel consumption per hour. On the other hand, transits can be covered at high speeds during shorter time spans, with a high fuel consumption. This means that somewhere along the axis of vessel speed, an optimum range or

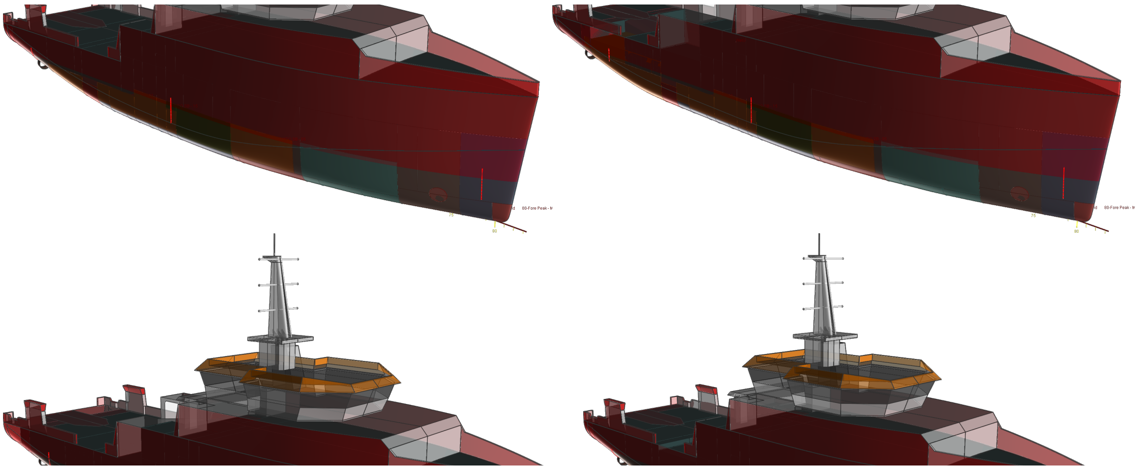


Figure 9.12: Methanol concepts FOCSV - top-left: original, top-right: lengthened, bottom-left: larger L/B constant, bottom-right: larger draft

autonomy in nautical miles is located. A certain speed at which the vessel is able to cover the longest distance in transit.

Using the Holtrop and Mennen method, the resistance and effective towing power curve of the different hull designs of the FOCSV are obtained. With the steps as described in subsection 9.4.1, this effective towing power is calculated to a delivered break power of the generator sets and eventually, a fuel consumption. These are estimates as the used efficiencies are assumed constant for all sailing speeds. Using these estimates the fuel consumption and autonomy is obtained at different speeds. This data can be plotted in order to analyze at which speed the longest possible range is obtained as shown in figure 9.13.

What already could be derived from the values in the previous subsection is pointed out by the range graph in figure 9.13, sailing slower than the current transit speed of nine knots could result in a larger transit autonomy or a transit autonomy comparable to that of MDO. More important, the autonomy of certain alternatives is limited, even when increasing ship dimensions. For example, the enlarged hydrogen concepts reach a lower autonomy than the concept with the same dimensions and using methanol. In terms of the desired speed, the autonomy is one consideration. However in some cases, vessel designs can be altered to enlarge the autonomy without having to lower the speed. Another more important consideration on the desired speed is the location of the economic speed, which will be discussed in section 9.4.8.

