# Most Suitable Future-Proof Energy Supply for a New-Build Semi-Submersible Crane Vessel.

## Energy Transition-Compliant Energy Supply for Heerema's Sleipnir: A Multi-Criteria Analysis

Master of Science Thesis

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TUDelft

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by

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Cover: HMC's SSCV Sleipnir

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# Preface

My journey at the TU Delft began for me in 2014, with a bachelor of Marine Technology. I pursued and completed this bachelors with great enthusiasm. During my studies, I became increasingly interested in the impacts of global warming and the potential of sustainable energy solutions. This interest and enthusiasm led me to choose a master's program in Sustainable Energy Technology at Delft University of Technology.

The master's program deepened my understanding of sustainable energy and its applications. I mainly focused on the technologies regarding energy storage, and, solar- and wind energy technologies. Despite studying these subjects with great pleasure, I have always maintained an interest in the maritime sector. Hence, I didn't hesitate when Heerema Marine Contractors offered me a graduation internship assignment. This assignment brought together both subjects of interest and enthusiasm.

Throughout the course of my graduation research, I gained substantial knowledge about conversion systems, electro-fuels, nuclear power, and decision-making methods, as these were all new areas for me. Reflecting on my time at Heerema, I recognize it as an incredibly educational and engaging period. Not only did I acquire knowledge, but I also gained valuable experience by gaining insights into the workings of the offshore sector. I hope this report provides similar interesting and valuable insights to any of its readers.

During the research, I have been extensively supported by a group of supervisors. Regarding the guidance from TU Delft, I would like to express my gratitude to Dr. Jan Annema for his frequent guidance, feedback, and pleasant communication. I also want to thank Dr. Ir. Henk Polinder for his supervision and valuable input during feedback sessions. Finally, I would also like to extend my thanks to Jesper Zwaginga for his almost weekly guidance sessions and deep involvement in this project. Despite his own busy schedule, he was always ready to assist me.

From Heerema, I would like to thank Meike Kolthof and Maarten Veldhuizen for their guidance, feedback, and the very pleasant way we collaborated at Heerema. Furthermore, I am grateful to my fellow graduate Jaco Carbutto for his support throughout, especially at times of "falling and getting back up". Lastly, I want to express my gratitude to the rest of the sustainability department at Heerema for their support and the positive atmosphere in the workplace.

*B.M. Hoeksma*
*Delft, September 2023*

# Summary

Currently, our society faces a pressing challenge: global warming. The solution lies in the energy transition, which replaces fossil fuels with clean sources. This requires a global effort across all sectors, including shipping. While a significant portion of shipping relies on polluting fuels, the European Union's Green Deal aims for climate neutrality by 2050, which applies to shipping as well. Emission reduction technology and low-to-zero emission energy supplies are emerging, yet choosing the right energy supply for new vessels remains complex, especially in meeting EU targets.

This study focuses on supporting the decision-making process for the energy supply of a new Semi-Submersible Crane Vessel (SSCV). The method facilitates a comprehensive comparison of energy supply options using multiple criteria. It also integrates decision-makers' preferences with the characteristics of alternative energy supplies, providing insights into the most suitable choice. This research features a case study centered on Heerema Marine Contractors' SSCV Sleipnir.

To create this method, a literature review on Multi-Criteria Decision Making (MCDM) methods was conducted. The Analytic Hierarchy Process (AHP) model was chosen as the foundational framework for the decision-making tool. During the research key limitations and requirements for designing an energy supply for a SSCV were identified. Furthermore, the research contains an examination of various fossil and sustainable fuels, including Marine Gas Oil (MGO), (E-)Liquefied Natural Gas ((E-)LNG), E-Hydrogen, E-Methanol, E-Ammonia, Uranium, and Thorium. Additionally, the study considers diverse energy conversion systems including Internal Combustion Engines (ICE), Proton Exchange Membrane Fuel Cells (PEMFC), Solid Oxide Fuel Cells (SOFC), Direct Methanol Fuel Cells (DMFC), Molten Salt Reactors (MSR), and Very High-Temperature Reactors (VHTR). A set of significant criteria are identified and the accompanying characteristics of the energy supplies regarding these criteria are gathered. The literature research is followed by a financial assessment. This assessment shows that the financial impact of fossil- and e-fuel energy supplies is highly dominated by Operational Expenditure (OPEX), while the nuclear energy supplies are highly dominated by its Capital Expenditures (CAPEX).

The preferences of Heerema's decision-makers are collected via a survey, revealing that the Technological Readiness Level (TRL) of the system, health risk, emissions, Levelized Cost Of Energy (LCOE), maintenance requirements, and efficiency of the conversion system are found to be the most important criteria according to the survey results. The preference weights assigned to the criteria are integrated with the energy supply characteristics, providing a score that indicates the suitability of each energy supply considering the SSCV's limits and requirements, aligned with the preferences of the decision-maker. Hence, the optimal energy supply choice can be deduced from this data.

Although the fossil fuel MGO is included to act as a base-case scenario during this case study, the results of the method show that MGO used in an ICE would be the best-suiting energy supply according to the preferences of the decision-makers. Since MGO energy supplies are assumed to be non-compliant with the EU-emission goals they are excluded. When excluding MGO from the results, methanol used in an ICE is identified as the best-suiting alternative. This can be attributed to its relatively high TRL, favorable overall characteristics, and absence of significantly low scores regarding the criteria assigned high priority by the decision-makers, in comparison to other energy supplies.

However, the validity of the presented results is reduced due to several factors. These include the reliance on assumptions about alternative energy supplies, a limited number of interviewees, and the sensitivity to uncertainties about future developments. Nevertheless, this study shows that the use of this method can provide insights into complex decision problems regarding future energy supply choices. Also, the study identifies a range of attractive energy supplies, with methanol used in an ICE ranked as the most suitable option. These high-ranking energy supplies can be an interesting subject for further studies.

# Contents

# List of Abbreviations

| | |
|---|---|
| **AHP** | Analytic Hierarchy Process |
| **CAPEC** | Capital Expenditure |
| **CAPEX** | Capital Expenditures |
| **CCS** | Carbon Capture and Storage |
| **$CH_2$** | Compressed Hydrogen |
| **$CH_4$** | Methane |
| **$CH_3OH$** | Methanol |
| **CO2 equivalent** | Carbon Dioxide Equivalent |
| **$CO_2eq$** | Carbon Dioxide Equivalent |
| **COP 21** | Conference of the Parties 21 |
| **CR** | Consistency Ratio |
| **DAC** | Direct Air Capture |
| **DMFC** | Direct Methanol Fuel Cell |
| **DP3** | Dynamic Positioning 3 |
| **E-fuels** | Electro-fuels |
| **E-LNG** | Electro-Liquefied Natural Gas |
| **ETS** | Emission Trading System |
| **EU** | European Union |
| **GHG** | Greenhouse Gas |
| **GWP** | Global Warming Potential |
| **HFO** | Heavy Fuel Oil |
| **HMC** | Heerema Marine Contractors |
| **HTGR** | High-Temperature Gas-cooled Reactor |
| **IAEA** | International Atomic Energy Agency |
| **ICE** | Internal Combustion Engine |
| **IGF Code** | International Code of Safety for Ships Using Gases or Other Low-flashpoint Fuels |
| **IMO** | International Maritime Organization |
| **LCA** | Life Cycle Assessment |
| **LCOE** | Levelized Cost of Energy |
| **$LH_2$** | Liquid Hydrogen |
| **LFO** | Light Fuel Oil |
| **LNG** | Liquefied Natural Gas |
| **MCDM** | Multi-Criteria Decision Making |
| **MGO** | Marine Gas Oil |
| **MSR** | Molten Salt Reactor |
| **NFPA** | National Fire Protection Association |
| **$NO_x$** | Nitrogen Oxides |
| **$N_2O$** | Nitrous Oxides  Laughing Gas |
| **O&M** | Operations and Maintenance |
| **OPEX** | Operational Expenditure |
| **PEMFC** | Proton Exchange Membrane Fuel Cell |
| **RES** | Renewable Energy Sources |
| **R&D** | Research and Development |
| **SMR** | Steam Methane Reformer |
| **SOLAS** | Safety of Life at Sea |
| **SOFC** | Solid Oxide Fuel Cell |
| **$SO_x$** | Sulfur Oxide |
| **SSCV** | Semi-Submersible Crane Vessel |
| **TRL** | Technology Readiness Level |
| **VHTR** | Very High-Temperature Reactor |
| **WTW** | Well-To-Wake |

# List of Symbols

| | |
|---|---|
| $A_{\text{comparison}}$ | Relative suitability score between energy supplies concerning a criterion |
| $E_{\text{bunkering}}$ | Energy per bunkering period |
| $E_{\text{bunker period}}$ | Required energy stored in fuel per bunker period |
| $E_{\text{effective}}$ | Required effective energy per bunker period |
| $ED_{\text{volumetric}}$ | Volumetric energy density |
| $F_{\text{Fuel consumption}}$ | Fuel consumption |
| $F_t$ | Fuel costs for the year |
| $I_t$ | Investment costs for the year |
| $M_{\text{conversion}}$ | Weight of conversion system |
| $M_{\text{energy supply}}$ | Weight of the energy supply |
| $M_{\text{storage}}$ | Weight of the storage facility |
| $\eta_{\text{conversion}}$ | Conversion Efficiency |
| $\eta_{\text{literature}}$ | Efficiency retrieved from literature |
| $\eta_{\text{specific}}$ | The efficiency of a specific energy converter in a specific work mode |
| $\eta_{\text{SSCV}}$ | SSCV operational profile-specific efficiencies for specific energy supply |
| $\eta_{\text{system}}$ | Average efficiency of a conversion system |
| $n$ | Lifetime of the energy supply |
| $occurrence$ | Occurrence per mode as a percentage of the total operational time |
| $P_{\text{installed}}$ | Installed power |
| $r$ | Discount Rate |
| $S_{\text{criterion}}$ | Suitability score for an energy supply regarding a specific criterion |
| $S_{\text{HMC}}$ | Average suitability scores of HMC decision-makers group |
| $T_{\text{bunkering}}$ | Bunkering period |
| $V_{\text{conversion}}$ | Volume of conversion system |
| $V_{\text{energy supply}}$ | Volume of the energy supply |
| $V_{\text{storage}}$ | Volume of the storage facility |
| $\rho_{E_M}$ | Volumetric energy density of fuel |
| $\rho_{E_V}$ | Volumetric energy density of fuel |
| $\rho_{P_M}$ | Volumetric power density of conversion system |
| $\rho_{P_V}$ | Volumetric power density of conversion system |
| $storage\ volume\ ratio$ | Volume storage ratio, between fuel volume and additional storage facility volume |
| $storage\ weight\ ratio$ | Weight storage ratio, between fuel weight and additional storage facility weight |
| $W_{\text{category}}$ | Preference weight of a category |
| $W_{\text{criterion}}$ | Preference weight of a criterion |

# List of Figures

# List of Tables

# 1 Introduction

This first chapter describes the problem background that has led to the initiation of this research, the research gap, the research question, the methodology of the research, and the research scope.

## 1.1. Problem background

At the moment, global warming is one of the biggest problems our society is facing. The answer to this problem is the energy transition. In this transition, greenhouse gas-emitting fossil fuels are replaced by clean, renewable energy carriers. This transition will have to be carried out globally by all emitting sectors. Including the shipping sector. The majority of shipping is currently powered by greenhouse gas-emitting fossil fuels [27]. This is also the case for the fleet of the offshore company Heerema.

### 1.1.1. Heerema Marine Contractors

Heerema Marine Contractors (HMC) is part of the Heerema Group. The Heerema Group was founded in 1948 by the Dutch engineer Pieter Schelte Heerema. The Heerema Group has developed into one of the world-leading companies in the design, construction, installation, and transportation of offshore facilities. HMC focuses mainly on the installation of offshore wind turbines and the transport, installation and decommissioning of offshore structures. HMC's headquarters is located in Leiden in the Netherlands but the company operates on multiple locations all over the globe. Heerema's fleet consists of four crane vessels, two tug vessels, and a number of support vessels and pontoons.

Since sustainability is an important topic within HMC and the Heerema Group a sustainability department was established. This department focuses on making the HMC operations more sustainable. The department mainly focuses on reducing GHG, increasing circularity, and creating awareness of sustainability within the company.

### 1.1.2. New build SSCV

Heerema is orientating on a new-build semi-submersible crane vessel (SSCV). This crane vessel will be used to decommission/install offshore structures and offshore wind turbines. Since the vast amount of the emissions originates from the energy supply of the vessel, the design choice regarding this future energy supply is of great importance [16]. Different internal and external frameworks have been set up to reduce greenhouse gas emissions. These frameworks are the Paris Agreement, EU Green Deal/ Fit for 55, IMO goals, and Heerema's internal ambition. The details of these frameworks will be described in paragraph 1.1.3. Since Heerema's new build will encounter these policies during its lifetime, it needs to meet the framework requirements. An increasing amount of sustainable propulsion options are being developed and becoming commercially available [68]. This creates possibilities as well as uncertainty regarding the future fuel/propulsion landscape.

### 1.1.3. Emission frameworks

The GHG emission reduction is driven by different frameworks set up by different authorities. The most significant policies for the maritime sector are the Paris Agreement [91], the European Green Deal

[40] in combination with Fit For 55 [42] and the International Maritime Organization (IMO) Sustainable Development goals [63].

The Paris Agreement was set up during the twenty-first session of the Conference of the Parties (COP 21) by the United Nations Framework Convention on Climate Change (UNFCCC) in December 2015. The Paris Agreement is a legally binding international treaty on climate change signed by 196 parties. The goal of the agreement is to limit global warming by 2 degrees Celsius compared to pre-industrial levels. [91] To comply with this goal, the parties should have reached net-zero GHG emissions in 2050.

To reach this goal, the European Union set up an accompanying framework called the European Green Deal. The EU Green Deal sets out the trajectory for the EU to be climate-neutral by 2050. This includes the goal of 55% GHG reduction compared to 1990 by 2030 [40]. The framework includes the Fit For 55 package. This package aims to make the EU's climate, energy, land use, transport, and taxation policies fit for reducing net GHG emissions [42].

The last external framework is set up by the International Maritime Organization (IMO). Their strategy is in line with the other two ambitions, only less ambitious. The IMO strategy aims at a reduction in the carbon intensity of international shipping by at least 40 percent by 2030 compared to 2008. IMO is pursuing efforts to achieve a 70 percent reduction by 2050, compared to 2008. Furthermore, IMO expresses a minimal reduction of the total annual GHG emissions from international shipping of 50 percent by 2050.

To provide a regulatory framework to achieve these targets, existing and proposed systems are being applied to take a technical and operational approach to reducing GHGs. An example of such a system is the European Union Emission Trading System (EU ETS). The EU ETS is a ”cap and trade” scheme where a limit is placed on the right to emit specified pollutants over an area and companies can trade emission rights within that area [63].

## 1.2. Problem definition

If one assumes that the lifetime of a new-build offshore vessel exceeds the target dates of these goals, the design has to meet the stated requirements. These requirements can be met by using a zero GHG-emitting energy supply on board the vessel. During this research, the term ”energy supply” will be used to refer to a system including fuel, storage, and one or more energy conversion units. A range of different techniques for such an energy supply are under development [115]. The decision process on which energy supply is the most suitable for a new-build offshore vessel is affected by uncertainty regarding the future marine fuel landscape and the development in energy supply techniques and costs [127]. This uncertainty results in diverse preferences and opinions among decision-makers. To support the decision process, it is important to gain insights into the impact of the use of one or more sustainable energy supplies on board a vessel. This study seeks to gain insights into the characteristics and impact of a certain energy supply on a SSCV while keeping its operational requirements into account. The problem is the complexity regarding the best-suiting choice of a new-build energy supply that is sustainable and feasible for a new build that is compliant with the stated long-term emission goals.

## 1.3. Research gap

Fragments of knowledge regarding the implementation of future, low/zero GHG emitting energy supplies are being gathered [12]. An indication of the current technical impact of the implementation is being developed as well [12]. Studies are being conducted on future fuel scenarios [33]. Since this information concerns both techniques that are under development as well as future scenarios, uncertainty should be taken into account [127]. These factors have not been combined specifically for a new-build SSCV. This study aims to insight decision problem by utilizing a decision method that considers the technical and financial impact of the future use of low/zero GHG-emitting energy supplies on a new-build SSCV. This tool is distinctive in its specialized applicability for addressing a decision problem concerning an SSCV new-build energy supply, aiming to yield outcomes that align more effectively with the specific requirements and limitations unique to SSCVs.

## 1.4. Research questions

This study aims to aid decision-makers engaged in determining the best-suiting energy supply for a SSCV, offering insights into literature and certain methodology regarding this process. This will be done by aiming to answer the main research question. This main research question is supported by several sub-questions. The main research question and the sub-questions are stated below.

### 1.4.1. Main research question

*Which energy supply is best suited for a new-build SSCV, meeting the European Union emission targets, taking into account the preferences of experts?*

### 1.4.2. sub questions

The research question is supported by the following sub-questions:

1. *What decision method is suitable for the decision problem at hand?*
2. *What requirements and limits of the new-build SSCV should be assumed?*
3. *What are the energy supply characteristics?*
4. *Which criteria should be considered during the decision-making?*
5. *What are the preferences of the experts?*
6. *How can the preferences of the experts and the energy supply characteristics be integrated into the decision model?*

## 1.5. Research scope

This section will describe which subjects will be included in the scope of the research, as well as subjects that will be excluded during the research. An argumentation of the exclusion is provided.