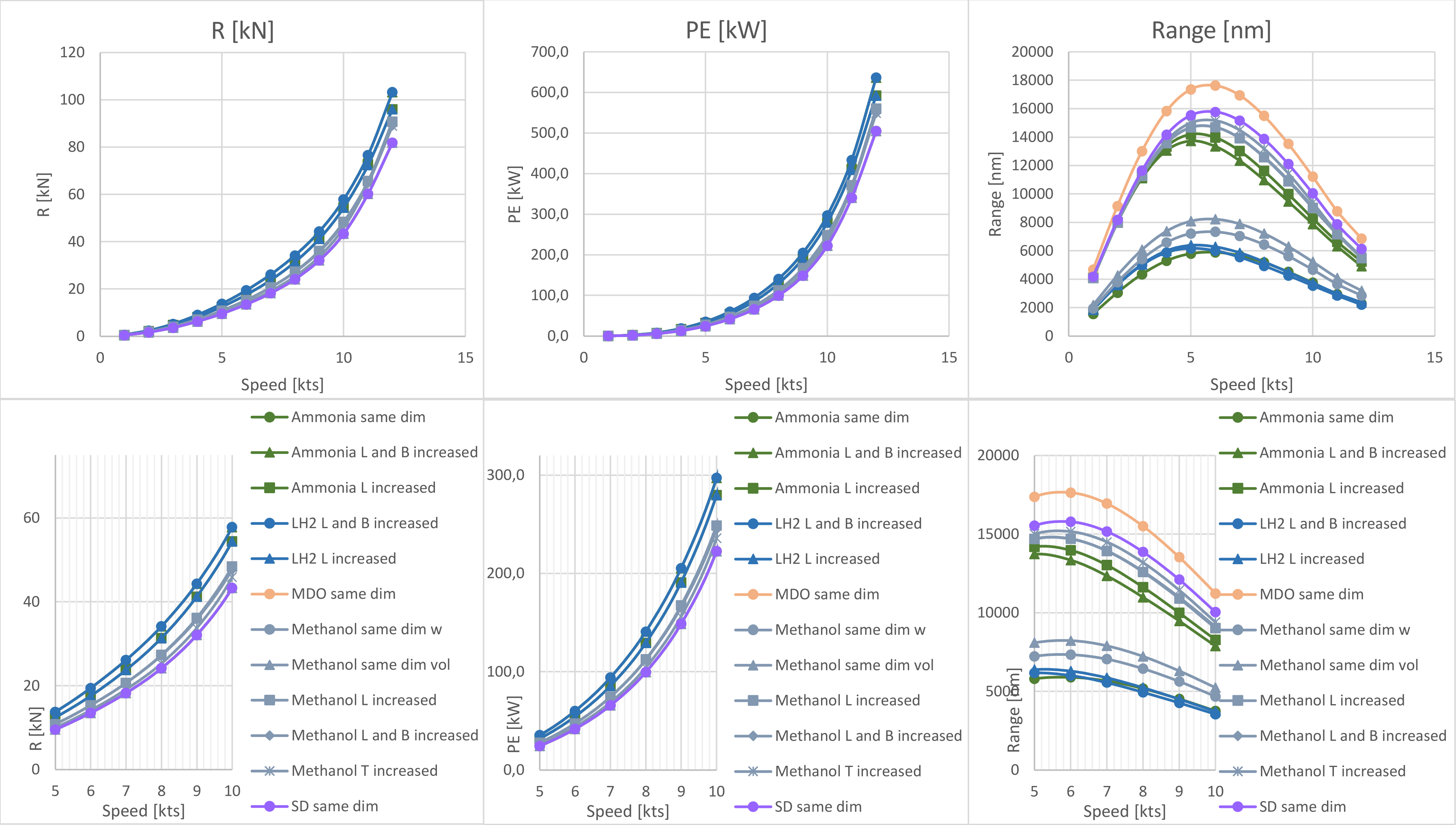


Figure 9.13: FOCSV resistance (R), effective towing power (PE) and range at different speeds (top: whole range, bottom: detail of 5 to 10 kts)

Fuel	Concept	Installation cost	Additional installation cost	[%]	Hull cost	Additional hull cost	[%]	Total additional investment cost	[%]
Ammonia	L & B increased, L/B constant	$ 1.535.510,00	$ 379.920,00	33%	$ 1.688.700,00	$ 452.400,00	37%	$ 832.320,00	5,5%
Ammonia	L increased	$ 1.535.510,00	$ 379.920,00	33%	$ 1.580.338,50	$ 344.038,50	28%	$ 723.958,50	4,8%
Ammonia	Same dimensions	$ 1.535.510,00	$ 379.920,00	33%	$ 1.236.300,00	$ -	0%	$ 379.920,00	2,5%
LH2	L & B increased, L/B constant	$ 1.931.260,00	$ 775.670,00	67%	$ 1.688.700,00	$ 452.400,00	37%	$ 1.228.070,00	8,2%
LH2	L increased	$ 1.931.260,00	$ 775.670,00	67%	$ 1.580.338,50	$ 344.038,50	28%	$ 1.119.708,50	7,5%
MDO	Same dimensions	$ 1.155.590,00	$ -	0%	$ 1.236.300,00	$ -	0%	$ -	0,0%
Methanol	L & B increased, L/B constant	$ 1.535.510,00	$ 379.920,00	33%	$ 1.357.200,00	$ 120.900,00	10%	$ 500.820,00	3,3%
Methanol	L increased	$ 1.535.510,00	$ 379.920,00	33%	$ 1.380.600,00	$ 144.300,00	12%	$ 524.220,00	3,5%
Methanol	T increased	$ 1.535.510,00	$ 379.920,00	33%	$ 1.236.300,00	$ -	0%	$ 379.920,00	2,5%
Methanol	Same dimensions	$ 1.535.510,00	$ 379.920,00	33%	$ 1.236.300,00	$ -	0%	$ 379.920,00	2,5%
Methanol	Same dimensions	$ 1.535.510,00	$ 379.920,00	33%	$ 1.255.800,00	$ 19.500,00	2%	$ 399.420,00	2,7%
Synthetic diesel	Same dimensions	$ 1.155.590,00	$ -	0%	$ 1.236.300,00	$ -	0%	$ -	0,0%

Table 9.3: Additional investment costs for different concepts, based on different fuel alternatives running a Dual-Fuel ICE

9.4.7 Additional investment costs

The proposed designs in this chapter bring additional investment costs. Both the larger hull and the propulsion installation make that the investment costs increase. Therefore this subsection will investigate the additional investment costs of the fuel alternatives.

A rough estimate of the added investment costs due to the increase in hull size is made. Using Delftship, the additional hull surface for the different designs is known. Assuming an average plate thickness of 10mm, based on drawings of the current design, the total weight of added steel is calculated. Using the assumption that a ton of welded steel costs 5000 $, the added investment costs are calculated. 1400 $ per ton for the material and 3600 $ per ton for the required man hours is assumed to come to 5000 $. The resulting investment costs are shown in table 9.3

The added investment costs for all alternative propulsion installations were assessed using the dashboard in the previous section. For this assessment, all designs have sufficient power using the current installed brake power, no need for more installed power is required therefore. However, for all alternatives, the difference in price for a dual-fuel installation on the FOCSV was assessed, using values from the dashboard. The added costs of this installation and the total of added investment costs are shown in table 9.3.