### 1.5.1. Inside the scope

The scope of this research is set to include fuels, techniques, and regulations with significant relevance during the lifetime of a new-build vessel.

Table 1.1 shows the fuels that are included in the scope. The values regarding fossil fuels serve as base and comparison data for the case study later in the research. Fossil fuels are not considered EU emission goal compliant. Apart from these comparison fuels, the stated low and zero-carbon-emitting fuels are included in the scope.

**Table 1.1:** Fuels included in scope

| Fuel | Type |
|---|---|
| MGO | Fossil fuel |
| E-LNG | Electro-fuel |
| E-Methanol | Electro-fuel |
| E-Ammoia | Electro-fuel |
| E-hydrogen | Electro-fuel |
| Uranium | Nuclear fuel |
| Thorium | Nuclear fuel |

In the course of this report, whenever the terms ”LNG,” ”methanol,” ”ammonia,” and ”hydrogen” are employed, they are referring to the e-fuel variant of these fuels, with an exception for the content covered in Chapter 4.

The energy conversion technologies presented in table 1.2 will be considered in this research:

**Table 1.2:** Conversion systems included in scope

| Conversion system | Abbreviation |
|---|---|
| Internal Combustion Engine - 4 stroke | ICE |
| Proton Exchange Membrane Fuel Cell | PEMFC |
| Solid Oxide Fuel Cell | SOFC |
| Direct Methanol Fuel Cell | DMFC |
| Very High-Temperature Reactor | VHTR |
| Molten Salt Reactor | MSR |

The aspects that will be considered per component during this research are associated storage methods, Technological Readiness Level (TRL), system weight, system volume, storage temperature, storage pressure, efficiencies, maintenance requirements, Capital expenditures (CAPEX), Operation Expenditures (OPEX) and, emission, fuel, conversion system-specific policies and safety regulations. The greenhouse gas emissions that are taken into account will be referred to as "$CO_2$ equivalent". In this research, this implies the following gasses: $CO_2$, $N_2O$, $CH_4$. The assumptions regarding "Well-To-Wake" emissions per energy pathway will be included. The GHG emission limits are the international set frameworks from the EU and IMO.

During the research, a model will be developed. Different decision methods will be reviewed. Since the decision problem regarded in the research deals with a high amount of variables and uncertainty, a suitable method is required. Therefore a set of different methods and theories that support these requirements fall within the scope of the research.

Moreover, ETS is incorporated into the decision-making model, allowing decision-makers to indicate the significance and priority of the ETS as a concept regarding the decision process. Keep in mind that ETS is not included in the financial evaluation in this research, due to its uncertainty. Furthermore, given the assumption that ETS applies solely to fossil fuels, its negative impact on the suitability of these energy supplies will exclusively affect the MGO base case scenarios. Keep in mind that these scenarios are not deemed viable as a future energy supply due to their non-compliance with EU emission goals. Therefore, this exclusion of the financial assessment will have an insignificant effect on the final results.

The term "decision-makers" frequently appears throughout this research and refers to the group of experts within Heerema who participate in the survey tool as part of the decision-making method.

The SSCV Sleipnir will be used for a case study of the model. The input of this case study will include an operational profile of the SSCV Sleipnir. The operational details within the scope are stated below:

- Minimal required power
- Minimal stored energy per bunker period.
- Different operational modes
- Weight and volume limits

### 1.5.2. Outside the scope

Starting from 2027, the offshore sector will be subjected to the Emission Trading System (ETS). This system aims to reduce emissions by assigning companies a limited amount of emissions they can produce. Companies can buy or sell emission allowances [40]. Uncertainty in long-term ETS development makes modeling complex. The effect of fluctuating ETS prices can have a significant effect on similar business cases. This complexity causes the financial impact of ETS to be outside of the scope of this research. Note that ETS will be included in the decision-making as a criterion, which will be explained in this report, but not in the financial evaluation of the energy supplies. The scope of this research does not include other environmental impacts besides GHG emissions. Drive train components apart from the energy supply system will not be taken into account. No other operation modes besides Sleipnir's are being considered. Furthermore, it is assumed that biofuels are mainly transition fuels. Therefore these will not be included in this research. The use of batteries is also outside the scope of the research. Batteries are not likely to have sufficient capacity to act as a main energy supply for big offshore vessels in the near future. Also, the high gravimetric energy density is a disadvantage of battery use on ships. Further research should be done on the use of batteries for peak shaving purposes. Carbon Capture Storage (CCS) will also not be included since the CCS operation requires a vast amount of extra fuel.

With the knowledge that CCS is only able to capture a portion of the emissions, the effective GHG abatement will not be sufficient for the new build goals [23].

## 1.6. Research approach

The methodology of the research can be separated into 4 stages. Each stage is described below.

### 1.6.1. Stage 1: Choosing a suitable Multi-Criteria Decision Making method

The first stage of the research will consist of examining and comparing various multi-criteria decision methods applicable to the problem at hand. From this comparison, the method that best aligns with the decision problem is selected. This chosen method will be utilized throughout the case study concerning the SSCV in this research. This phase will be described in chapter 2

### 1.6.2. Stage 2: Gathering information

The second stage consists of gathering information regarding the characteristics of the SSCV Sleipnir, selected fuels and conversion systems, and approaching the financial impact of the different energy supplies on the SSCV. Thie gathering of information will be done by online literature research as well as by consulting experts inside and outside of Heerema and by part-taking in conferences regarding relevant subjects. The approach regarding the financial impacts is made by calculations that consider the specific requirements and limits of the SSCV. The gathered information regarding the SSCV Sleinpir characteristics is described in chapter 3. The information regarding the fuel characteristics is described in chapter 4. The information regarding the conversion system characteristics is described in chapter 5. The method and results of the financial impact approach are described in chapter 6.

### 1.6.3. Stage 3: Utilizing the Multi-Criteria Decision Making model

The third stage describes the utilization of the selected Multi-Criteria Decision Making Method model regarding the SSCV case study. The selected MCDM model progresses through three phases. In this research, these phases are labeled ”Model Phase A, -B and -C”. In this report, each methodology per ”Model Phase” is described in a separate chapter. Included in each chapter is the presentation of the results regarding this specific ”Model Phase”. A schematic overview of the Model Phases is presented in 1.1. The model will be used to conduct a case study. Since the parameters of the new build vessel are yet to be determined, the parameters of the Sleipnir will be used as input. The specific parameters will regard ship dimensions and operational profile/requirements.

#### Model Phase A: Criteria selection and preference weights

”Model Phase A” describes the selection of criteria that accompany the energy supply decision process and, therefore, be included in the decision model. This criteria selection is based on literature and on consulting experts within Heerema. Subsequently, ”Model Phase A” describes the gathering of the preferences of decision-makers/experts regarding the different criteria. These preferences are gathered through conducting a survey within Heerema. The decision-makers supplying preferences are experts selected from a company-wide set of departments to ensure that different perspectives on the decision are taken into account. Finally, the gathered preferences will be processed into criteria weights, representing the importance of each criterion within the decision process based on the preferences of the decision-makers. ”Model Phase A” is described in chapter 7.

#### Model Phase B: Alternative scores

”Model Phase B” describes the processing of the gathered information and characteristics regarding each energy supply into energy supply-specific scores. These scores represent the performance of each energy supply regarding a specific criterion. These scores will be used later in the model. ”Model Phase B” is described in chapter 8.

#### Model Phase C: Energy supply suitability

”Model Phase C” describes the process of combining the preferences of the experts with the assigned energy supply-specific scores. The steps in ”Model C” result in a ranking of best-suiting energy supplies to the preferences of the experts. ”Model Phase C” is described in chapter 9.

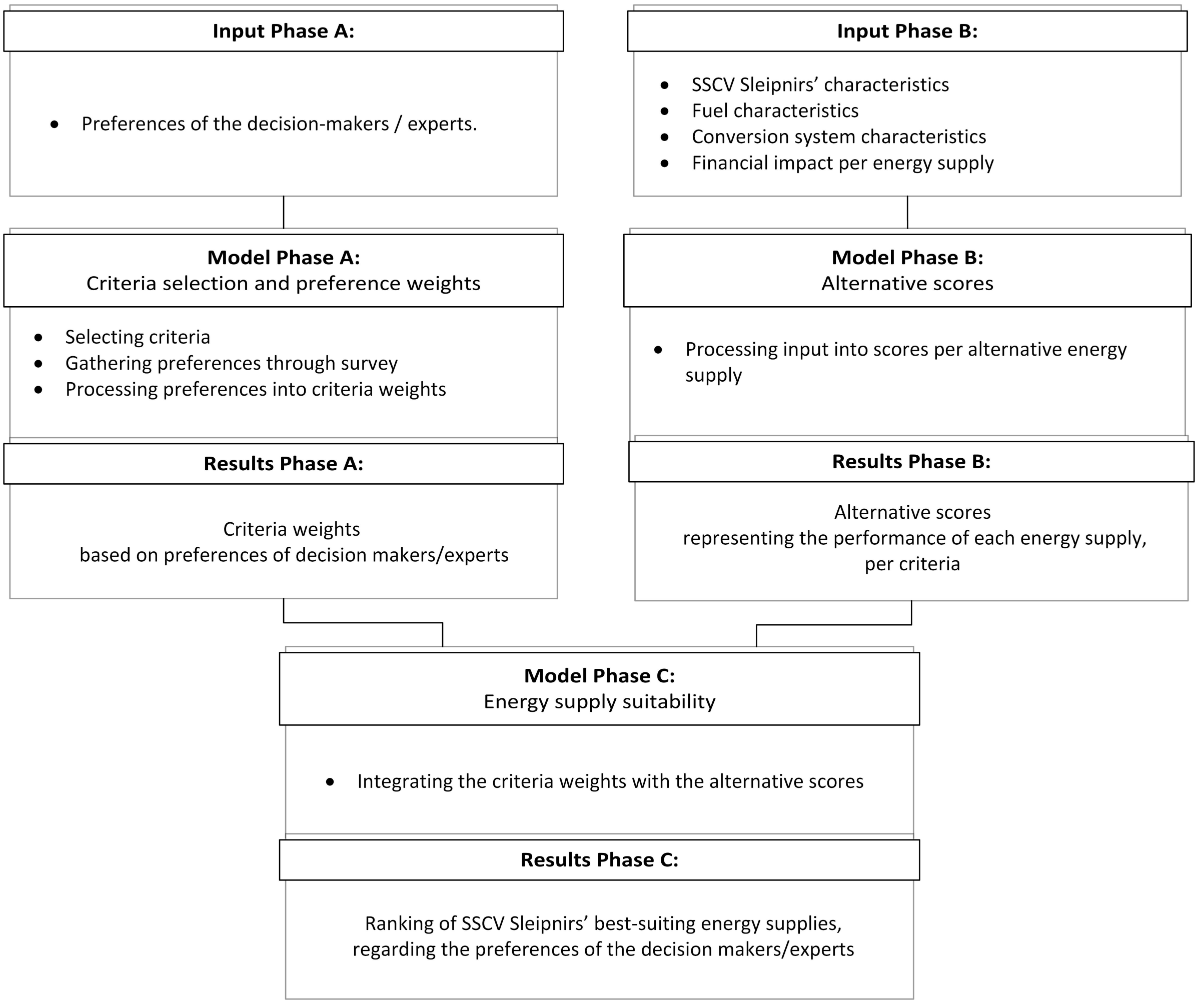


**Figure 1.1:** Schematic overview of the MCDM model

### 1.6.4. Stage 4: Discussion, conclusion, and recommendations

The final stage in this research regards the discussion of the methodology and the results of Phase A, -B, and -C. This discussion critiques the limitations and strengths of the method to assess its reliability. Following, the conclusion that can be retrieved from the observations will be presented, and finally, recommendations regarding future research will be given. The discussion is described in chapter 10. The conclusion and recommendations are described in chapter 11.

# 2
# Multi-Criteria Decision-Making methods

This second chapter describes the choice regarding the academic method and theory that will be used to support the research. Section 2.1 describes the working and advantages and disadvantages of two different decision methods. Section 2.2 describes the argumentation and decision regarding the chosen method during the research.

## 2.1. Multi Criteria Decision Making

There are different grounds on which someone prefers certain fuels above others. There are many energy pathways to consider. Which all have their own advantages and disadvantages. It is important to assess which criteria should be taken into account when making a substantiated energy supply system choice for a new build vessel. To tackle these problems, a Multi-Criteria Decision Making method (MCDM) can be applied. Multi-Criteria Decision Making (MCDM) models refer to a set of mathematical tools that are appropriate for assessing and selecting the most preferred alternative options based on multiple criteria. These models belong to a broad category of research models that address decision-making problems involving numerous criteria. The ultimate goal is to choose the most appropriate criteria that yield the best possible outcome [10]. There are many different methods within MCDM. All of these methods have their own specific fields of application. For the problem concerning the different aspects within the design process of a new-build, the following two methods are considered interesting: Analytic Hierarchy Process (AHP) [10] and the Best-Worst Method (BWM) [93].

### 2.1.1. Analytic hierarchy process

The Analytic Hierarchy Process (AHP) is a technique designed for ranking critical management problems. AHP enables decision-makers to assign weights to the criteria and subsequently rank and prioritize various choices. As a result, the differentiation of more significant criteria from less significant ones can be made. AHP can therefore be used to measure the importance of certain criteria according to the judgment of experts. The steps of a basic AHP method are given below [95]:

1. Define the problem and hierarchy: Identify the decision problem, the criteria to be considered, and the alternatives. [95] Create a hierarchy that represents the decision problem build-up. This is done by setting up a goal, followed by the criteria and the sub-criteria that have an impact on the achievement of this goal. lastly, identified the alternative options that can be chosen.[95]
2. Pairwise comparisons: Make pairwise comparisons of the criteria and sub-criteria at each level of the hierarchy. This involves comparing each criterion against every other criterion and assigning a numerical value to indicate the relative importance or preference between them. [95]
3. Calculate priorities: Use the pairwise comparison data to calculate the relative priority of the criteria. The weights indicate the degree of importance of each criterion in relation to the others. [95]

4. Check consistency: Check the consistency of the pairwise comparisons by calculating the consistency ratio. The consistency ratio is a measure of how well the judgments made in the pairwise comparisons agree with each other [96].
5. Define alternative scores. Each alternative needs to be assigned a score of performance regarding each criterion. This scoring process can be done by literature, calculations or by consulting experts.
6. Aggregate weights and scores: Aggregate the criteria weights with the assigned alternative scores. The criteria weights associated with a certain alternative are combined into a final weight for this choice. [112].
7. Evaluate choices: Evaluate the choices based on the aggregated preferences and select the most preferred choice [97].
8. Sensitivity analysis: Conduct sensitivity analysis to assess the stability of the results under different assumptions or conditions [86].

### Define the problem and hierarchy

The first two steps in the AHP are to define the decision problem and establish a hierarchical structure that represents the problem. The hierarchy should have a goal or objective at the top layer, followed by criteria that are necessary to achieve the goal and choices that can be evaluated against the criteria. The hierarchy can be visualized as a tree diagram. This tree diagram shows the goal at the top and the criteria and choices branching out of it. An example is shown in figure 2.1 [95].

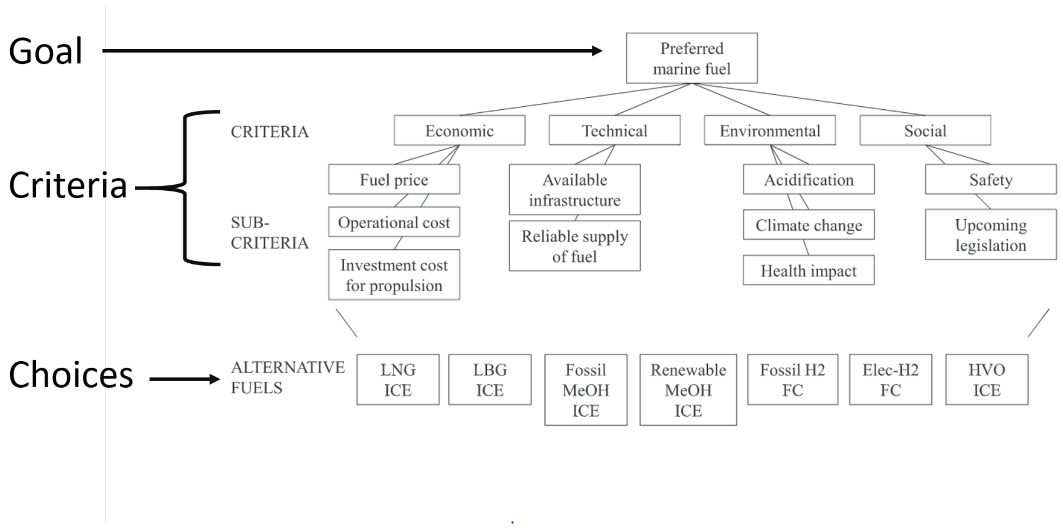


**Figure 2.1:** Hierarchy tree for a decision problem when selecting the alternative marine fuel with the highest overall performance for the included criteria and sub- criteria. [52].