As already shortly described in the previous subsection, these added investment costs can be included in the transit costs as depreciation per day of transit. Assuming a 25 year lifespan and 365 days in a year. Because alternative fuel prices are so high however, this resulted in added costs of under 2.5% on the total transit price in almost all cases. In most of the cases this amount was even under 1% and is therefore not considered crucial in the choice for an alternative fuel. An estimation of the added investment costs as a percentage of the total base price of the FOCSV is included in table9.3. The added investment costs for a hydrogen concept are highest at 15% based on a dual-fuel ICE concept. Also, ammonia can incur relatively high extra investment costs due to the increased vessel dimensions. The other concepts are slightly more or equally expensive as the conventional FOCSV.

9.4.8 Economic speed

As pointed out in section 9.4.6, one consideration to adjust the speed could be the achievable autonomy of an alternative. However, a more important aspect to adjust transit speed is the economic speed. The fuel consumption and fuel costs of the different concepts are calculated. The added investment costs of the different concepts are also calculated. Using the distinction be-

Fuel	**Concept**	**CAPEX total**	**OPEX* total**	**Operational days lifetime**	**Daily costs**	**Additional daily costs**	**[%]**
Ammonia	L & B increased, L/B constant	$ 15.832.320,00	$ 6.300.000,00	9125	$ 2.425,46	$ 91,21	3,9%
Ammonia	L increased	$ 15.723.958,50	$ 6.300.000,00	9125	$ 2.413,58	$ 79,34	3,4%
Ammonia	Same dimensions	$ 15.379.920,00	$ 6.300.000,00	9125	$ 2.375,88	$ 41,64	1,8%
LH2	L & B increased, L/B constant	$ 16.228.070,00	$ 6.300.000,00	9125	$ 2.468,83	$ 134,58	5,8%
LH2	L increased	$ 16.119.708,50	$ 6.300.000,00	9125	$ 2.456,95	$ 122,71	5,3%
MDO	Same dimensions	$ 15.000.000,00	$ 6.300.000,00	9125	$ 2.334,25	$ -	0,0%
Methanol	L & B increased, L/B constant	$ 15.500.820,00	$ 6.300.000,00	9125	$ 2.389,13	$ 54,88	2,4%
Methanol	L increased	$ 15.524.220,00	$ 6.300.000,00	9125	$ 2.391,70	$ 57,45	2,5%
Methanol	T increased	$ 15.379.920,00	$ 6.300.000,00	9125	$ 2.375,88	$ 41,64	1,8%
Methanol	Same dimensions	$ 15.379.920,00	$ 6.300.000,00	9125	$ 2.375,88	$ 41,64	1,8%
Methanol	Same dimensions	$ 15.399.420,00	$ 6.300.000,00	9125	$ 2.378,02	$ 43,77	1,9%
Synthetic diesel	Same dimensions	$ 15.000.000,00	$ 6.300.000,00	9125	$ 2.334,25	$ -	0,0%

Table 9.4: Daily costs FOCSV for different concepts
*OPEX is assumed constant based on qualitative assessment in chapter 7

tween fuel costs and fixed or in this case investment and operational costs, the optimal economic speed for the different alternatives will be calculated in this section.

As the fuel consumption at the different speeds is known, the fuel price for a set transit distance or per nautical mile can be calculated. A specified distance can be set, for example 6220 nautical miles, the distance between IJmuiden and Houston, Texas. Or costs per nautical mile can be assessed. Again, sailing slowly results in a low fuel consumption per day but also a transit of more days. By plotting the calculated fuel price, an optimum in sailing speed can be identified in figure 9.14. The plot points out that the difference in fuel price at different transit speeds is less crucial for MDO than for the more expensive alternative fuels. Therefore it is relatively more expensive to sail at higher transit speeds using an alternative fuel than while using MDO.

The fixed costs are built up from the investment costs for the ship and the fixed operational costs. The added investment costs of the different alternatives are discussed in the previous paragraph. The fixed operational cost are based on input from Fugro stakeholders. An estimation including costs for crew, insurance, provisions and special surveys and dockings during the ship's life-time is provided by Fugro. Based on this value and the qualitative review of OPEX in chapter 7, this value is assumed to be constant for all different fuel alternatives used in a dual-fuel ICE. An overview of these fixed daily costs is shown in table 9.4.

The table shows that the fixed costs do not differ much between fuel alternatives. This can also be seen in the left part of figure 9.14. Especially when considering that the fuel price of the different alternatives is very high compared to MDO. The fuel price for different speeds is shown in the middle graph of figure 9.14. To the right, the total costs per nautical mile are shown.

All costs together can be assessed in figure 9.15. These are twelve concepts assessed on fixed, fuel and total costs. Therefore this graph is difficult to grasp, but provides an idea of the build-up. A graph comparing each concept to MDO can be found in appendix **??**.

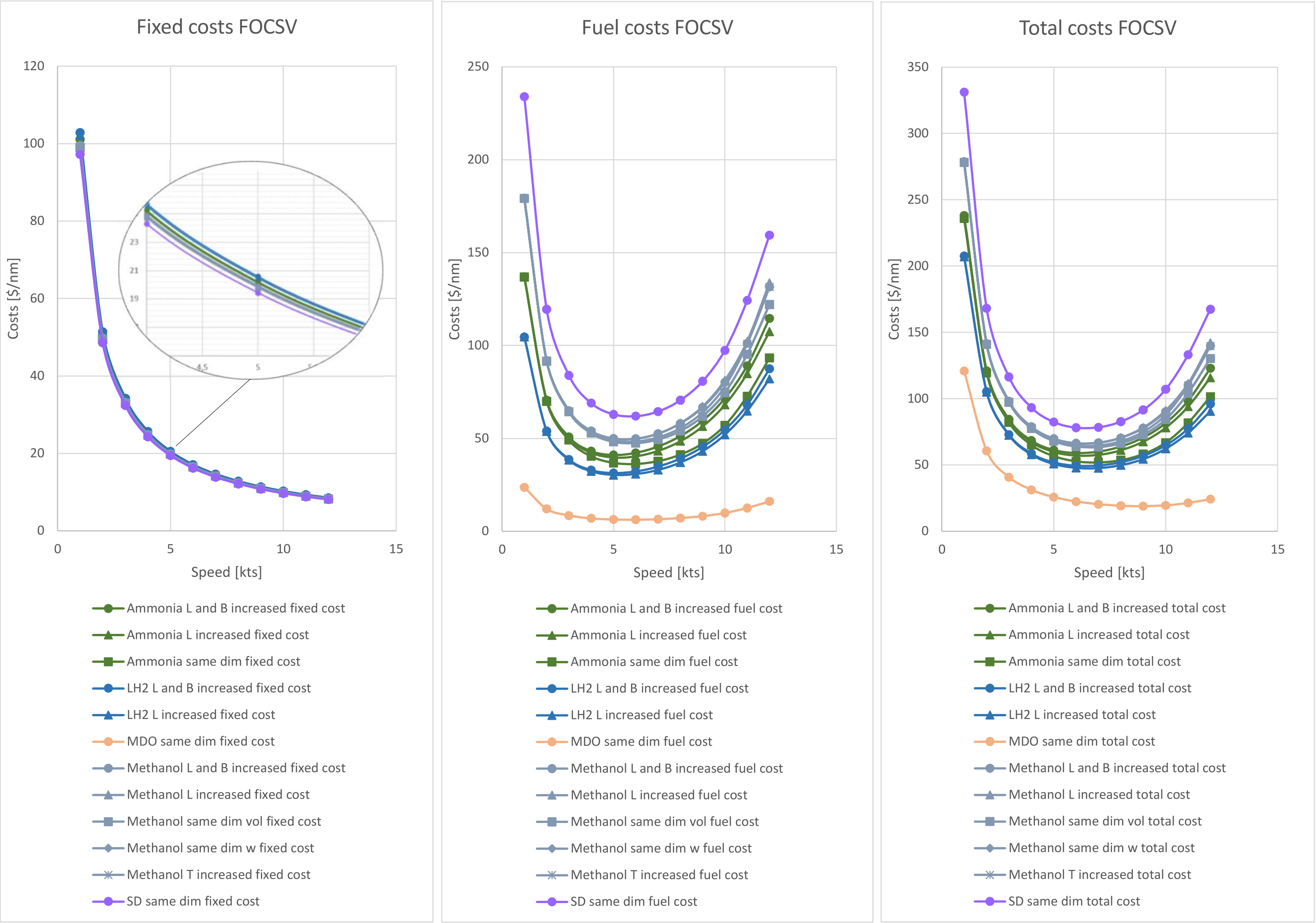


Figure 9.14: Left: Fixed costs - Middle: Fuel costs - Right: Total costs

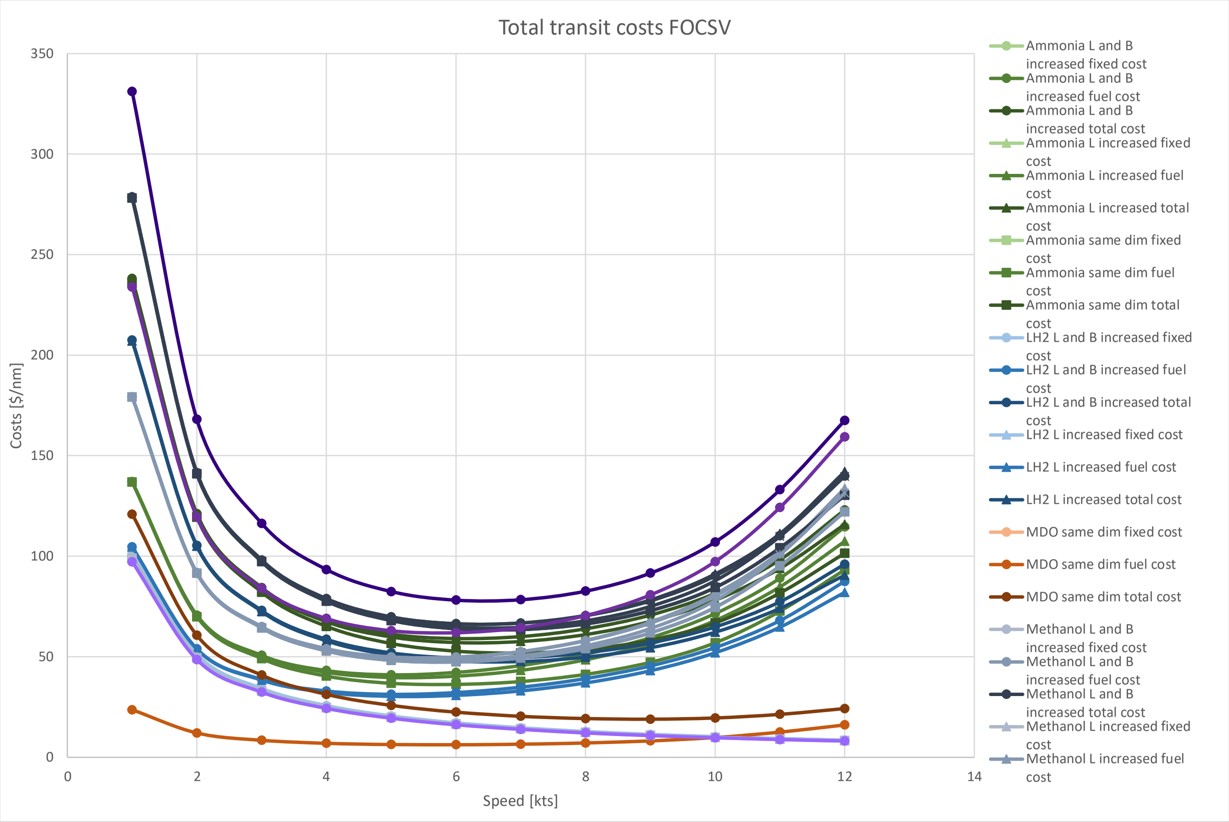


Figure 9.15: Cost build-up fuel alternative concepts

From both the plots in this section and section 9.4.6, assessing the ideal transit speeds for range and an economic viewpoint, it can be concluded that a transit speed lower than nine knots would be more optimal. MDO is less susceptible to the investigated factors, sailing at speeds of nine or more knots still provides sufficient range and a relatively low increase in fuel price. However, for all investigated alternative fuels this is different. Range is already compromised using alternative fuels and can quickly be insufficient when sailing at speeds more than nine knots. Moreover, the difference in transit price increases rapidly when sailing at higher speeds, especially when using the relatively expensive alternative fuels. The increase in investment costs is present, but has a low impact on the economic speed, because of the high price difference between MDO and the assessed alternatives. When including the depreciation of the additional investment for the designs for example, this results in a marginal addition to the transit price. It is out of the scope of this research to investigate all other factors that are impacting the optimal transit speed and to investigate the optimal transit speed itself. Based on the three investigated factors however, it is likely that transit speeds have to be reduced when using alternative fuels because of fuel cost and to a lesser extent, required autonomy. To suppress this large increase in fuel costs, it can be considered to mix the expensive renewably produced alternatives with their cheaper fossil- or bio-based versions until the fuels become cheaper due to economy of scale for example.

9.5 Unmanned Survey Vessels

Earlier, this thesis pointed out that Fugro is looking to extensify the use of remotely operated Unmanned Survey Vessels (USV). As these vessels are relatively new, the operational profile and fuel consumption are difficult to assess. Moreover, Fugro is still experimenting with different designs, different in size and deployability. For that reason, precise output as mentioned above is not yet available to synthesize. However there are some considerations and possible advantages that can be mentioned.