*Note that the figure 2.1 serves solely as an illustrative representation of an AHP hierarchy tree's structure. The criteria and sub-criteria depicted in the figure may not necessarily correspond to those considered in this research.*

### Pairwise comparisons

After the hierarchy has been established, the decision-maker must compare the hierarchy elements through a pairwise comparison to determine their relative weight. The decision-maker is asked to relatively rank the criteria according to the weight scale shown in table 2.1. [95]

| Intensity | Definition | Explanation |
|---|---|---|
| 1 | Equal importance | Two elements contribute equally to the objective |
| 3 | Moderate importance | Experience or judgment slightly favors one element over another |
| 5 | Strong importance | Experience or judgment strongly favors one element over another |
| 7 | Very strong importance | One element is favored very strongly over another |
| 9 | Extreme importance | Favoring one element over another has the highest order of affirmation |

**Table 2.1:** Fundamental scale of absolute numbers used in pairwise comparisons of choices and criteria according to Saaty [52]

In a pairwise comparison, a matrix is formed in which each criterion is weighted relative to each other. An example of such a pairwise matrix is given in table 2.2. This matrix shows that criterion 1 is three times as important to the decision-maker relative to criterion 2.

| | Criterion 1 | Criterion 2 | Criterion 3 | Criterion 4 |
|---|---|---|---|---|
| Criterion 1 | 1.00 | 3.00 | 7.00 | 9.00 |
| Criterion 2 | 0.33 | 1.00 | 5.00 | 7.00 |
| Criterion 3 | 0.14 | 0.20 | 1.00 | 3.00 |
| Criterion 4 | 0.11 | 0.14 | 0.33 | 1.00 |

**Table 2.2:** Example of a pairwise comparison matrix

### Calculate priorities

The fourth step is the priority calculation. After the pairwise comparison, each criterion's priority in the hierarchy must be calculated. The priorities are calculated using a mathematical formula that takes into account the pairwise comparison judgments and the hierarchical structure of the problem [96].

### Consistency check

The fifth step involves verifying the consistency of pairwise comparisons using the consistency ratio (CR). The CR quantifies the degree of agreement between the judgments made in pairwise comparisons. If the CR exceeds a predetermined threshold, typically 0.1, the judgments are considered inconsistent and require reevaluation. Consistency is crucial since inconsistent judgments may lead to unreliable and inaccurate outcomes. [96]

### Define alternative scores

In this step, each alternative is assigned a score based on its performance regarding a specific criterion. This is done by retrieving background information concerning the performance from literature, consultations with experts, or (scaling-) calculations.

### Aggregate preferences

The next step is to aggregate the weights of the criteria with the alternatives at each level of the hierarchy. Criteria weights are calculated by multiplying the priorities assigned to each sub-criterion by the priorities assigned to its parent criterion. These criterion weights are multiplied by the alternative score regarding the specific criterion. This is done for all alternatives regarding each criterion. The resulting values are then summed to obtain the overall compatibility score of the alternatives. This compatibility score implies the suitability of the alternative based on the preferences of the decision-maker. [96]

### Evaluate choices

The seventh step involves evaluating the choices based on the aggregate preferences and selecting the most preferred choice. The evaluation involves multiplying the weights of criteria and choices to obtain a score for each choice. The choice with the highest score is selected as the most preferred choice. This step allows the decision maker to make an informed decision based on the criteria that are most important to them. [69]

### Sensitivity analysis

Finally, a sensitivity analysis is conducted to assess the stability of the results under different assumptions or conditions. This involves testing the robustness of the results by changing the weights or criteria and observing the impact on the final decision. The sensitivity analysis helps to ensure that the decision is reliable and robust and can be trusted even in uncertain or changing circumstances. [98]

### Advantages and disadvantages of AHP

The advantages and disadvantages: of the AHP are summed up in this subsection:

Advantages:

- Due to its structured approach, AHP is often considered more suitable for more complex problems[114][96]. The structure helps to decompose the complex problem in manageable components.
- The pairwise comparison is able to derive the relative weights of criteria and sub-criteria. This makes a complex problem also more manageable and transparent. [95]
- The consistency check ensures that the decision makers' pairwise comparisons are valid and consistent. This makes the results of this method more reliable. [96]
- The AHP has a sensitivity analyze integrated. This is valuable since it provides nuance and robustness to the decision problem. [95]

Disadvantages:

- AHP can be time-consuming when dealing with a large number of criteria and choices.
- The AHP method involves the subjective judgment of the decision maker, this can result in a biased and unreliable outcome. [95]

### Applications of AHP

As stated, AHP can be used in numerous applications where there is a complexity of different criteria present in a decision problem. To delve deeper into the application, it is interesting to evaluate the application of AHP in the decision problem regarding the marine fuel transition. A set of interesting papers are summarized below.

The first paper considered is ”Alternative marine fuels: Prospects based on multi-criteria decision analysis involving Swedish stakeholders” by J. Hansson et al. [52] This study evaluates the possibilities for six alternative fuels for the shipping industry in 2030, including biofuels, using a multi-criteria decision analysis approach based on the estimated fuel performance and input from a panel of maritime stakeholders and by explicitly taking the influence of stakeholder preferences into consideration. The six alternative marine fuels considered are LNG, LBG, grey and green methanol, grey and green hydrogen, HVO, and HFO. These fuels are ranked by ten performance criteria and their relative importance is determent. The criteria include social, technical, economic, and environmental aspects. Due to the stakeholder's criteria preferences, the options are ranked compared to each other. This is done following the AHP steps explained in this subsection. The outcome of the study is that for the ship owners, fuel producers, and engine manufacturers, the economic criteria, especially fuel price, are the most important. These groups rank LNG and HFO the highest. On the other hand, Swedish authorities rank environmental and social criteria the highest. Especially GHG emissions and the potential of meeting future regulations. For this group, hydrogen ranks the highest. [52]

The second paper regards the research ”Criteria and Decision Support for A Sustainable Choice of Alternative Marine Fuels” by K. Andersson et al. [7]. This research attempts to provide an understanding of the different types of criteria used in current evaluations of potential marine fuels and to identify the most significant criteria. The author's own observations from evaluating marine fuels are combined with a literature review of specific scientific journals and interviews with shipowners to accomplish this. The literature varies because diverse viewpoints exist regarding the purpose of alternative fuels and the evaluation methods [7]. The study identifies four main aspects that should be taken into account when assessing alternative maritime fuels: environmental effect, availability, safety, and cost. The environmental impact criteria take into account things like greenhouse gas emissions, local air pollution, and effects on biodiversity. The fuel's production and distribution are taken into account when using the availability requirement. The safety criteria examine the fuel's safety risks, such as fire and explosion dangers. Finally, the cost criteria include both the historical and ongoing costs associated with the fuel. Between fuels that can be used in ships that are already in service and fuels that can be used in new kinds of propulsion systems, there are certain differences in the minimal set of criteria that are advised to be taken into account when evaluating future maritime fuels [7]. The different criteria are depicted in figure 2.2.

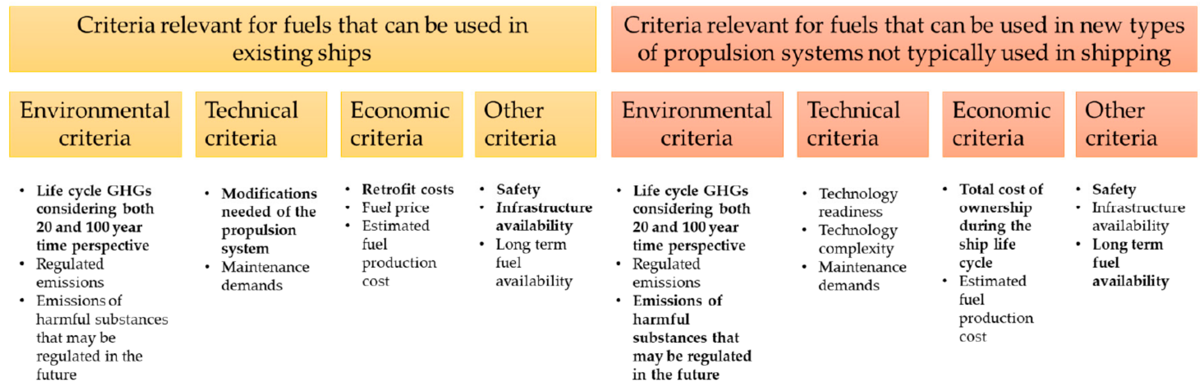


**Figure 2.2:** A set of suggested criteria to consider when evaluating future marine fuels [7].

The paper is an example of the application of a decision support framework. It is not specifically stated that AHP is used. However, the report does propose a decision framework using criteria and weights that can be used to compare different fuels. Therefore it is similar to the AHP method, and given the paper's subject, it is interesting to consider this approach.

### 2.1.2. Best-Worst Method

The Best-Worst method (BWM) is another multi-criteria decision-making technique introduced in 2015 by Jafar Rezaei. BWM also evaluates different criteria to each other. There is a similarity in the methods of BWM and AHP. The main difference is in the comparison technique of the different criteria. Where AHP compares every criterion, BWM defines the most important (the best) and the least important (the worst) criterion. Then the user compares the best criterion to the others. The same is done for the worst criteria. Based on this information, the criteria-specific weights are calculated [93]. Another difference is the result of the method: the AHP results show how the criteria preferences result in a hierarchy of best choices. The BWM shows how the preferences per criterion result in the relative relationship of these criteria. The steps of the BWM are described in short below:

1. Define a set of criteria: The criteria considered should be chosen. For example $C_1$ to $C_5$. [93]
2. Define the best and the worst criteria: The decision maker selects the best and the worst criteria in general. No other comparisons are made here. [93]
3. Best-to-other comparison: Determine the preference of the best criterion compared to the other criteria. For the Best-to-other comparison, a score of 1-9 can be applied per criteria. Note that the best criterion compared to itself gets a score of 1 ($C_{best-best} = 1$)[93].
4. Other-to-worst comparison: Determine the preference of the other criteria compared to the worst criterion. Again a score of 1-9 should be applied. Again note: ($C_{worst-worst} = 1$) [93]
5. Calculate the weight per criterion: Based on the comparison input, the weight per criteria can be calculated. For the mathematics of this calculation please consult "Best-worst multi-criteria decision-making method" by J. Rezaei [93].
6. Check consistency: Check the consistency ratio (CR) of the weight calculation. The consistency ratio is a measure of how well the scores applied in both comparisons agree with each other. If the CR is above a given amount, the results are not reliable. [93].

#### Advantages: and Disadvantages: of BWM

Advantages::

- The BWM is relatively simple and easy to understand.
- Allows for clear identification of most important criteria.

Disadvantages:

- BWM involves the subjective judgment of the decision maker. This can result in a biased and unreliable outcome.

- The BWM has no integrated sensitivity analysis. This makes the method less robust.
- The BWm makes relatively fast and simple comparisons. This results in a less reliable outcome and consistency ratio compared to AHP, for example.

## 2.2. Preferred decision method

The decision problem in this study is complex and benefits from nuance. The decision problem contains a large number of criteria and alternatives. For more complex problems, AHP is often considered more suitable [114]. The reasoning for this preference is: The BWM is limited by the number of criteria in contrast with AHP [93] [114]. In general, the method is usable for up to 9 different criteria. Another reason is the hierarchy-based structure of AHP. AHP breaks the complex decision problem down into criteria and sub-criteria when needed. This enables the decision-maker to decompose the complex problem into manageable components [87]. Also, the interrelations of the criteria and sub-criteria can be included. Furthermore, the pairwise comparison of the AHP gives a more detailed comparison of each criterion. All the different measure points/input makes the consistency check also more valuable. The AHP has a sensitivity analysis integrated where BWM has not. This is also valuable for more complex problems [96]. Considering the stated characteristics of the decision problem at hand and the characteristics of both decision methods, AHP is deemed to be the most suitable method for the decision problem in this research. Therefore AHP is the multi-criteria decision method used in this research.

# 3

# SSCV Sleipnirs' characteristics

This chapter describes the characteristics and limits of SSCV Sleipnir. SSCV generally differ in specific characteristics. This chapter aims to provide guidelines for mapping the characteristics of SSCVs with similar operational profiles as Sleipnir. Sleipnirs' characteristics will be used in the case study during this research. The SSCV characteristics will define the boundary conditions and guidelines for the energy conversion system design. Section 3.1 describes the boundary conditions regarding the operational requirements of the Sleipnir. Section 3.2 describes the static volume and weight limits of the SSCV.

## 3.1. Operational requirements

The considered operational boundary conditions for the Sleipnir consist mainly of two aspects. First, a minimal amount of available energy per bunker period. Second, the capability of accommodating the execution of several operational modes and therefore, a minimal power requirement. The available energy per bunker period depends on its fuel capacity. The capability of complying with the required operational modes and minimal power is met due to its installed engine power. This research assumes the energy capacity and power currently present at the Sleipnir as the boundary condition for the case study.

Currently, the installed power at Sleipnir is 12 engines of 8 MW. Which results in 96 MW of effective power. The power requirements for SSCV Sleipnir can be determined for multiple operational modes. The different modes of the SSCV Sleipnir are itemized and described below:

[redacted]

Every different mode is accompanied by a typical energy requirement. The specific energy requirement is due to a combination of types of loads during each mode. The different loads are itemized below. Table 3.1 shows which loads are present during each operational mode.

[redacted]

**Table 3.1:** Loads present during certain operational mode

[redacted]

The average energy requirement, as well as the occurrence per mode of the SSCV Sleipnir, is considered over the years 2019-2023. This data is retrieved from an in-house Heerema database. The energy requirement is based on the fuel consumption history per work mode. Since the engines installed on the SSCV Sleipnir are dual-fuel engines on LNG and MGO, the fuel consumption per day of a certain mode is separately converted to MWh per day. The occurrence of each mode is also retrieved from the historical data. This percentage is depicted in table 3.2.

**Table 3.2:** Occurrence of operational mode based on operational data of 2019-2023

[redacted]

The historic energy requirement per fuel per mode is calculated using formula 3.1. The fuel consumption, occurence and bunkering period are found in inhouse data from Heerema. The conversion efficiency is discussed in section 5.2. The volumetric energy density is discussed in section 4.2.1.

$$E_{\text{bunkering}} = F_{\text{Fuel consumption}} * T_{\text{bunkering}} * ED_{\text{volumetric}} * Occurance * \eta_{\text{conversion}} \tag{3.1}$$

**Table 3.3:** Symbol clarification $E_bunkering$ formula

| Symbol | Description | Unit |
|---|---|---|
| $E_{\text{bunkering}}$ | Energy per bunkering period | *MWh / bunkering period* |
| $F_{\text{Fuel consumption}}$ | Fuel consumption | *$m^3$ / day* |
| $ED_{\text{volumetric}}$ | Volumetric energy density | *MWh / $m^3$* |
| Occurance | Occurance | *%* |
| $T_{\text{bunkering}}$ | Bunkering period | *days* |
| $\eta_{\text{conversion}}$ | Conversion Efficiency | - |

All energy requirements of MGO and LNG are determent per mode and depicted in table 3.4. The total energy requirement per bunkerperiod for the new-built is assumed the same as the historic energy requirement from the SSCV Sleipnir. This energy requirement is 21154 MWh per 6 weeks.

**Table 3.4:** History energy requirement per fuel per bunkering period (6 weeks)

[redacted]

For the SSCV-specific efficiency calculation in section 5.2 and accompanying energy requirements, when considering different energy pathways and fuels, it is important to consider the engine capacity factor during each mode. Since SSCV Sleipnir is classified as a Dynamic Positioning class 3 (DP3) ship, each operational mode is required to have a specific amount of available power online in case of a spike in energy demand [47]. This available online power is referred to as ”spinning reserve”. To meet these regulatory conditions, Heerema applies certain engine capacity factors per mode. The engine capacity factor refers to the percentage of its online power which is being used in this specific load. Note that this does not necessarily mean all installed engines are online, but the engines that are online will operate at the given load. The engine capacity factors assumed by Heerema are depicted in table 3.5 per mode. During this research, these mode-specific capacity factors are assumed for each energy conversion system.

**Table 3.5:** SSCV-specific engine capacity factor assumed by Heerema for each mode and corresponding delivered power.

[redacted]

## 3.2. Static limits

The general static guidelines for this research are considered the limits of Sleipnirs’ current system, including maximum fuel storage weight and volume. Also, the engine room volume is considered. These guidelines are not boundary conditions during the case study. But the current static limits of the Sleipnir will be used to compare and evaluate the impact regarding static conditions of other energy supplies. The reason for these guidelines is the maximum transit draught of the vessel. This maximum transit draught is preferred to be maintained so the new-built vessel is not limited in its operations. The transit draught of the SSCV is currently 12 meter. According to experts at Heerema, the transit draught requirements can be met when carrying a maximum amount of fuel with reasonable marge for cargo. The underwater body of the SSCV Sleipnir consists of columns and pontoons. A schematic overview of this design is depicted in Figure 3.1. Currently, the LNG and MGO used in the Sleipnir are stored in the columns of the vessel. The volume and weight of the fuel at full capacity are shown in table 3.6. The 4 engine rooms are located in the hull above the columns. The dimensions of the engine room are depicted in table 3.7. The final storage weight and volume limits are determined by multiplying the fuel volume and weight by, respectively, a volumetric storage ratio and a gravimetric storage ratio. These ratios represent the required volume and weight to accommodate the storage facilities. The volumetric storage ratio of MGO 1.1 and of LNG 2.4 [62]. The gravimetric storage ratio of MGO is 1.4 and of LNG 1.7 [62]. The limiting factors are summarized in table 3.8.

[redacted]

**Figure 3.1:** Schematic side view of the design of the SSCV Sleipnir

**Table 3.6:** Current maximum available storage volume and accompanying weight on SSCV Sleipnir

[redacted]

**Table 3.7:** Dimenstions of a single engine room of the SSCV Sleipnir

[redacted]

**Table 3.8:** Overview of static limits new-built

[redacted]

# 4
# Fuels

This chapter considers a brief introduction to different considered fuels in Section 4.1. Following, the fuel and storage characteristics are discussed in Section 4.2. Subsequently, the emissions due to the use of each fuel are discussed in 4.3. Finally, the safety issues accompanying each fuel are discussed in Section 4.4.

## 4.1. Fuel introductions

This section provides a brief introduction to the different fuels. This introduction regards two relevant currently used fossil fuels, electro-fuels, and nuclear fuels, in 4.1.1, 4.1.2, and 5.1.3, respectively.

### 4.1.1. Currently used fossil fuels

At present, international shipping relies primarily on three types of fuel for its energy needs. Heavy Fuel Oil (HFO) accounts for nearly 79% of the fuel consumption, followed by Marine Gas Oil (MGO) at around 20%, while the use of liquefied natural gas (LNG) represents only about 1% of the total fuel usage [73]. These currently used fossil fuels can be separated into two different groups: fuel oils and liquid natural gas. The group of fuel oils consists of multiple different oils. In this research, the two most commonly used fuel oils are considered (HFO and MGO). [106]. After this consideration, MGO was set as a baseline for further research. This is because MGO is a more environmentally friendly fuel than HFO and is currently used by Heerema.

#### Fuel oils

As said Heavy Fuel Oil (HFO) is in currently the most used marine fuel [106]. HFO is considered a residual fuel, implying that HFO consist of oil which is a rest product of the oil refining process [72]. Because it is a residual material, the oil contains heavy metal impurities such as sulfur. The emissions of HFO are $SO_x$, $NO_x$, $CO_2$, $N_2O$. Furthermore, HFO has a high viscosity and has to be heated to a temperature of 130 C to flow [11]. In case of spillage, HFO is a treat for the environment. The spilled HFO emulsifies with the seawater. This emulsion can have many times the volume of that of the original spilled liquid. Although the environmental impact of HFO is known, it still remains the most used marine fuel because of its availability, costs and the fact that most large marine engines are designed on this fuel. The use of Light Fuel Oils (LFO) is increasing in the past years. LFO is a low-sulfur variant of HFO. [11].

MGO is considered a high-quality marine fuel. MGO differs from HFO in its production method. MGO consists of various distillates. Distillates are the components of crude oil that evaporate during a distillation process and are later condensed from gas to liquid form. During this distillation process, the heavy metal impurities are filtered from the MGO. This results in less harmful emissions during combustion [92]. One of the advantages of MGO is its low viscosity which allows the fuel to be pumped into the engine at lower temperatures of around 20 °C [79]. This research will take the characteristics of MGO as a baseline to compare other alternatives. This is because MGO is a more environmentally friendly fuel than HFO and is currently used by Heerema.

LNG

LNG (Liquefied Natural Gas): LNG is a relatively clean fossil fuel, and it produces significantly fewer emissions HFO and MGO when being completely burned. The mass of Liquefied Natural Gas consists of 70 to 99 % of methane (CH4). This is the energy-carrying component of the fuel. A common problem with the use of LNG is methane slip. Methane slip means that unburnt gas is released in the atmosphere during operation. The global warming potential (GWP) of methane is 30 times as high as that of $CO_2$. Therefore, the GHG reduction potential depends heavily on the methane slip measures [38]. Furthermore, normal LNG is still a fossil fuel. Methods are developed to produce synthetic LNG from renewable energy sources. This makes E-LNG a clean alternative fuel. More information about this type of LNG can be found in 4.1.2. LNG must be transported and stored in a cooled liquid state, which can be challenging. With sufficient methane slip measures, LNG could reduce the Well-to-wake GHG emissions by 18% compared to MGO and HFO during a ships life cycle. [35]. With regard to the emission goals of the European Union, LNG will not be included in the case study during this research. A fuel that is included in the case study is a "low to zero"-emission variant of LNG, electro-LNG (E-LNG). E-LNG will be described in chapter 4.1.2.

### 4.1.2. E-fuels

In this subsection, a general explanation and application of different "electro-fuels" (E-fuels) is given. During this research, the term E-fuel is defined as fuels with minimal GHG emissions during production (well-to-tank) as well as combustion (tank-to-wake). The production of E-fuels consists of a synthetic process combined with electrolysis powered by renewable energy sources. The production costs of e-fuels are highly dependent on renewable energy prices. These prices are estimated to drop in the future years. The E-fuels considered are E-LNG, E-hydrogen, E-methanol, and E-ammonia. Following to this chapter, when the terms "LNG," "hydrogen," "methanol," and "ammonia" are mentioned, they refer to the named E-fuel versions of these respective fuels.

E-LNG

E-LNG consists of the same molecules as fossil LNG. It is the same gas. The only difference can be found in the production process. E-LNG is produced in a process called power to gas (P2G). In this process, hydrogen atoms are split from oxygen atoms by electrolysis. Carbon which is captured from the air, is combined with this hydrogen which results in methane ($CH4$). Since the current chemical industry has sufficient experience with this process. It can be done on a larger scale. The characteristics and storage methods of the gas are the same as normal LNG. The well-to-wake GHG emission reduction of E-LNG is 94% compared to fossil LNG. The production costs of E-LNG are 3.5 times higher than that of normal LNG. [74]

E-Hydrogen

As said, hydrogen can be produced from renewable energy sources due to electrolysis. When used as a fuel, it produces only water vapor as a byproduct. It can be used in fuel cells or internal combustion engines to power ships, or it can be used to create synthetic fuels. Hydrogen is a flammable gas that is highly explosive. Compared to other gases, for example, LNG, the safety-related characteristics are different. These characteristics will be described in 4.4. Hydrogen can be stored in liquid form ($LH_2$) and in compressed gas form ($LH_2$). Hydrogen is the smallest molecule in size. This means current gas transportation infrastructure needs to be adjusted to prevent hydrogen leakage. In the meantime, hydrogen is one of the lowest densities, therefore, making storage volume a problem on ships [9].

E-Methanol

Methanol is widely used in the chemical industry. The molecular formula of methanol is $CH_3OH$. Methanol can also be used as a marine fuel. Methanol produced as an E-fuel is called E-methanol. E-Methanol can again be produced using renewable energy and renewable feedstock. Also, in this production process, $CO_2$ is captured in a renewable way. For example, by direct air capture or by a carbon capture and storage integrated bioenergy process. The captured $CO_2$ will then be chemically combined with green hydrogen [65]. Methanol has a well-to-wake emission reduction of 95% compared to fossil LNG [74]. One of the advantages of methanol is the fact that methanol is liquid under atmospheric pressure. Therefore, methanol can be stored similarly to other bunker fuels [65].

#### E-Ammonia

Ammonia is also a globally used commodity. Most of the nowadays produced ammonia is used as a feedstock for fertilizer for the food industry. The molecular formula of ammonia is $NH_3$. Almost half of the hydrogen produced in the world is used as a feedstock for ammonia. Currently, almost all of the ammonia production is powered by fossil fuels. By obtaining this hydrogen using renewable electrolysis, green ammonia is produced. The applications for ammonia in the maritime industry are currently being explored. Ammonia is a carbon emission-free fuel. However, ammonia use could increase the emissions of nitrogen oxides ($NO_x$ and $N_2O$) which are harmful to the environment. It is important to note that ammonia is a hazardous chemical, which can lead to fatal incidents when not properly handled. Therefore saving transport and storage of ammonia is of the highest importance. On the other hand, ammonia has been handled safely for over a century and so these techniques have a high majority. Ammonia is stored at atmospheric pressure and in a liquid state at -33 °C [64]

### 4.1.3. Nuclear fuels

Nuclear power is a GHG emission-free energy production method. The use of nuclear power requires a relatively very small volume of fuel. Small volumes of enriched uranium and thorium can be used to power a vessel for years. Nevertheless, it is not a widely used energy supply system on ships. Among others, this has to do with the high CAPEX as well as the nuclear waste, which has to be safely stored for centuries. Another disadvantage of the use of nuclear is the lack of global regulations. Instead, ports have local regulations which often do not allow nuclear-powered ships to enter. Furthermore, there is a negative social safety stigma connected the use of nuclear due to the widely known nuclear disasters like the accident with the Chernobyl reactor in 1986. Marine nuclear power has been used in over 160 vessels, mainly for the navy and icebreakers. Pressurized water reactors are the current common technology requiring an active safety system. Because water is both used as a coolant and 'moderator,' When this moderator is not available, the nuclear reaction becomes unstable. Which results in a nuclear melt-down, making them inherently unsafe in case of failure. The additional safety measures make a nuclear reactor expensive. Currently, a new generation of reactors is being developed (*"Generation IV"*). Two examples of the new reactor types are the Molten Salt Reactor (MSR) and the Very High-Temperature Reactor (VHTR). The advantage of these two reactors is the fact that they are inherently safe. For example, the MSR uses salt to sustain the reaction. When there is a meltdown, the salt gets automatically removed from the system, which stops the reaction. Therefore, MSR is supposed to be resistant to a meltdown. When these reactors are commercially available is uncertain. Currently, the expectation is that small modular generation IV reactors will be available for on-shore applications in 2030-2035. As mentioned, there are two types of nuclear fuels that currently are being used in reactors: enriched uranium and enriched thorium [81] [49].

#### Uranium

Uranium is a rare heavy metal that occurs in the Earth's crust but also in seawater in concentrations of 2-4 parts per million. Uranium was formed in a supernova 6.6 billion years ago. Uranium has a slow radioactive decay, which means that it is able to provide energy for a long period of time continuously. Where hydrogen is the lightest element, uranium is one of the heaviest of all naturally-occurring elements. Like other elements, uranium exists in multiple different nuclei compositions called isotopes. The isotope U-235 is of interest since it can be split under certain conditions. This process is called nuclear fission. After splitting the isotope, the element becomes fissile. A fissile element continuously releases a high amount of energy. For some reactors, it is necessary to enrich the uranium before it can be used as fuel. Enriching uranium is done by increasing the percentage of the U-235 isotope in the element. This process is called isotope separation. Enriched uranium typically consists of 5% of U-235. [8]. To make sure the uranium fuel will endure years of service at high temperatures and in an intense radiation environment, it must be held in a robust physical form. The uranium is stored in ceramic pellets covered and sealed into zirconium alloy tubes. Zirconium is exceptionally resistant to corrosion and high temperatures. It allows neutrons to pass during a nuclear fission reaction [119]. The costs of the uranium fuel rods are relatively low. An estimated 3% of the operational costs of a nuclear power plant consist of fuel costs [118]. When the fuel rods are transported, they need to be covered in proper shielding to prevent the containment of radioactive content. After use, the nuclear fuel has to be properly decommissioned as the waste is a hazardous material when returned into the biosphere. The radioactive waste is leveled as either Low-Level Waste (LLW), Intermediate-Level Waste (ILW), or

High-Level Waste (HLW). LLW typically are parts of the reactor that have been lightly contaminated during operation. This type of waste does not require shielding during handling and transport and is suitable for disposal near-surface facilities. HLW is typically the fissile material in the reactor core. This material needs to be stored under sufficient shielding and cooling. The United States Energy Information Administration (EIA) estimates the costs of waste management at 5% of the operational costs. It is important to note that the amount of waste depends on the type of fuel as well as the type of reactor [120].

#### Thorium

Another naturally-occurring metal that can be used as a nuclear fuel is thorium. Thorium is three times more abundant in the Earth's crust than uranium but cannot be found in seawater. The use of thorium in reactors is relatively new. Thorium is less radioactive than uranium. It is rather fertile than fissile, which means that it needs to interact with fissile material for fuel purposes. Commonly recycled plutonium is used to create a fissile thorium fuel. In nature, thorium only exists in the isotope Th-232 which, like uranium, decays very slowly (three times the age of planet Earth). To make thorium useable in a thermal neutron reactor, it needs to be made fissile by absorbing a neutron from another fissile material. After this neutron absorption, thorium produces protactinium-233. The protactinium undergoes chemical separation from the parent material and transmutes it into uranium U-233, which is an excellent fissile material. Therefore thorium needs a fissile material as a "driver" [121]. An advantage of thorium, apart from its relative abundance, is the fact that it produces much less long-lived radioactive waste than uranium. This is a major advantage since long-term radioactive waste management is often a bottleneck for commissioning new reactors [49] Also, thorium reactors are inherently safer than uranium-fueled reactors. This is because thorium-fueled reactors operate at lower pressure and temperatures [4]. Finally, thorium reactions have a much higher efficiency. A kilogram of thorium produces 35 times the energy a kilogram of uranium can produce. This is due to the fact that a higher percentage of the internal energy of the element can be utilized during the reaction [107]. The current drawbacks of a thorium reactor are the high costs and relatively low technical and operational experience. This is projected to improve due to the commissioning of thorium-fueled molten salt reactors. [107]

## 4.2. Fuel and storage characteristics

This section provides an explanation and an overview of a set of fuel and storage characteristics. The fuel characteristics are discussed in 4.2.1. The fuel characteristics considered are density, volumetric energy density, gravimetric energy density, Technological Readiness Level (TRL), and flash point. The storage characteristics are discussed in 4.2.2. The characteristics considered are storage temperature, storage pressure, storage volume ratio, and storage gravimetric ratio. An overview of all the characteristics is presented in Table 4.1.

**Table 4.1:** Fuel and storage characteristics

| **Characteristic** | **Unit** | **MGO** | **LNG** | **Liq. $H_2$** | **Comp. $H_2$** | **Methanol** | **Ammonia** | **Uranium** | **Thorium** | **Source** |
|---|---|---|---|---|---|---|---|---|---|---|
| Formula | - | $C_nH_2n+2$ | $CH_4$ | $H_2$ | $H_2$ | $CH_3OH$ | $NH_3$ | U-235 | Th-233 | |
| Density | Kg/L | 0.84 | 0.42 | 0.07 | 0.04 | 0.79 | 0.68 | 19.1 | 11.7 | [62] |
| Volumetric energy den. | MJ/L | 35.8 | 20.8 | 8.5 | 5.6 | 18.2 | 14.1 | 1.52E+09 | 9.29E+8 | [44] [83] |
| Gravimetric energy den. | MJ/kg | 42.7 | 49.2 | 120 | 120 | 19.9 | 18.6 | 7.94E+07 | 7.94E+07 | [73] [111] |
| TRL | - | 9 | 9 | 6 | 6 | 7 | 5 | $7^a$ | $4^a$ | [62] [22] |
| Flash point | °C | 60 | -188 | -253 | flam. gas$^b$ | 9.7 | 132 | x | x | [75] [117] [70] |
| Storage temperature | °C | 25 | -162 | -253 | 25 | 25 | -33 | 25 | 25 | [39] [99] [62] |
| Storage pressure | bar | 1 | 1 | 1 | 700 | 1 | 1 | 1 | 1 | [39] [99] [62] |
| Storage volume ratio | L/L | 1.1 | $2.4^c$ | $2.1^c$ | $2.4^c$ | 1.1 | $2.0^c$ | x | x | [62][116] |
| Storage gravimetric ratio | kg/kg | 1.4 | 1.7 | 10.3 | 19.2 | 1.3 | 1.6 | x | x | [62] |

$^a$ *The nuclear fuel TRLs are considered for nuclear fuels specifically adjusted for use in Gen IV reactors.*
$^b$ *Gaseous hydrogen is a flammable gas at any temperature. Therefore a flash point temperature is not applicable.*
$^c$ *Fuel to be stored in cylindrical tanks.*

### 4.2.1. Fuel characteristics
In this section, a set of characteristics of each fuel type are discussed. The values of these characteristics are included in the overview of Table 4.1.

#### Densities
The energy density is provided in the lower heating value (LHV). This is defined as the amount of heat released during the combustion of a specific quantity under certain conditions. At LHV, it assumed that the latent heat of vaporization of water in the reaction products is not recovered. The LHVs of the fuels are depicted in table 4.1. An exception has to be made for nuclear since nuclear fuel is not used in a combustion process. Generally, the energy density of a nuclear fuel is measured in its fission yield. The exact fission yield depends on the conditions where this fission reaction takes place. In other words: the fission yield depends on the reactor type the fuel is used in. The Energy density depicted in table 4.1 for uranium and thorium is the theoretical energy density during the maximum fission yield of the material. In section 5 the real energy yield of the fields in different reactors will be discussed. Since the density of the fuels depends on the conditions, the common storage temperature and pressure per fuel is also given in table 4.1. These conditions will be further discussed in the section 4.2.2.

#### Technological Readiness Level
Technological readiness levels (TRL) are part of a measurement system that assesses the level of maturity of a technology. This measurement system originates from NASA. The system allows to compare the progress of different technologies to each other. The system uses TRL level 1 to TRL level 9. The meaning of each TRL level is depicted below [94] [56].

The TRLs depicted in table 4.1 indicate the maturity of the fuel production and distribution processes of the fuel itself. It is important to note that these TRLs refer to fuels specifically ready for the use in the energy converters discussed in 5.3. In 5.3 the TRLs of the energy conversion systems are discussed separately.