First of all, these USVs miss an accommodation, meaning that relatively more deck space is available compared to the conventional ships. This makes the application of cylindrical and pressurized tanks more easy. This is an advantage for both hydrogen and ammonia.

When operated from another vessel, the autonomy of an USV can be kept modest, meaning that hydrogen or even batteries could become an alternative to consider. However, if the available information is comprehended correctly, at least some of these vessels also have to be able to operate completely autonomously and therefore also need a significant autonomy.

A considerable advantage would be to operate the USV using the same fuel as it's potential mother ship. This would mean that the vessel could be refuelled without needing additional fuel installations on board of the mother vessel.

Other than above arguments, the choice for an alternative fuel for the USVs is one of many different considerations than for the regular vessels as assessed in this thesis. As prototypes are still being produced, this type of vessel still has a certain extent of design versatility. This could come in handy when considering configurations of future fuel installations. None of the alternatives assessed in this chapter are considered unfeasible for use on an USV at this stage.

To choose the best fuel alternative for the FOCSV however, the dashboard can be used to identify the suitability of different fuel alternatives. Because no fuels are considered unfeasible, the most decisive factor should be that the USV uses the same fuel as it's mother ship or has a large autonomy of itself. For both factors, methanol would be the most suitable outcome. Otherwise, the other fuel alternatives could all be suitable to use on USVs and even batteries could be a good solution when the USVs are operating from a mother ship requiring a smaller autonomy for their task.

9.6 Conclusion

Ammonia

A future design using ammonia as fuel is expected to, although autonomy is compromised, be able to comply to Fugro autonomy standards. However attention has to be spent to the toxicity of ammonia. Moreover tanks would need to have a different geometry due to storage conditions. To be able to store sufficient fuel volumes, vessel designs have to be altered significantly.