- **TRL 1**: Basic principles observed and reported.
- **TRL 2**: Technology concept and/or application formulated.
- **TRL 3**: Experimental proof of concept.
- **TRL 4**: Technology validated in lab.
- **TRL 5**: Technology validated in relevant environment.
- **TRL 6**: Technology demonstration in a relevant environment.
- **TRL 7**: System prototype demonstration in operational environment
- **TRL 8**: System complete and qualified
- **TRL 9**: Actual system proven in operational environment *(competitive manufacturing in the case of key enabling technologies)*

The European Union categorizes TRLs in four phases:

- **Phase 1**: Discovery (TRL 1-3)
- **Phase 2**: Development (TRL 4-6)
- **Phase 3**: Demonstration (TRL 7-8)
- **Phase 4**: Deployment (TRL 9)

#### Flash point
A flash point of a chemical substance is the lowest temperature at which enough vapor forms under normal pressure to create a flammable mixture with the air above the liquid level [123]. The flash point is an important fuel characteristic in terms of safety in the storage and handling of fuel. There are mechanical as well as chemical countermeasures to deal with the flammable vapors of fuels. One of the examples is a nitrogen blanket to shield the vapor from reacting with oxygen [99]. The countermeasures and impact of the flash point temperatures are respectively discussed in 4.2.2 and 4.4.

### 4.2.2. Storage characteristics

In this subsection, the storage conditions and systems for the fuels are considered. Furthermore, an overview of all the storage characteristics is given in table 4.1. The characteristics considered are storage temperature, storage pressure, storage volume ratio, and storage gravimetric ratio. The storage volume ratio is the volume of fuel without storage in comparison to the same amount of fuel contained in a storage system. The storage gravimetric ratio shows the weight of fuel in comparison to the weight of the same amount of fuel contained in a storage system. Additional system volume and weight originate from the tank shape, tank casing, safety measures, and additional components required to maintain storage conditions. The tank shape can have a big impact on the volume of the storage system. Some fuels require a cylindrical shaped tank. Since most compartments of ships are rectangular, such a tank can cause empty space in the compartment [116].

MGO

MGO can be stored in ambient temperature and pressure. MGO is stored in a bunker tank. A bunker tank is generally a hull-integrated storage tank. This means that it uses space between bulkheads or double bottoms as its storage volume. Therefore the storage system is very volumetric efficient [116].

LNG

LNG needs to be stored under a temperature of -162 °C at an ambient pressure of 1 bar. To be able to store fuel at such low temperatures and maintain these conditions, cryogenic storage is required. Cryogenic storage is mostly used to reduce the volume of a fuel that is in gas form at ambient conditions. This volume reduction by cryogenic storage can be up to a factor of 600 compared to the fuel in gas form[29]. Cryogenic storage is done in a cylindrical tank with a cylindrical casing. The space between the tank and its casing consists of isolation. The fuel inside the tank remains at its low temperature by letting the boil-off gas escape from the tank. This method is referred to as auto-refrigeration. Disadvantages of cryogenic storage of LNG are energy loss due to the boil-off process and safety risks during handling of the boil-off gas [34]. This boil-off gas can be used as fuel in an internal combustion engine or can be re-liquefied during an energy-intensive process using cooled nitrogen. Some gas escapes into the atmosphere during handling or combustion. This is called methane slip. As can be seen in table 4.2, releasing the methane ($CH_4$) has a significant effect on global warming [54].

Hydrogen

Pure hydrogen can be stored in two ways on a ship. The first method is as a liquefied gas. The Liquefied storage will be at a low temperature of -253 C under a slightly compressed by 1-10 bar. This storage is cryogenic, and liquefied hydrogen is often abbreviated as $LH_2$. Cryogenic storage is done in similar tanks as described for LNG. Cryogenic storage has relatively high energy compared to compressed hydrogen storage. Cryogenic storage also has some disadvantages. First of all the use of cylindrical storage tanks is usually not a volume-efficient storage method on board a ship. Secondly, the boil-off gas of hydrogen causes a safety risk since the gas is highly flammable. Furthermore, 30-35 percent of the hydrogen's energy is required to liquefy the gas. Which is 3 times as high as the required energy to store the hydrogen in the compressed form [59].

The second method is in the form of compressed gas. The hydrogen is stored at ambient temperature and under high pressure (250-700 bar) [78]. Since the hydrogen molecule is the smallest of all molecules, hydrogen is one of the more challenging gasses to store or transport [78]. Compressed hydrogen is stored in high-pressure tanks. Again a cylindrical tank shape is not ideal on board of a vessel. There are four types of compressed hydrogen storage tanks. Type I is the cheapest but also the heaviest and unable to handle pressure over 300 bar. Type IV is the lightest and able to handle pressure up to 1.000 bar. This makes it suitable for vehicle applications [71]. It must be stated that there is no notable application of compressed hydrogen on commercial vessels yet. Therefore there is no specific information on storing hydrogen at high pressure on board commercial vessels. The first commercial ship on compressed hydrogen received the approval of its design in December 2022 [62].

Methanol

Since methanol is liquid at ambient temperatures and pressures, the storage and transport methods are similar to that of conventional liquid fossil fuels. This can be done volume efficiently [65]. The conventional tanks need to be adjusted with a special coating. The preferred storage location of methanol is often below the waterline. Therefore it is attractive to use a number of ballast tanks as methanol fuel storage. In table 4.1, Due to the low evaporation temperature (flash point) of the liquid methanol, two more adjustments might be required. First, the use of shielding called ”cofferdams” are needed to contain the methanol vapor and shield the fuel from external water mixing with the fuel. Secondly, a nitrogen blanket may be placed to prevent methanol vapor from reacting with oxygen and becoming a flammable mixture [99].

#### Ammonia

Since ammonia has been produced, stored, and used for many decades in the chemical industry, there is a high maturity in the accompanying handling techniques. There are also developed staff training methods, industry codes, and regulations to ensure safety and security. 18-20 Mt of ammonia was transported by ship in 2020. Ammonia is stored in liquid form by refrigeration at -33 °C and at atmospheric pressure [64]. Ammonia is usually stored in 4 types of tanks on board of ships. Type A, Type B, Type C, and membrane tanks. Type A, type B and the membrane tank are suitable for storing ammonia in a liquid form at -33 °C. Type C tank is a pressure tank. In this tank, ammonia can be stored at ambient temperature at a pressure of 8.6 bar [105]. The shape of type A, type B and the membrane tanks can be easily fitted to the shape of the ship’s hull. Type A and membrane tanks must be fully double-walled [2]. Type B requires partial double walling since they are equipped with fatigue analysis tools that can anticipate small leaks using cryogenic barriers and inert shielding gas protection where needed [2]. The type C tank is a pressure tank that is cylindrical, which causes loss of space on board of ships. No double walls are required when using a type C tank. Certain extra safety measures have to be in place when storing the ammonia under pressure [105].

#### Uranium and Thorium

Uranium and thorium are treated and stored similarly. As stated, the fuels are stored in ceramic pellets which are stacked in zirconium alloy tubes [119]. These fuel rods are highly radioactive. Therefore they need to be in a shielded environment [8]. A nuclear ship can operate for around 20 years on one batch of nuclear fuel. Therefore the onboard fuel is stored inside the reactor core [8]. The reactor core is shielded such that no crew is exposed to radiation. The reactor compartments are prohibited for crew [5]. The shielded compartment is water-tide. In case of leakage or even the sinking of the vessel, the compartment should be (salt)water resistant up to high pressure to prevent leakage of radioactive material into the environment [81] [49] [5].

## 4.3. Fuel emissions

Emissions differ per fuel and per process in which the fuel is converted into energy. There are several emission gasses and particles that cause global warming. In this research emissions are stated in the measure of $CO_2$-equivalent ($CO_2eq$). $CO_2eq$ is a metric measurement tool to express the impact on global warming caused by different green house gases (GHG). The impact is based on the global warming potential (GWP) of each gas. The amount of GWP of a gas compared to the GWP of $CO_2$ is the $CO_2eq$ weight of this gas [77]. The GHG’s considered during this research are: carbon dioxide ($CO_2$), Methane ($CH_4$) and Nitrous oxide ($N_2O$). The global warming potential of these gasses is depicted in table 4.2

**Table 4.2:** $CO_2eq$ values of $CH_4$ and $N_2O$

| **GHG** | **$CO_2eq$** |
|---|---|
| $CO_2$ | 1 |
| $CH_4$ | 25 |
| $N_2O$ | 298 |

The $co_2eq$ values can be used to express the impact of the emissions of a certain fuel on global warming. The impact of a certain fuel is given as an emission factor. An emission factor depicts the mass $CO_2eq$ emitted per amount of energy produced ($gCO_2eq$/MJ). Emission factors are generally based on measurements during laboratory experiments. These experiments consists of measuring the GHG emissions while burning a fuel under standardized conditions [55]. The emission factors of the considered fuels are given in 4.3. Note: in Chapter 5 other energy conversion technologies than combustion are discussed. These other methods can also lead to other emissions. These will be discussed in Chapter 5.

**Table 4.3:** GHG emissions during production, and combustion per fuel

| | Production | | | Combustion | | | Total | Source |
|---|---|---|---|---|---|---|---|---|
| [$gCO_2eq$/MJ] | $CO_2$ | $CH_4$ | $N_2O$ | $CO_2$ | $CH_4$ | $N_2O$ | $CO_2eq$ | |
| **MGO** | 14.3 | 0.0 | 0.0 | 75.1 | 0.2 | 1.1 | 90.7 | [74] [62] |
| **LNG** | 13.7 | 4.0 | 0.0 | 57.3 | 1.0 | 0.7 | 76.7 | [74] [62] |
| **E-LNG** | -50.4 | 0.0 | 0.0 | 57.3 | 1.0 | 0.7 | 8.6 | [74] [62] |
| **L.H$_2$** | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | [74] [62] |
| **C.H$_2$** | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | [74] [62] |
| **E-Methanol (DAC)** | -67.5 | 0.0 | 0.0 | 69.7 | 0.2 | 0.7 | 3.1 | [74] [62] |
| **E-Ammonia (DAC)** | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 5.3 | 5.3 | [74] [62] |
| **Uranium**$^a$ | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | [62] |
| **Thorium**$^a$ | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | |

$^a$ Given the table's focus on combustion emissions and the impracticality of using nuclear fuels in combustion, the table presents emissions from conventional nuclear reactor conversion. With the high energy density of nuclear fuels and virtually zero emissions during conversion, it is reasonable to assume close to zero g$CO_2$eq/MJ emissions.

*The scope of this study includes assumptions regarding "Well-To-Wake" emissions. To decrease complexity and uncertainty, the WTW assumptions solely include the emissions during production and conversion. Table 4.3 is used to illustrate the emissions assumed to be accompanying the process of production and combustion of E-fuels. The implication of the table is that E-fuels have (close to-) net-zero emissions. During this study, the presented emissions are assumed as "Well-To-Wake" emissions for the combustion of the fuels.*

In table 4.3, the emissions factors of different fuels during combustion are depicted. The table shows the emission factors of production, and combustion. It is important to note that the total emissions are assumed the sum of production and combustion. First of all, for E-fuels, it is assumed that hydrogen production is powered by renewable energy. Therefore there are no emissions during this process [65]. Secondly, some E-fuels have negative production emissions. This means that the GHGs used as feedstock for the production of the fuels are obtained directly from the environment using Direct Air Capture (DAC). These GHGs are again emitted during conversion, this is depicted in the combustion columns. The total emission column shows the net emissions of these fuels. This can be seen for the E-LNG and E-methanol [62] [74]. Ammonia production consists of a similar method. Nitrogen is captured from the air with a system powered by renewable sources. It is important to note that the nitrogen used as feedstock is not specifically captured as the GHG $N_2O$, therefor this is not included in table 4.3. After the direct air capture of the nitrogen, it is combined with renewable hydrogen in a synthesis process. After using ammonia as a fuel, the nitrogen is again released into the atmosphere, partly as the GHG $N_2O$. [105].

## 4.4. Safety

This section discusses the safety aspects of each fuel. Safety on board of vessels is set to a fixed "equivalent safety" level for different marine fuels, an increase of risk is not tolerated [78]. Comparing fossil fuels and e-fuels to nuclear fuels in terms of safety is difficult because the key safety hazards lie in different areas. For the liquid and gaseous fuels, the hazards can mainly be found in terms of flammability (related to the flash point temperature), reactivity with other materials and health hazards. For nuclear, the hazards are mainly in radioactivity and radioactive contamination of personnel or the environment. Note that the hazards and their ratings discussed in this section are fuel characteristics and not risk assessments. The risk assessments per fuel in combination with various conversion technologies, is described in 5.7.

Exposed nuclear fuel is always an unacceptable safety hazard [8]. The risks accompanied by nuclear propulsion depend highly on the handling of the fuel and the system, regulations, and reactor design. The safety risks of the system are discussed in section 5.7.

The hazards of gaseous and liquid fuels depend on the characteristics of the fuel as well as the experience and safety measures available regarding the specific fuel. A hazard evaluation of the fuel characteristics, while taking into account experience within the industry and available safety measures, is depicted in table 4.4. Here risks are rated using the National Fire Protection Association (NFPA) rating. The NFPA is the biggest fire protection organization in the world. The goal of the NFPA is to reduce the chance of fires and other hazards through education and academic research. The degree to which health, flammability, and reactivity hazards are present is specified. A numerical rating from zero (showing a minimum hazard) to four (representing a severe hazard) is used to describe the severity of the hazard. Health hazards are those classified as toxic, highly toxic, or corrosive material. Flammability hazards are those classified as explosive, flammable cyanogen, flammable gas, flammable solid, and ignitible liquid. Reactivity is classified as an organic peroxide, oxidizing cyanogen, pyrophoric, unstable, or water-reactive material [109].

**Table 4.4:** NFPA hazard ratings of considered fuels

| | Health | Flammability | Reactivity | Special | Source |
|---|---|---|---|---|---|
| **MGO** | 1 | 2 | 0 | - | [28] |
| **LNG** | 3 | 4 | 0 | - | [90] |
| **LH2** | 0 | 4 | 0 | - | [60] |
| **CH2** | 0 | 4 | 0 | - | [60] |
| **Methanol** | 2 | 3 | 0 | - | [101] |
| **Ammonia** | 3 | 1 | 0 | - | [6] |
| **Uranium** | $U^a$ | $U^a$ | $U^a$ | $RAD^b$ | [3] |
| **Thorium** | $U^a$ | $U^a$ | $U^a$ | $RAD^b$ | [50] |

$^a$ = *unkown*
$^b$ = *Radioactive material*

### 4.4.1. MGO

MGO can cause irritation to skin and eyes. MGO may be harmful when swallowed. Personal should wear protective clothing. MGO can ignite if exposed to heat. Proper storage and handling procedures should be followed. Grounding storage container to prevent static discharge and storing away from ignition sources are examples of storage procedures. MGO should be stored in a well ventilated area, as the MGO vapor can ignite. It should be stored protected from heat and moisture. Measures to prevent spills and promptly containment and cleanup of any spillage that occurs should be in place, as MGO can be harmful to aquatic life [28].

### 4.4.2. LNG

Since LNG is a cryogenic liquid, it can inflict frostbite or cold burns when in contact with skin or eyes. Additionally, it is an asphyxiant and can displace oxygen, which can cause suffocation in places with poor ventilation. Users must use proper precautions, including wearing protective clothing and respiratory gear when in direct contact with the fuel. LNG is highly flammable and therefor should be properly stored and handled in a ventilated area away from ignition sources. LNG can be harmful to aquatic life and spillage should be prevented and measures in case of spillage should be present [90].

### 4.4.3. Hydrogen

Hydrogen is highly flammable, ignites easily and might even self-ignite. The combination of these properties causes the use of hydrogen to be an overall risk. To control this risk, safety systems and measures have to be implemented. Since the small size of H2 molecule leakage is a risk. Since hydrogen leakage can potentially lead to a high-risk situation, more sophisticated safety systems are needed for hydrogen compared to other gas fuel systems [78]. Another potential safety hazard is the fact that hydrogen flames are almost invisible [26]. While overall hydrogen is a highly reactive material, it is also commonly used in the chemical industry. Therefore its reactivity is well-understood and can be safely managed with appropriate handling and storage procedures[78]. Hydrogen gas is non-toxic, in extreme situations, it can replace oxygen in the air, which could cause asphyxiation if inhaled in large quantities. Nausea, headaches, and dizziness can occur with exposure to high hydrogen concentrations. Liquid hydrogen is stored under low temperatures. Protective equipment should be worn when handling the liquid [60]. Compressed and liquid hydrogen should be stored in containers that are impact resistant to prevent the high-pressure hydrogen from leaking during an impact [60].

### 4.4.4. Methanol

Methanol is also a highly flammable gas that is toxic and can be can cause serious health effects when ingested, inhaled, or absorbed through the skin. Protective clothing is required. Inert gas is often used to prevent methanol vapour from reacting with oxygen [110]. Methanol can corrode certain metals such as aluminium and zinc. Therefore coatings in equipment and storage units might be necessary. Methanol is toxic to aquatic life and can cause damage if it is released into the water or soil [101].

### 4.4.5. Ammonia

Ammonia is toxic gas in ambient conditions Ammonia's odor is strong and can be detected by most people at low concentrations. Exposure to ammonia should be limited to permissible limits. In low concentrations, ammonia can irritate the eyes lungs and skin. Direct contact with ammonia can be deadly. Ammonia storage is sometimes required to use inert gas shielding to prevent ammonia from reacting with oxygen and forming a flammable mixture [2]. Ammonia is widely used for decades and is commercially available. Due to the maturity of the handling and storage techniques the risks can be limited [105]. Ammonia has the lowest fire hazard risk compared to the other fuels according to NFPA standards. Handling and storage of ammonia should be done by trained personnel wearing protective clothes [6].

# 5
# Energy conversion systems

This chapter introduces the different conversion technologies in section 5.1. Furthermore, the possible energy supply pathways and accompanying efficiencies are discussed in section 5.2. Subsequently, the Technological Readiness Levels of the energy supplies are presented in Section 5.3. Section 5.4 describes the gravimetric and volumetric power densities of the conversion systems. Section 5.5 describes the maintenance requirements of the energy supplies. Section 5.6 discusses the energy supply-specific emissions. Section 5.7 describes the safety and risk assessments of the energy supplies. Finally, Section 5.8 discusses the regulations per fuel used in a conversion system.

## 5.1. Conversion technologies

This section provides a short description of each energy conversion system. Subsection 5.1.1 describes the Internal Combustion Engine. Subsection 5.1.2 describes the Proton Exchange Membrane Fuel Cell (PEMFC), Solid Oxide Fuel Cell (SOFC), and Direct Methanol Fuel Cell (DMFC). Finally, Subsection 5.1.3 describes the working of a Molten Salt Reactor (MSR) and a Very-High Temperature Reactor (VHTR).

### 5.1.1. Internal combustion engine

Internal combustion engines (ICE) are often used on large offshore vessels like the SSCV Sleipnir to transform chemical energy into mechanical energy through a series of combustion reactions inside the engine [53]. There are different types of internal combustion engines.

The first difference is between a 2-stroke and a 4-stroke engine. in a 2-stroke engine, the complete conversion cycle is completed in 2 strokes of the piston, whereas a 4-stroke engine uses 4 strokes of the piston to complete the cycle. The advantage of a 2 stroke is high efficiency. A disadvantage is its low rotational speed and low power density. 2 Stroke engines are mainly used as a direct shaft configuration with the propeller. 4 Stroke engines are more common for the use of generating electricity. [51].

The second difference can be found in spark- or compression-igniting engines. This engine configuration depends on the fuel that is used. Fuels with a high auto-ignition temperature need a spark to promote ignition. Fuels with a low auto-ignition temperature combust at the increased temperature due to the increasing pressure in the combustion chamber without promotion by a spark. The efficiency of a compression engine is usually higher [51].

The engine principles of conventional and common design for offshore vessel propulsion are considered. These engines are 4-stroke, reciprocating, compression ignition engines with stationary cylinders, horizontal driving pistons, and rotating crankshafts located below the cylinder [53]. Similar designs are present at SSCV Sleipnir. The energy conversion process of such an ICE consists of 4 steps. These steps are depicted in figure 5.1 and explained below:

- **Intake stroke:** Air is drawn into the cylinder through an open intake valve.
- **Compression stroke:** The piston compresses the air, increasing the temperature and pressure. At the top of the compression stroke fuel is injected.

- **Power stroke:** Ignition of fuel due to high temperature initiates power stroke. The piston is pushed down due to combustion and expansion of gases. Power is generated.
- **Exhaust stroke:** Exhaust gases are pushed out of the cylinder through the exhaust valve.

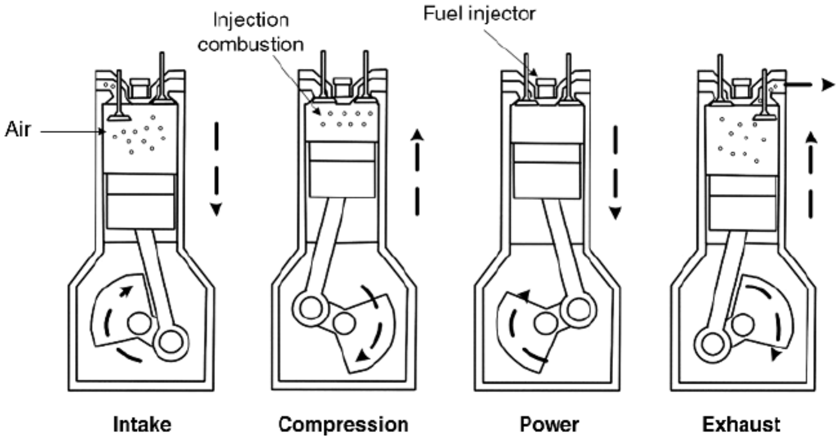


**Figure 5.1:** Schematic overview 4 stroke ignition engine cycle [43]

The mechanical energy will later be transformed into electricity via generators. The generators have a high efficiency (up to 95%) [51]. MGO [53], E-LNG [76], compressed and liquid hydrogen [51], methanol [30] and ammonia [31] are compatible with an ICE under the condition that certain adjustments are made. These adjustments are due to the different characteristics of the fuels, such as energy density, viscosity, ignition characteristics, chemical characteristics, and exhaust characteristics. Adjustment concerns fuel system modifications, combustion adjustments, change of materials/coatings, engine calibration, and exhaust system modifications. The efficiencies concerning the various energy conversion pathways of the different fuels in an ICE differ. The different efficiencies per pathway will be discussed in 5.2.

All E-fuels are in need of a pilot fuel that ignites during the compression step. This will promote the ignition of the E-fuels, which have a higher auto-ignition temperature [76] [76] [30] [31]. Since the combustion of Ammonia in an ICE results in a high amount of $NO_x$ in the exhaust gas, extra exhaust treatment is needed [30].

### 5.1.2. Fuel cells

A fuel cell is an electrochemical device that extracts chemical energy from a fuel and transforms it directly into electricity. Typically this process includes a hydrogen-carrying fuel that reacts with oxygen or another oxidation agent. The output of the reaction is typically $H_2O$, low emissions and electricity at a high efficiency. Fuel cells typically have a low power output. This can be increased by stacking multiple cells in series. The efficiency of fuel cells is typically the highest at low to medium loads. The modular characteristics of a fuel cell make it a redundant energy converter [113]. Proton exchange membrane fuel cells (PEMPC) and solid oxide fuel cells (SOFC) are considered the potentially the most promising fuel cell technologies by market studies as well as studies by DNV [51]. The two fuel cell technologies will be discussed below.

#### Proton exchange membrane fuel cell

The PEM fuel cell is a low-temperature fuel cell that achieves high power density and has a good reaction to changing loads. PEMFCs consist of a cathode and an anode separated by a polymer membrane. At the anode side, hydrogen is fed to the system. The hydrogen atoms are split into electrons and protons by a catalyst. The protons are conducted through the membrane, while the electrons are transported through an external circuit. At the cathode side of the cell, oxygen is introduced to the system. Here the oxygen reacts with the protons from the membrane and the electrons from the external circuit to form water. The transport of the electrons in the external circuit produces electrical power. The water is a rest product of the reaction. The efficiency of a PEMFC is generally around 55% [51].

The working principle of a PEMFC is depicted in figure 5.2. Disadvantages of PEM fuel cells are: complex water management at the operational temperature of 65 to 85 °C, the need of the scarce catalyst material platinum, and the limited tolerance for fuel impurities [113]. To prevent this from happening, the hydrogen fuel needs to be of a high purity level (minimal 99.5%). Because of this requirement, all carbon-containing fuels need to be separated from the hydrogen atoms before the hydrogen can be used in the PEMFC. For methanol and methane, this is done through a steam reformer. Ammonia could potentially work in a PEMFC but the characteristics of the chemical structure of fuel cause corrosion of the material in the cell. Therefore also, for ammonia, the hydrogen atoms need to be isolated before they can be introduced into the PEMFC. There is one exception: methanol can be used directly in a modified fuel cell with the same working principle as a PEMFC. This is called a Direct Methanol fuel cell (DM fuel cell) [113]. The lifetime of a PEMFC varies from a few thousand to tens of thousands of hours of operations depending on: material quality, operating conditions, and maintenance [51].

### Solid oxide fuel cell

SOFC is a high-temperature fuel cell operating at a temperature of 500 to 1000 °C. SOFC offers a higher flexibility of fuel possibilities than a PEMFC. Among others, gasses and liquids like LNG, hydrogen, methanol, LNG, and ammonia can be directly used in the fuel cell [51]. The SOFC has a solid ceramic electrolyte. Solid ceramic is an insulator, therefore, will not conduct electrons. Because of the properties of solid ceramic, it is able to transport oxygen ions. High temperatures are required to gain sufficient oxygen ion conductivity. The working principles of the SOFC are depicted in figure 5.3. Due to the stable solid ceramic electrolyte, the lifetime of a SOFC is the longest of all current fuel cells. An operational lifetime of 60 thousand hours is expected [51]. The efficiency of a SOFC is up to 60% for low-temperature operations and 70% for high-temperature operations [113]. Disadvantages of SOFC are high costs [113], internal reformation of hydrocarbon fuels due to high temperatures and poor dynamic behavior. Currently, there are no SOFCs commercially available [51].

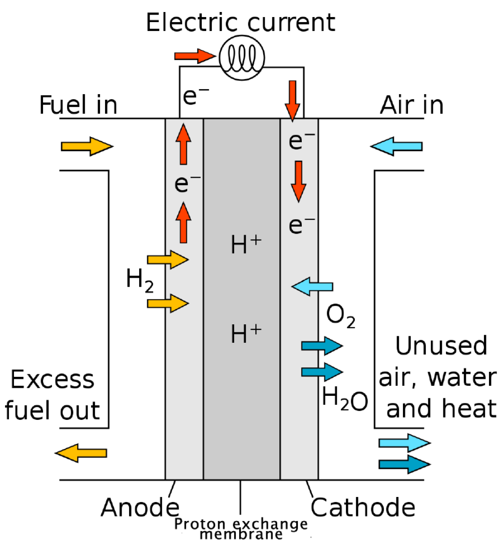


**Figure 5.2:** Working principle of a PEMFC [17]

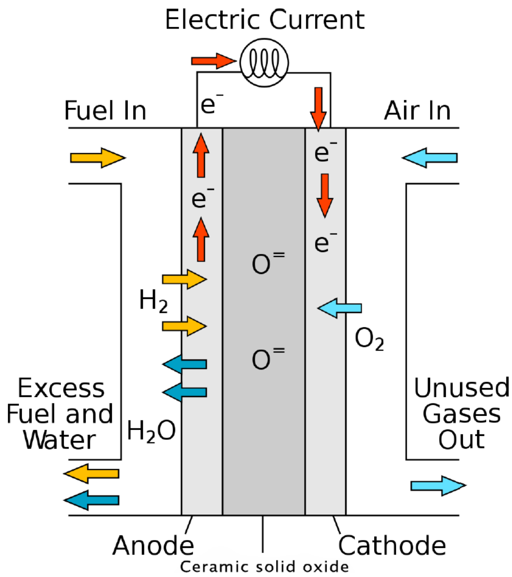


**Figure 5.3:** Working principle of a SOFC [17]

### 5.1.3. Nuclear Reactors

#### Molten Salt Reactor

The molten salt reactor is characterized by its core. The MSR's fuel is dissolved in molten salt. The MSR can use uranium and thorium as fuel [61]. The salt circulates through the system and is heated due to the fission reaction. The heat of the salt is transferred to a steam turbine system which generates electricity. A schematic overview of the system and process is depicted in figure 5.4. A key safety measure is the "Freeze Plug". The freeze plug is an actively cooled piece of ice, which will melt when the salt gets too hot, for example, due to a fission reaction which is out of control. with the melting of the plug, the salt with the dissolved fuel will flow out of the core and into the emergency dump tanks. This will stop the reaction. This makes the MSR design passively safe. The modular design of the MSR makes the reactor suitable for application on ships and has a positive effect on the maintenance requirements [49].

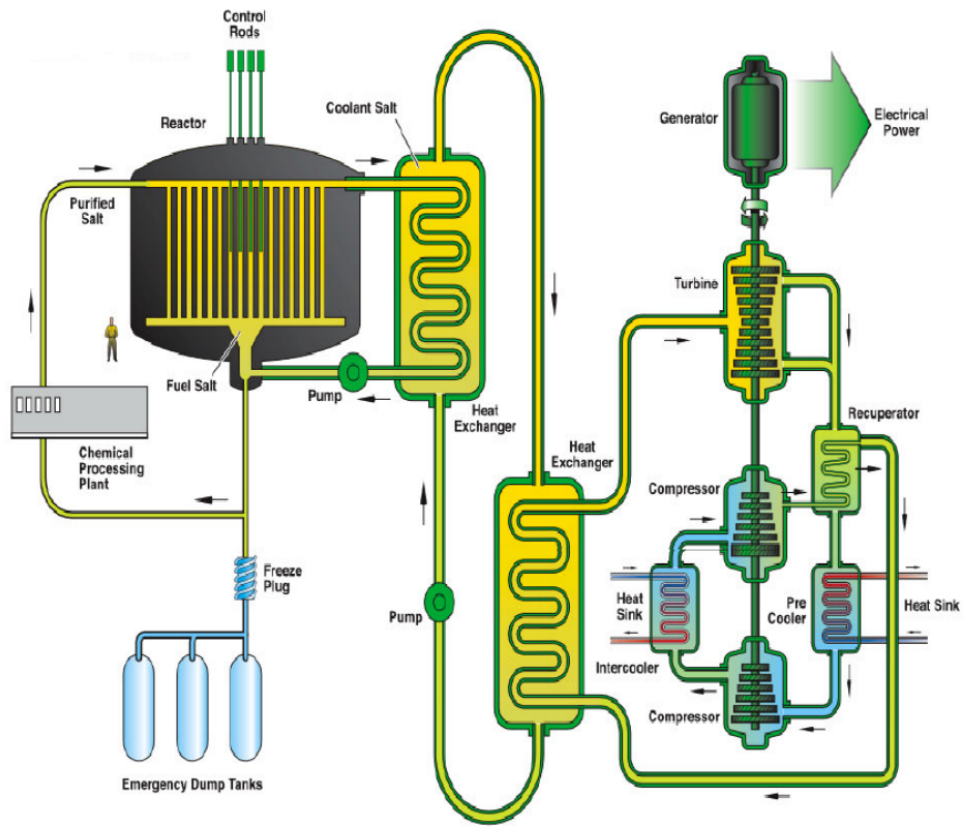


**Figure 5.4:** Schematic overview MSR used for electricity production[61]

#### Very-High-Temperature Reactor

Very-High-Temperature Reactor (VHTR) is, like the MSR, a generation IV reactor design. The VHTR is a thermal (above 1000 °C) reactor design which is cooled by helium gas and moderated by solid graphite [61][82]. The TRI-structural ISOtropic (TRISO) coated fuel is located in the core. The fission reaction heats the helium coolant gas, which transfers the heat via a heat exchanger to the next step. The VHTR is primarily used to generate electricity and hydrogen using high-temperature heat [61]. A schematic overview of a VHTR system used to produce hydrogen is depicted in figure 5.5. The core layout allows the heat to decay through natural convection in case of failure. VHTR has the potential to be inherently safe. VHTR have a high thermal efficiency and modular construction [61].

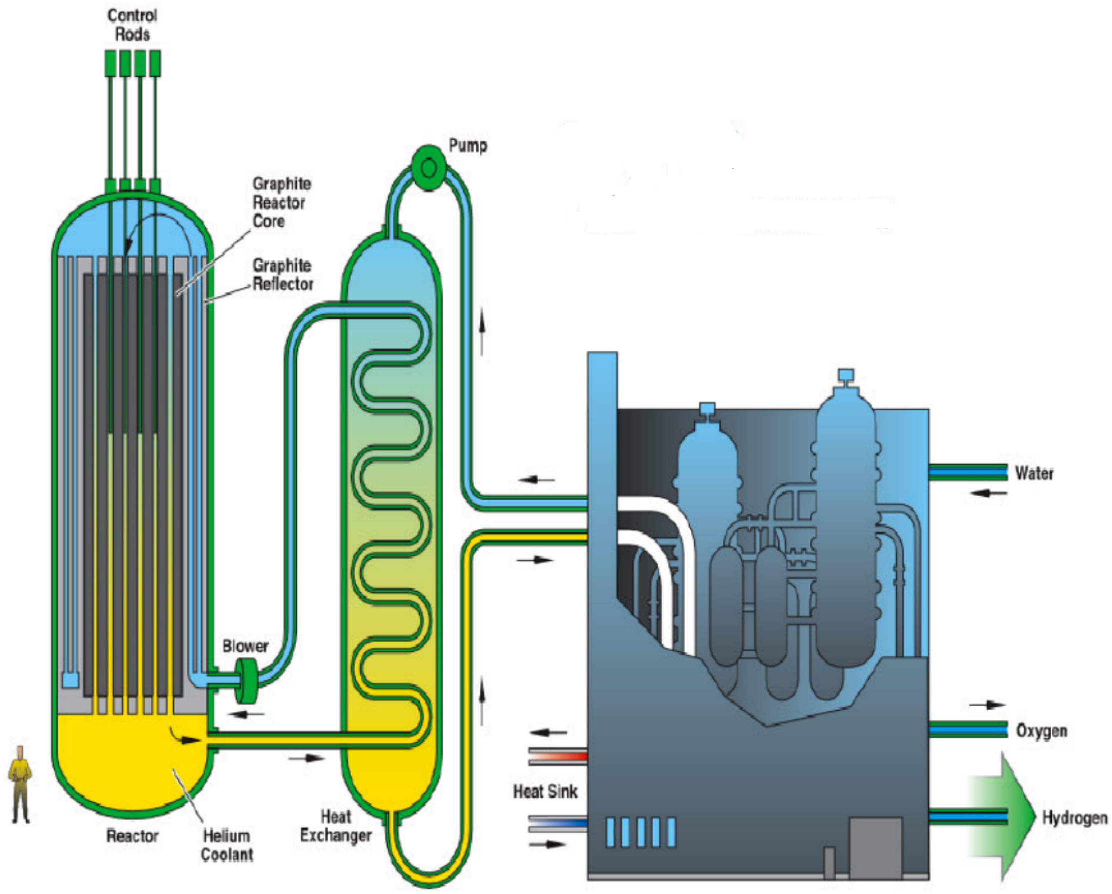


**Figure 5.5:** Schematic overview VHTR used for hydrogen production [61]

## 5.2. Energy supply pathways and efficiencies

The discussed fuels can be converted into electrical energy via the discussed energy converters. The fuel-, conversion system combinations for this conversion are discussed in this section. The efficiency of the converter is depending on the fuel utilized. A schematic overview of the possible energy supply pathways and accompanying generally assumed efficiencies are presented in figure 5.2.