Liquid hydrogen

An alternative for which vessel dimensions would have to be increased for sure, is hydrogen. However, even with increased dimensions, it is questionable if the autonomy becomes sufficient. The main drawback of liquid hydrogen is the insufficient autonomy of a hydrogen application. Vessels with comparable dimensions as the current fleet, will not be capable of making a transit required for Fugro operations without bunkering underway.

Methanol

Methanol would also give in on autonomy, however it's smaller density makes that a larger volume can be carried on board of similar sized vessels, resulting in a less compromised autonomy. Moreover, methanol storage is easy and no strict regulations on storage locations are in place. Making that even more methanol can be stored in a similar sized vessel. Not due to weight restrictions as mentioned earlier but due to the fact that more locations inside the hull become suitable for fuel storage. When increasing vessel dimensions, autonomies comparable to MDO can be achieved. To actually cover these distances and to limit fuel costs, transit speeds have to be decreased.

ICE technology

ICE technology is expected to be slightly more expensive compared to a MDO ICE, for all investigated alternatives. An ICE running on hydrogen will be most expensive. Also spark-ignition engines are more expensive than dual-fuel engines. CAPEX of FC technology is still difficult to estimate due to the large range in price levels. (HT)-PEMFCs could become cheaper, but are expected to remain more expensive until significant numbers are being produced. SOFC technology will remain more expensive the coming years, how much more expensive is still very uncertain.

FC technology

While all considered alternatives do fit in available space in current designs, FC technology requires additional battery packs to cope with power peaks and transients. Fugro is already investigating hybrid conversions, therefore it is assumed that hybrid layouts will come into place in future designs and this doesn't bring additional drawbacks to any of the considered alternatives.

Propulsion technology

Due to the diesel-electric setup of Fugro vessels, no significant changes to propulsion system design have to be made, vessels in operation nowadays are comparable on that aspect to those in future. All alternatives, but the SOFC, are suitable to place in a similar sized and weighing machinery spaces. A SOFC will be lighter, but more voluminous.

Fuel costs

Fuel prices are and will be significantly higher than MDO prices, even in the coming years. Hydrogen is the cheapast fuel available, as it is a commodity needed for the production of the other fuels considered. Ammonia is the second cheapest alternative as it doesn't require captured carbon but nitrogen for production. For that reason the price range is also less uncertain than the other fuels considered, this could possibly be an advantage for this fuel type. Methanol and synthetic diesel prices are still very uncertain and will remain more expensive in the coming years. The exact fuel prices per day, under different circumstances and for each vessel specific, can be looked up in the presented dashboard. Moreover, the concept study in the last part of this chapter pointed out that transit speeds have to be decreased because of the high increase in fuel costs at higher speeds.

Investment costs

The relative increase in investment costs for a dual-fuel ICE concept are investigated in the last part of this chapter. Also the increase in CAPEX due to the larger hull are elaborated on. While these investment costs increase significantly in some cases, these costs are negligible when compared to the increase in fuel costs.

Economic speed

Plotting economic speed graphs of the assessed alternatives pointed out that the economic speed using alternative fuels is lower than the current economic speed. Added CAPEX and OPEX play (almost) no role in this speed shift. The high increase in fuel costs makes that the economic speed has to be at least reconsidered and probably lowered when sailing on alternative fuels.

While these fuels will remain too expensive to be economically viable for a while, vessels should switch to renewable fuels. The coming years must point out how these fuel need to become economically viable. One alternative could be to blend the renewably produced fuel types with the same fossil produced fuel types to decrease cost during a transition period in which the production of alternative fuels is scaled up.

10

Conclusion

This thesis was conducted to find the most suitable fuel alternative for Fugro vessels that will be operational from 2030 onwards. This can be phrased in the following research question:

What is the best fuel alternative for future Fugro vessels?

By carrying out a more qualitative analysis including Fugro stakeholders in chapter 8 together with quantitative case analysis in chapter 9, it can be concluded that methanol is the most suitable carbon neutral fuel alternative for future Fugro vessels.

Although methanol has a higher fuel price than ammonia and hydrogen, the technology is available, fuel storage is simple and straight-forward and besides being a low-flashpoint fuel, this fuel is relatively safe to human kind and environment. Moreover, this fuel scores best on autonomy. When considering that methanol fuel tanks are allowed to be situated in more places than MDO tanks, the autonomy is even less compromised when the same weight of fuel is taken in.

Depending on future developments in price and availability, ammonia can also be a suitable alternative fuel. While expected to be cheaper, it's toxicity and potential damage to the environment are believed to be major drawbacks. Especially when considering how important these aspects were weighted by stakeholders in the Analytic Hierarchy Process. Therefore, this alternative is less recommended, especially when synthetic hydrocarbon fuels like methanol and diesel are developed successfully.

While hydrogen scored best under almost all scenarios from the AHP, the case application of alternative fuels in Fugro vessels pointed out that liquid hydrogen is not suitable to attain standards on autonomy. Fuel tanks should enclose a large volume, meaning that vessel designs should become larger and even then, the autonomy would be limited.

Synthetic diesel would be very desirable as no infrastructure would have to change. Even more, onboard installations could remain the same as conventional MDO installations. This fuel also scored well during the AHP synthesis. However, it is expected that this fuel will remain very expensive and more expensive than methanol. For that reason it is considered less viable that this will become a suited solution for Fugro vessels.