### 5.2.1. Energy supplies types and general efficiencies

#### Internal Combustion Engine energy supplies

The fuel conversion efficiency of MGO in a state-of-the-art 4-stroke internal combustion engine is 45% [88]. The fuel conversion efficiency of LNG in a 4-stroke internal combustion engine is 38% [15]. The fuel conversion efficiency of hydrogen in an internal combustion engine is tested at 42% [85]. The overall fuel conversion efficiency of methanol in an internal combustion engine is 40% [125]. The fuel conversion energy of ammonia in an internal combustion engine is 50% [122]. During this research it is assumed that the efficiencies using these different fuels occur in similar load conditions.

#### Fuel Cell energy supplies

The theoretical efficiency of hydrogen in a PEMFC is 83%. In practice, the overall efficiency of hydrogen in a PEMFC during operations is 60%. [113] [124]. Methanol can be used in a direct methanol fuel cell (DMFC), which has a similar design to a PEMFC. DMFC has an efficiency of 20% [102]. All gaseous and liquid fuels included in this research can be used in a high-temperature SOFC [51]. Research by L. van Biert considers the efficiency of MGO in a SOFC. In the research, the efficiency of MGO in a SOFC is set at 50% [113]. The efficiency of hydrogen in a SOFC is between 60% to 70% depending on the operation temperature [113] [89]. The overall conversion efficiency of methanol in a SOFC is 54% [126].

### Indirect energy supplies

As stated in section 5.1.2 carbon-based fuels need to be reformed into hydrogen before being used in a PEMFC. Ammonia needs to be cracked to separate the hydrogen atoms before they can be used in a PEMFC. The steam methane reformer process has an efficiency of 70% [104] to 90% [20] depending on the carbon-based fuel. The efficiency of the high-temperature ammonia cracking process is 72% [25]. When integrating the cracking/reforming step efficiency with the PEMFC hydrogen conversion efficiency, the total efficiencies per fuel are LNG 42%, Hydrogen 60%, Methanol 54%, and Ammonia 43%. Apart from using the reformed and cracked fuels in a PEMFC, The obtained hydrogen can also be used in a SOFC or an ICE. These indirect energy supplies are accompanied by fuel-specific total efficiencies. During this research, these energy supplies will be referred to as indirect. The abbreviations used are ICE (indirect), PEMFC (indirect), and SOFC (indirect).

### Nuclear energy supplies

The fuel conversion efficiency of the nuclear fission reactions is not included in this research. It is assumed that because of the extremely high energy density of the fuel, potential losses during fuel conversion will not be problematic. The heat generated in a nuclear MSR and VHTR is transferred to a steam turbine system. The steam turbine converts the heat into electricity with an efficiency of 33% [15]. Generally, steam turbines using a Brayton cycle principle are suggested to convert heat from a MSR or VHTR to electricity [67]. This type of steam turbine will be considered during this research.

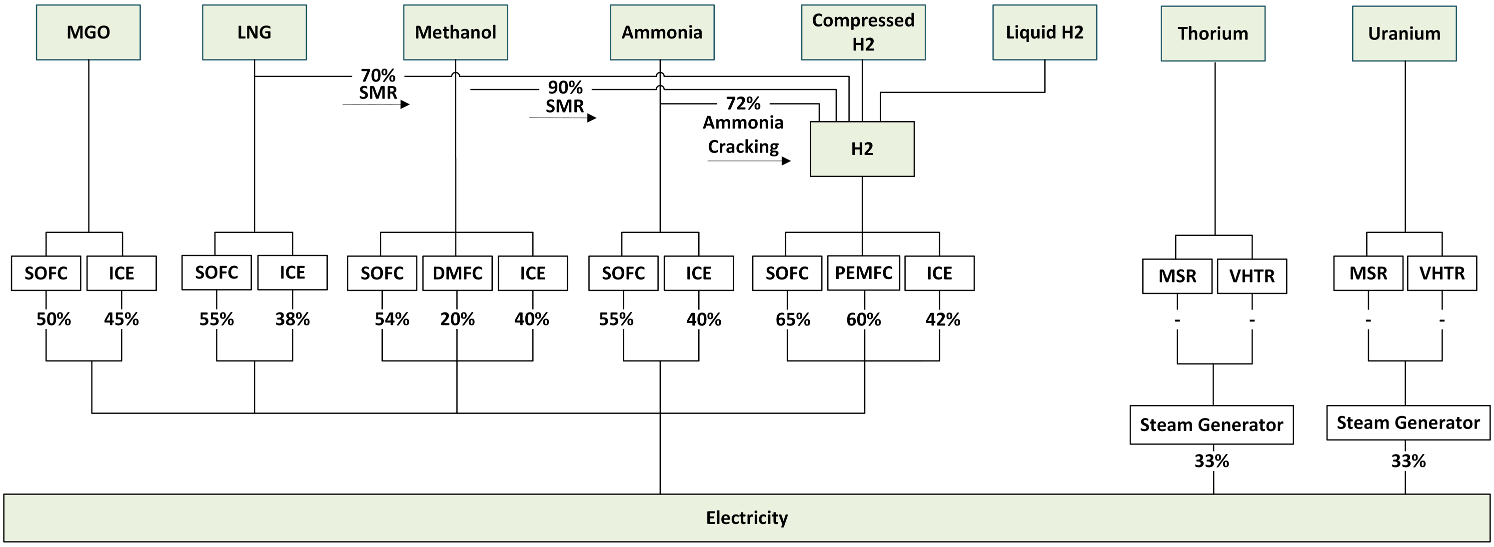


**Figure 5.6:** Energy conversion pathways including efficiencies

## 5.2.2. SSCV's operational profile specific efficiencies

Note that all of the above-stated efficiencies are the general efficiencies for specific energy converters. When considering specific operational loads and behavior, the efficiencies will differ from the general values. Therefore it is important to study the behavior of the efficiencies under different loads. Figure 5.7 shows the development of the efficiency per energy conversion system under different loads. The efficiencies also depend on the fuel used in the conversion system. The data presented in figure 5.7 is based on an ICE running MGO, PEMFC, and SOFC running on hydrogen, DMFC running on methanol, and a Brayton Cycle Steam Turbine running on the heat produced by any nuclear reactor [18][67][14].

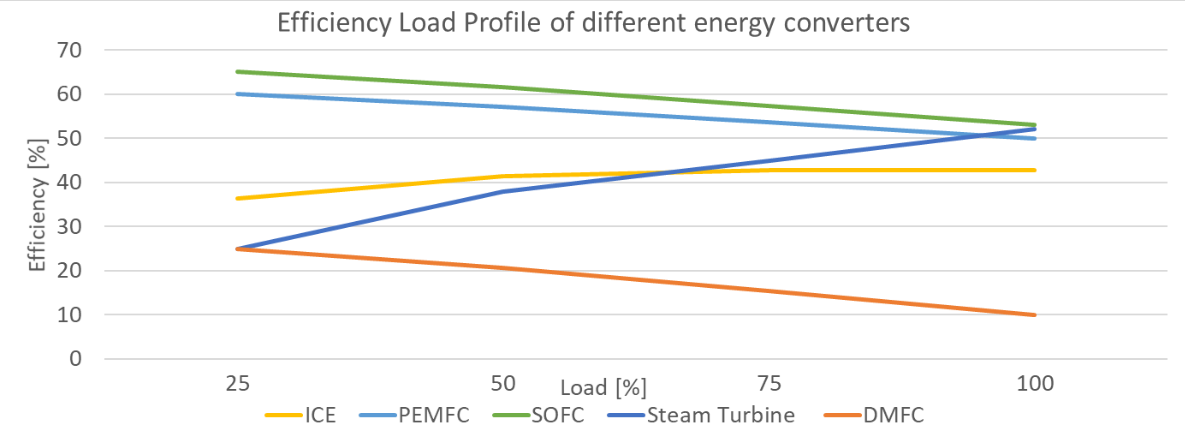


**Figure 5.7:** Efficiency Load Profile of different energy converters [18][67][14]

Note that the steam turbine efficiency again is considered as the efficiency for the nuclear pathways. Furthermore, the graph shows that fuel cells experience a decrease in efficiency under an increasing load, while the combustion engine and the steam turbine experience an increasing efficiency when the load increases. During this research, the efficiencies of the steam methane reformer and ammonia cracker are assumed to be constant. The calculation and values regarding the operational-specific efficiencies regard are described and presented in Section 8.1.

## 5.3. Technological Readiness Levels

The technological readiness levels of the different energy converters in combination with different fuels are depicted in table 5.1. The TRL of Steam Methane Reformer is 9 [20]. The TRL of ammonia cracking technology is 3 [122]. The TRLS of energy supplies that include ammonia cracking are therefore limited by the low TRL of the ammonia cracking technology.

**Table 5.1:** TRL of various energy conversion systems and fuel pathways.

| | ICE | PEMFC | SOFC | DMFC | ICE (indirect) | ICE (indirect) | ICE (indirect) | MSR | VHTR |
|---|---|---|---|---|---|---|---|---|---|
| **MGO** | 9 | - | 5 | - | - | - | - | - | - |
| **LNG** | 9 | - | 5 | - | 6 | 7 | 5 | - | - |
| **LH$_2$** | 6$^c$ | 6$^c$ | 5 | - | - | - | - | - | - |
| **CH$_2$** | 6$^c$ | 6$^c$ | 5 | - | - | - | - | - | - |
| **Methanol** | 7 | - | 5 | 5 | 6 | 7 | 5 | - | - |
| **Ammonia** | 5 | - | 4 | - | 3 | 3 | 3 | - | - |
| **Uranium** | - | - | - | - | - | - | - | 3 | 5 |
| **Thorium** | - | - | - | - | - | - | - | 3 | 4$^c$ |
| **Source** | [62] | [62] [57] | [62] | [62] | [20][122] | [20][122] | [20][122] | [61] [48] | [61] [48] |

$^a$ *General TRL for conversion technique (not fuel specific).*
$^b$ *Conversion pathway limited by TRL ammonia cracking of level 3 (explained in 5.6) [57].*
$^c$ *TRL of energy supply limited by the TRL of the fuel.*

## 5.4. Power densities

The gravimetric and volumetric power density of a conversion system describes the weight and volume, respectively, of a conversion system divided by its power. These characteristics can be used to determine the weight and volume of the energy supply. These power densities include the weight and volume of additional auxiliary systems. Table 5.2 represents these gravimetric and volumetric energy densities per energy supply.

**Table 5.2:** Gravimetric and volumetric power density of conversion systems.

| | **Grav. power density** [kg/kw] | **Vol. power density** [l/kw] | **Source** |
|---|---|---|---|
| **ICE** | 11 | 18 | [62] |
| **PEMFC** | 18 | 29 | [62] |
| **SOFC** | 60 | 110 | [62] |
| **DMFC** | 18 | 29 | [62] |
| **MSR**[a] | 266 | 159 | [58] |
| **VHTR**[a] | 316 | 185 | [58] |
| **SMR** | 29 | 26 | [62] |
| **Ammonia Cracker** | 22 | 50 | [62] |

[a] *The gravimetric and volumetric power density values of the nuclear conversion systems include the steam generator system.*

## 5.5. Maintenance requirements

Another important characteristic of an energy supply is the maintenance requirement of a system. Maintenance requirements can be measured on different aspects. During this research, the relative maintenance requirements of the different energy supplies are based on the yearly maintenance costs of each system. To facilitate this requirement, a power demand of 96 MW is considered for all energy supplies. The maintenance requirements expressed in yearly costs per system are presented in Table 5.3. The presented values include maintenance cost of the conversion system as well as the maintenance costs of the storage facility.

**Table 5.3:** Yearly maintenance costs of different energy supplies of 96 MW [million euro/year].

| [M€/year] | **ICE** | **PEMFC** | **SOFC** | **DMFC** | **ICE (indirect)** | **PEMFC (indirect)** | **SOFC (indirect)** | **MSR** | **VHTR** |
|---|---|---|---|---|---|---|---|---|---|
| **MGO** | 0.50 | - | 1.27 | - | - | - | - | - | - |
| **LNG** | 1.53 | - | 1.34 | - | 1.40 | 1.40 | 1.40 | - | - |
| **$LH_2$** | 2.29 | 1.96 | 1.79 | - | - | - | - | - | - |
| **$CH_2$** | 2.29 | 1.96 | 1.79 | - | - | - | - | - | - |
| **Methanol** | 0.93 | - | 1.34 | 8.21 | 1.39 | 1.39 | 1.39 | - | - |
| **Ammonia** | 1.24 | - | 1.35 | - | 1.39 | 1.38 | 1.38 | - | - |
| **Uranium** | - | - | - | - | - | - | - | 9.72 | 9.72 |
| **Thorium** | - | - | - | - | - | - | - | 9.72 | 9.72 |
| **Source** | [19] | [18] | [68] | [18] | [19] [21] | [18] [21] | [21] [68] | [58] | [58] |

## 5.6. Energy supply emissions

The emissions of each pathway depend on the fuel and the conversion technology. The emission depicted in table 4.3 represents the GHG emissions during combustion in an ICE. Table 5.4 shows the emissions per energy supply when the efficiency losses by the conversion system are included.

Steam methane reformer technology is able to separate carbon atoms from hydrogen from carbon-based fuels. The $CO_2$ atoms can be concentrated, captured, and stored as a rest product. The steam methane reformer technology is a well-established technology within the hydrogen industry. The TRL of the steam methane reformer technology depends on the specifics and is between TRL 7 and TRL 9 [84]. In this process, a carbon capture storage system is coupled to each point where $CO_2$ is released. Therefore the emissions of a steam methane reformer are zero [84].

Ammonia cracker technology has a TRL of 3. EU is currently issuing budgets for research into ammonia cracker efficiencies and emissions [57]. Because of a lack of current knowledge, it is unknown what the exact GHG emission will be during the cracking process. During this research, it is assumed that these emissions will be zero. This is partly due to the fact that the rest products of the reformer are pure chemical materials that generally can be captured and stored more easily than the rest products of combustion processes [25]. The reaction equation of the cracking process is depicted in 5.1.

$$2NH_3 + (3/2)O_2 -> N_2 + 3H_2O \tag{5.1}$$

Definite direct methanol fuel cell (DMFC) technology emissions are also still unknown. During this study, it is assumed that the emissions of DMFC will be zero. This is because the rest product of the fuel cell is chemical pure $CO_2$ and can be captured and stored more easily than the rest products of combustion processes [102]. The reaction equation of the cracking process is depicted in 5.2.

$$CH_3OH + 1.5O_2 -> 2H_2O + CO_2 \tag{5.2}$$

**Table 5.4:** GHG emissions of energy conversion pathways when efficiency losses included. [gCO$_{2eq}$ / MJ$_{effective}$ ]

| [gCO$_{2eq}$ / MJ$_{effective}$] | ICE | PEMFC | SOFC | DMFC | ICE (indirect) | PEMFC (indirect) | SOFC (indirect) | MSR | VHTR |
|---|---|---|---|---|---|---|---|---|---|
| **MGO** | 201.5 | - | 0.0 | - | - | - | - | - | - |
| **LNG** | 201.8 | - | 0.0 | - | - | - | - | - | - |
| **LNG** | 22.6 | - | 0.0 | - | 0.0 | 0.0 | 0.0 | - | - |
| **LH$_2$** | 0.0 | 0.0 | 0.0 | - | - | - | - | - | - |
| **CH$_2$** | 0.0 | 0.0 | 0.0 | - | - | - | - | - | - |
| **Methanol** | 7.7 | - | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | - | - |
| **Ammonia** | 13.3 | - | 0.0 | - | 0.0 | 0.0 | 0.0 | - | - |
| **Uranium** | - | - | - | - | - | - | - | 0.0 | 0.0 |
| **Thorium** | - | - | - | - | - | - | - | 0.0 | 0.0 |

# 5.7. Safety

## 5.7.1. Fossil- and e-fuels safety

MGO is widely used in ICE conversion systems in the marine industry. Therefore, the safety standards and regulations are detailed and highly mature. Proper fuel handling on board vessels is essential to avoid spills, leaks, and contamination, as MGO is harmful to personnel and the aquatic environment. All engine crew must receive proper and regular training [46].