With regards to the powertrain to be chosen, Fuel Cell technology is still relatively undeveloped. How this technology develops in the coming years is crucial in choosing which converter to install. When the technology becomes widely available, product lifetime is increased and costs go down. Both (HT)-PEMFCs and SOFCs are suitable to install on board of Fugro vessels. Assuming a diesel-electric, hybrid propulsion system design. For the coming years, ICE technology seems the most suitable converter strategy, with engine manufacturers offering various types of ICE technologies suitable of combusting alternative fuels.

Which alternative fuels will be considered in this research?

The selection of assessed fuels is narrowed down during the literature research. All fuel alternatives that are at least carbon-neutral, except for bio-fuels. This is because it was concluded during the first part of the literature research that feedstock issues are foreseen when these fuels are scaled up to a significant level. Also nuclear and batteries are put out of scope during literature research. Nuclear because of the minimal chance of being an available alternative, batteries because of their very limited energy density. Hydrogen ammonia, and all synthetic or e-fuels are kept in scope.

The Analytic Hierarchy Process outcomes narrow down the fuel selection again to four alternatives that are considered in detail during the case study. These are hydrogen, ammonia, synthetic methanol and synthetic diesel. Synthetic methane (e-LNG), DiMethylEther are excluded because of their low scores in the AHP method. While ammonia isn't scoring high either, the significant advantages of this alternative make that it is considered nonetheless.

What are the operational profile and corresponding vessel parameters of future Fugro vessels?

Fugro operates a wide range of different types of vessels. A selection is made of four vessel types that are the latest purpose-built vessels the company is operating for their different types of operations. Load balances, propulsion lay-outs, vessel parameters and operational data are acquired, analyzed and discussed in chapter 3. Moreover, an assessment of future vessel developments is done. Data trends in comparable vessel types are analyzed and literature on future legislation and CO2-reduction measures is consulted. From this part of the research, it is concluded that there are no significant indications that Fugro vessels or their operations will change. Also Fugro stakeholders were consulted on vessel developments, above-mentioned vessel types are indicated to remain relevant, the ambition to also start deploying Unmanned Survey Vessels on a large-scale is a key-takeaway from these interviews.

What are the criteria influencing the decision on alternative fuels?

Based on literature, a long list of possible criteria is set up and discussed. Based on this case and the long list, a list of criteria is acquired. These are subdivided in four main criteria groups. Technological, economical, environmental and other. Some of these criteria are quantifiable, others have to be scored qualitatively, for example because of their value uncertainty in about ten years.

What are future scenarios on exogenous factors, and how will these influence the choice on alternative fuels? (e.g. future policies)

Consulted literature on regulations reveal that the ambition of Fugro to start deploying carbon-neutral vessels from 2030 onwards is ambitious enough to comply to regulations. Future policies that incur exogenous factors are difficult to quantify. The most important identified parameters are cost and availability of the assessed fuels in future. Therefore scenarios are included, these scenarios include decreasing fuel or installation costs and increasing availability for example.

What is the best method to score each of the criteria of different alternative fuels?

The AHP prescribes scoring to be done along a fundamental scale that rates relative intensity of importance. Together with the stakeholder weighting of the AHP this provides a relative score for each alternative. Because this way of scoring is qualitative, this provides the opportunity to include parameters in this problem that are not (yet) possible to quantify. The chosen value from the fundamental scale is based on information found in literature.

How are the fuel alternatives scoring on these criteria?

This thesis discussed the alternative fuels identified during the literature research extensively in chapter 7. All considered fuel alternatives are investigated and scored qualitatively on the criteria as posed in section 6.5. This provides the opportunity to score parameters that are difficult to quantify in the choice for an alternative fuel.

The extensive study of the available fuel alternatives also provided a large amount of values on the different alternatives. For example, cost and converter size can be quantified using data from literature research. It has to be noted that these values sometimes vary over a wide range and are still uncertain as some alternative fuel technologies are not yet used in practice. However, using this quantified data together with the collected Fugro fleet parameters and operational profile resulted in a dashboard in which some assessed parameters of the alternatives can be compared to the current MDO parameters. On some criteria this gives a *quantified score*, for example on expected capital expenses or required volume.

What is the best method to decide on the choice for an alternative fuel?

The Analytic Hierarchy Process is chosen as preferred method to score the different alternatives in chapter 6. As many conditions of this assessment are uncertain or even unknown, a method based on solely economic criteria is deemed unfit. The AHP provides a relative comparison to predict important criteria and potential outcomes under incomplete information or uncertain developments. Also a structured way to include stakeholders in this process is possible using this method.

An extensive assessment of different fuel alternatives is carried out, including motivation on all the different criteria in chapter 7. Together with the stakeholder weighting included in the AHP, this results in a score for the different fuel alternatives. Under almost all scenarios included, hydrogen, methanol and synthetic diesel are scoring best. Ammonia often ends as *best of the rest*.

11

Discussion

11.1 Discussion

How this study answered the research questions is discussed in the previous chapter. This part will outline the discussion and remarks that remain after the conclusions.

Remarks on, for example the AHP method. While this method shows clear results, it also showed some interesting outcomes regarding criteria weighting. For example that environmental subcriteria were weighted important by stakeholders from Fugro, while research/science stakeholders were less decisive in the critical weighting of environmental criteria. For that reason a scenario excluding the environmental criteria was also assessed, resulting in hydrogen scoring worse. Also the case study results showed that hydrogen has major drawbacks and isn't suitable for Fugro vessels in their current deployment capabilities. Therefore, the results of the AHP can be questionable on this subject. Nevertheless, the AHP did succeed in providing results and narrowing down the choice for alternative fuels by clearly pointing out the most promising alternatives. Also, the criteria weighting by stakeholders is considered important and valuable.

The results of the AHP are to be investigated further before giving a final advise on the best alternative fuel. AHP pointed out LH2 as best alternative, which was disproved by the more quantifiable approach in the case study. This last chapter investigates the feasibility of the best alternatives from the AHP method. Also, it provides more tangible results for stakeholders. Providing considerations on potential design changes and operating speed, which didn't come out of the Analytc Hierarchy Process.

Also, the AHP method coped with a lot of intangible and difficult criteria like availability and safety. This resulted in a list of fuels that fulfill certain requirements and comply to stakeholder preferences. A remarkable outcome for example is that stakeholders are scoring the consequences of a spill as very important, making that ammonia is considered less suited for this case.

For the AHP method used in this thesis a lot of stakeholders from different stakeholder groups were consulted. Therefore this thesis also provides an insight into stakeholder preferences for the choice of a zero-carbon alternative fuel. This insight could be insightful to others investigating alternative fuels for future vessels.

The both methods described in chapter 8 and 9 supplement each other, providing a solid foundation for a choice on an alternative fuel, by pointing out a best alternative, both in a qualitative as well as a quantitative approach. Moreover, the questionnaire provided an option to weigh different criteria and provided a good opportunity to involve stakeholders and get insight into their preferences and aspects they consider important in the choice for an alternative fuel.

Another result of this study, which doesn't necesarrily adds to the conclusion but is helpful for future research is a tool that gives different parameters for applied alternatives at a glance. This was presented in chapter 9. When some parameters on alternative fuels become less uncertain, this tool can aid in assessing different alternatives in more detail. For example, the choice for a certain type of converter.

An important finding of this study is that for almost all fuel alternative concepts, vessel dimensions would have to be increased in order to attain autonomies comparable to the current vessels using MDO. Methanol is the only fuel alternative providing a significant autonomy compared to diesel while keeping vessel dimensions the same. This raises the question whether the operational profile of Fugro vessels at this time is the way forward in the long-term. Fugro's fleet nowadays is designed to be able to operate cross-Atlantic for example. It could be that the introduction of alternative fuels in future will force Fugro to reassess this choice, meaning that only some specialized vessels are capable of make such long transits, while another type of vessel is bespoke for more coastal operations.

Whether operating coastal or over longer distances, the compromised autonomy and high fuel costs make that it is likely that transit speeds must be reduced when using alternative fuels on Fugro vessels. The last chapter pointed out that the economic speed reduces due to high fuel costs, fixed costs will also change, but have relatively low impact compared to the increase in fuel costs.

The added investment costs due to an increasing ship size or more expensive alternative fuel installations are marginal when compared to the fuel costs of the assessed alternatives. However, CAPEX could increase up to 10% when considering concepts running a dual-fuel ICE on alternative fuels.

Alternative fuels that are carbon neutral are still very expensive. It can be argued that the fuels are too expensive to operate profitably. Moreover, who is paying the surplus costs that these fuels bring? The shipping company, in this case Fugro, or a client for which the company is operating? Another possibility is the implementation of incentives. In other words, alternative fuel prices are more expensive than conventional fuels and this price has to be lowered, the question how and by which instruments is difficult and very relevant. One way to cope with high fuel prices could be to mix synthetic fuels with fossil fuels. Resulting in lower prices during a transition period.

11.2 Recommendations

What remains after the conclusion and discussion are recommendations for future work, based on the results in this thesis.

Because it is likely that transit speeds have to be reduced because of the high price of alternative fuels, Fugro could consider to revisit their economic transit speed. This thesis pointed out that future alternative fuels will be very costly, therefore the relationship to other factors influencing the economic speed becomes different. The factors influencing the economic speed include operational expenses due to for example fouling or crew costs or an extra day in transit and one day less in operations for example.

Lastly, the next step for Fugro is to develop a concept model using methanol as fuel. Due to the choice for this fuel, the ship design doesn't have too change much but specific and detailed choices on the actual application have to be made. What converter is used, where are the fuel tanks placed, what are considerations for piping and other detailed choices that have to be made when designing a vessel. This thesis worked out a brief first cycle of the design spiral based on the FOCSV, an additional design study should expand on this and make several cycles to come up with a concept design.

When another or a similar AHP round would be conducted, the criteria could be reassessed. Filling in the stakeholder poll can be regarded as difficult due to the amount of criteria in this study. Moreover, autonomy eventually an important factor as shown in chapter 9, it could be that gravimetric and volumetric density do not encompass autonomy enough.

Additional research into policies bringing down future fuel costs needs be conducted. What policies or regulation could encourage the uptake of cleaner alternative fuels without creating supply or compliance problems for the shipping industry.

Case studies into alternative fuels for different sorts of companies are also interesting to see how different conditions influence the choice for an alternative fuel. Moreover, more determination of companies on the preferred alternative fuel can bring clarity to fuel suppliers. These fuel suppliers can react to this demand by setting up production and infrastructure, benificial for both the suppliers and consumers.

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