The handling, storage, and use of (E-)fuels have been assessed by a study by the safety consortium ”Together in Safety” [110]. The fuels included in the research are LNG, hydrogen, methanol, and ammonia. The risk is assessed in four categories: navigation, external events, ship operations, and bunkering. The study combines the change of occurrence of an incident with the consequences of this specific incident. The rating of the risks differs from 1, ”broadly acceptable,” to 3, ”intolerable risk”. As can be seen in table 5.5 all risks are within the acceptable range. Navigation risks cover scenarios where the vessel's navigation is made difficult or impossible due to malfunctions or weather and sea conditions. External events include collisions with other vessels or ignition near the fuel storage. Ship operations include operations and propulsion handling by trained and untrained crew. Cargo operations near the fuel and propulsion systems are also included. Bunkering considers risk scenarios while bunkering. Fuel preparation, use, and monitoring regard loss of power on the ship and loss of monitor and control systems. Finally, end-of-life considers the consequences when the propulsion system is scrapped.

LNG and hydrogen are rated similar in terms of risk. LNG has a lower risk in navigation. This originates from the scenario considering the loss of tank pressure control, tank breach, and loss of propulsion [110]. Methanol conversion systems are considered to have the lowest risks of the options in table 5.5. Only during bunkering, it has a higher risk rating than LNG and hydrogen [110]. Ammonia has some risks that are classified as ”high/tolerable”. This mainly originates from hazards such as grounding, collision leading to hull breach and leaks, or loss of containment during bunkering. Safety equipment and more extensive training for the crew could lower this risk rating [110].

**Table 5.5:** Risk assessment different energy supplies

| | LNG | Hydrogen | Methanol | Ammonia | Source |
|---|---|---|---|---|---|
| **Navigation** | 1.4 | 1.5 | 1.1 | 1.8 | [110] |
| **External events** | 1.5 | 1.5 | 1.3 | 1.8 | [110] |
| **Ship operations** | 1.8 | 1.8 | 1.4 | 2.0 | [110] |
| **Bunkering** | 1.0 | 1.0 | 1.7 | 2.2 | [110] |
| **Fuel prep., use and monitoring** | 1.0 | 1.0 | 1.0 | 1.0 | [110] |
| **End of life** | 2.0 | 2.0 | 2.0 | 2.0 | [110] |

### 5.7.2. Nuclear safety

The risk assessment of nuclear energy conversion systems has different key aspects than systems on combustion or electrochemical fuels. For example, the difference between the impact of a flammable hazard and a radiation hazard. Therefore the systems will not be compared on the same scale. A study by the Nuclear Innovation and Research Office (NIRO) assessed the key aspects of different modular reactors [61]. In terms of risk assessments, three overall aspects can be determined: ”safety”, ”security” and ”waste & environment”. NIRO assessed the safety, security and waste & environmental risks of each reactor an a scale of very high (4), high (3), medium (2) and low (1). Table 5.6 depicts the assessed risks.

MSR’s medium degree of safety is partly due to the limited experience. The fact that MSR operates near atmospheric pressure has a positive effect on its safety. THe MSR design is expected to be inherently safe. In case of overheating the salt (the reaction medium) will be passively removed from the system. Since the freezing point of salt is high, there is a safety concern concerning solidification and blocking during cooldown faults, which may limit passive safety. The need for salt purification to prevent corrosion of the system can be problematic. In terms of security MSR’s score is also ”medium”. There is a relatively high risk of the possibility to reproduce certain parts and materials by risky parties or institutions. The nature of the fuel composition that is used might reduce the barriers to accessing highly fissile and radioactive materials. Security and safeguards need to be designed to offer adequate protection. Finally, waste & environmental scores ”high”. MSRs produce a relatively low volume of radioactive waste. Although, a new waste management infrastructure is needed to process the contaminated salt during decommissioning [61].

VHTR’s high degree of safety is partly because of the knowledge and experience derived from the use of High-Temperature-Gas-Cooled reactors (HTGR). These reactors work on the same principle, only at lower temperatures. VHTRs are designed to be passively safe and avoid the release of fission/radiation under all normal and fault conditions. These positive characteristics are due to the robust nature of the fuel and installed passive safety features in the reactor design. In terms of security VHTR’s score ”very high” in terms of protection against the reproduction of certain parts and materials by risky parties or institutions. VHTR’s score ”high” in terms of protection against sabotage. Finally, waste & environment scores ”medium” due to the relatively high volumes of radioactive waste and the low experience with pre-conditioning and disposing of the specific pre-treated fuel [61].

**Table 5.6:** Risk assessment nuclear reactors by NIRO

| | MSR | VHTR | Source |
|---|---|---|---|
| **Safety** | Medium | Very High | [61] |
| **Security** | Medium | Very High | [61] |
| **Waste & Environment** | High | Medium | [61] |

## 5.8. Regulations

First, the existing and planned regulatory frameworks within the offshore/shipping sector related to ETS and GHG emission reduction are discussed. Secondly, the regulations regarding the use of energy supplies within the marine environment are discussed.

### 5.8.1. ETS and emission reduction regulations

There are two main authorities regarding international offshore/shipping that have the ambition to reduce emissions: IMO and the European Union. The IMO has set ambitions to reduce 50% of the emissions by 2050 [63]. The IMO has not been able to implement any definite regulations until currently [33]. The European Union plans to integrate offshore/shipping in the emission trading system (ETS), in approximately 2027 for offshore vessels. This system provides the industry with a limited amount of emission credits. These credits represent the allowed amount of carbon emissions by the company that possesses them [41]. Initially, ETS will only tax carbon emissions. The EU is expected to expand the system to include methane and nitrous oxide starting from 2027 [33] [40]. It is important to note that all E-fuels, where the carbon feedstock is obtained in a renewable way, are expected to be excluded from the ETS regulation [32].

### 5.8.2. Fossil- and e-fuels regulations

MGO will be included in the ETS system since it is carbon-based and not produced with renewable energy. MGO regulations regarding fuel handling on ships are well-established. The MGO fuel quality needs to be of a certain level. This is to avoid engine damage and maintain compliance with prescribed MGO emissions. Effective fuel treatment, including filtration and centrifugation, will remove contaminants and water from the fuel before it is injected into the engine. Keeping accurate records of fuel consumption, treatment, and quality is essential for compliance with regulations [46].

LNG regulations are set in place by the IMO in the *"International Code of Safety for Ship Using Gases or Other Low-flashpoint Fuels"* (IGF Code). The regulations encourage designers to adopt a risk-based design approach that fulfills the functional requirements [110]. When E-LNG is considered, the EU does not include the TTW emissions to the ETS or carbon tax regulations [32].

Regarding compressed and liquid hydrogen, although they are being developed, there are no international regulations and guidelines available for their use as a fuel in the marine environment yet [110].

There are well-established international regulations and Class rules for the use of Methanol as fuel onboard vessels. In contrast to the other E-fuels, methanol is liquid under ambient conditions. Methanol's flash point remains under 60° C. Therefore, additional fire prevention is obligatory during handling and storage. Typically methanol tanks are surrounded by cofferdams and have inert gas shielding the vapor space above the fuel. IMO regulations allow methanol storage against the shell when the tank is situated below the lowest possible waterline[110].

For ammonia, the framework of regulations, rules, and guidelines regarding the use of ammonia as fuel is still under development. Liquid ammonia has been carried in bulk onboard ships as cargo and the lessons learned from this industry should be considered [110].

### 5.8.3. Nuclear regulations

Regulations concerning the use of nuclear energy conversion on vessels are important for the development of these systems. Different institutes are focusing on the principles and regulations of nuclear at sea. The International Atomic Energy Agency (IAEA) published 10 key principles. These principles concern safety and security for people and the planet. The IMO integrated the regulation framework SOLAS chap VIII into their guidelines. These regulations date back to 1980 and are not fit for the current and future reactor designs. Some countries have national regulation institutes in place that regulate and control navel nuclear power. Nevertheless, these regulations are only applicable to national waters. The lack of international regulations remains a problem. For offshore vessels like the SSCV, uncertainty concerning regulations can be a risk. For example, when Sleipnir is not allowed to enter the harbor, which is required for Heerema's operations [108].

# 6 Financial assessment

This chapter describes the approximation of the financial impact of each energy supply. The Capital Expenditures (CAPEX) are discussed in Section 6.1. The Operating Expenditure (OPEX) is discussed in Section 6.2. and Levelized Cost of Energy (LCOE) is discussed in Section 6.3. In these sections the specific financial impact for the considered SSCV is approached. Finally, the some take-aways regarding the presented data will be discussed in Section 6.4.

The financial impact is an important aspect regarding the design choice for an energy supply. Three main aspects of this financial approximation are considered: Capital Expenditure (CAPEX), Operating Expenditure (OPEX), and Levelized Cost of Energy (LCOE). During these approximations, financial forecasts will be made, which are accompanied by a level of uncertainty. Three different forecast scenarios are used to take this uncertainty into account. These forecast scenarios range from low-, mid- to high-cost expectations.

## 6.1. CAPEX

Capital Expenditure (CAPEX) refers to the funds spent by a business to buy, enhance, or maintain physical assets per year. In the case of an energy supply, this mainly concerns the initial investment cost of the complete system. This concerns the initial investments associated with energy converters and storage facilities, including essential auxiliary systems. Furthermore, when necessary, the capital investment also includes other additional systems, such as steam methane reformers or ammonia crackers. For the financial approximations, three scenarios are used. The expected CAPEX ranges between low and high forecasts. The CAPEX of the storage systems depicted in table 6.1 presented in the unit [Euro/kWh]. Be aware that, since nuclear fuel is stored inside the reactor, there are no additional storage facility costs for nuclear reactors. Both tables also include the expected lifetime of each component. CAPEX of the energy conversion systems is depicted in Table 6.2 and presented in the unit [Euro/kW].

**Table 6.1:** CAPEX of storage facility per fuel.

| | Cost [Euro/kWh] | | | Lifetime [Years] | Source |
|---|---|---|---|---|---|
| | **Low** | **Mid** | **High** | | |
| MGO | 0.07 | 0.08 | 0.10 | 30 | [13] [68] |
| LNG | 0.11 | 0.14 | 0.17 | 20 | [13] [68] |
| Hydrogen | 0.66 | 0.83 | 1.00 | 20 | [13] [68] |
| Methanol | 0.11 | 0.14 | 0.17 | 30 | [13] [68] |
| Ammonia | 0.12 | 0.15 | 0.18 | 25 | [13] [68] |

**Table 6.2:** CAPEX and expected lifetime per energy conversion unit

| | Cost [Euro/kW] | | | Lifetime [Years] | Source |
|---|---|---|---|---|---|
| **ICE** | **Low** | **Mid** | **High** | | |
| MGO | 192 | 240 | 288 | 20 | [68] [13] |
| E-LNG | 376 | 470 | 564 | 20 | [68] [13] |
| Hydrogen | 376 | 470 | 564 | 20 | [68] [13] |
| Methanol | 212 | 265 | 318 | 20 | [68] [13] |
| Ammonia | 296 | 370 | 444 | 20 | [68] [13] |
| **PEMFC** | | | | | |
| Hydrogen | 584 | 730 | 876 | 20 | [37] [13] |
| **DMFC** | | | | | |
| Methanol | 1320 | 1650 | 1980 | 20 | [103] |
| **SOFC** | | | | | |
| MGO | 1024 | 1280 | 1536 | 20 | [37] [13] |
| E-LNG | 1024 | 1280 | 1536 | 20 | [37] [13] |
| Hydrogen | 1024 | 1280 | 1536 | 20 | [37] [13] |
| Methanol | 1024 | 1280 | 1536 | 20 | [37] [13] |
| Ammonia | 1024 | 1280 | 1536 | 20 | [37] [13] |
| **Nuclear** | | | | | |
| Nuclear MSR | 4800 | 6000 | 7200 | 20 | [58] |
| Nuclear VHSR | 4800 | 6000 | 7200 | 20 | [58] |
| **Additional** | | | | | |
| Steam Methane Ref. | 296 | 370 | 444 | 10 | [84] [13] |
| Ammonia Cracker | 200 | 250 | 300 | 10 | [122] [13] |

*Note: The conversion system's lifetime varies based on how frequently and intensively it is used. it is worth noting that the estimated lifespan of the PEMFC and SOFC is derived from a study commissioned by the U.S. Department of Energy in 2016 [37]. Due to the fast ongoing advancements of fuel-cell technology, improved durability may be expected.*

Since the required installed power and storage capacity differ per system due to variations in efficiencies, these CAPEX are sized per system to facilitate comparison. The average expected CAPEX per energy pathway in the first year (t=1) is presented in figure 6.1. Note that depending on the expected lifetime some components require new investments earlier than other components. These characteristics are included when calculating LCOE.

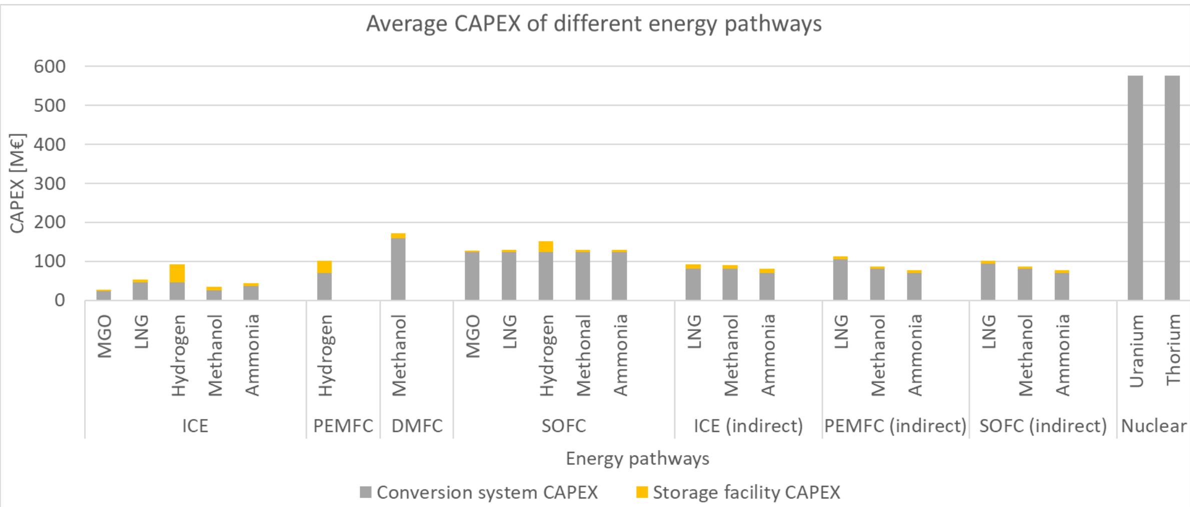


**Figure 6.1:** Average CAPEX of different energy pathways [$10^6$ Euro]

## 6.2. OPEX

Operating Expenditure (OPEX), are continuing costs for a business or project due to regular ongoing operations. These costs don't include capital or one-time investments, but ongoing costs like payroll, maintenance, utilities, and other necessary operational costs. For an energy conversion system, the main OPEX are identified as fuel and maintenance costs [67].

### 6.2.1. Fuel costs

The first part of the OPEX consists of fuel costs. When considering the fuel costs over the lifetime of an energy supply, a high level of uncertainty should be kept in mind. Fuel price projections are done by DNV in the "Marine Forecast to 2050" report [33]. The forecasts again use the high, mid, and low scenarios. Also, historic fuel prices from 2019 are considered [13]. The discussed fuel prices are depicted in table 6.3. First, note that the price of E-ammonia is expected to be lower than the price of E-hydrogen. These expectations are based on the assumption that due to the difference in density between ammonia and hydrogen, E-ammonia is cheaper to store and transport than E-hydrogen [36] [24]. Secondly, note that the nuclear fuel prices are relatively low compared to other fuels. This is due to the high energy density of the fuel and the enriched uranium fuel price of between €2300,- to €9500,- per kg, and the enriched thorium fuel price of €140,- to €560,- per kg [58].

It is important to note that, while ETS is a criterion considered in the decision-making method described in chapter 7 to 9, this research does not incorporate the quantification of the financial impact of ETS. This exclusion is due to the uncertainty of the ETS price and the assumption that it only applies to MGO energy supplies, which are solely used as base case scenarios and are not regarded as potential future energy supplies due to their fossil nature. Keep in mind that the ETS regulations will be applicable starting from 2026 for offshore vessels, and therefore, the total fuel costs of MGO are expected to be higher in reality. The MGO fuel price considered is only used as a reference value regarding the current situation. The high and low expected fuel price developments are presented in table 6.3 and figure 6.2.

**Table 6.3:** Current and expected fuel price scenarios

| | Fuel prices [Euro/kWh] | | | | | | Source |
|---|---|---|---|---|---|---|---|
| | 2019 | | | 2050 | | | |
| | **Low** | **Mid** | **High** | **Low** | **Mid** | **High** | |
| MGO$^a$ | 0.05 | 0.05 | 0.05 | 0.03 | 0.04 | 0.06 | [13] [33] |
| E-LNG | 0.10 | 0.16 | 0.18 | 0.09 | 0.12 | 0.16 | [13] [33] |
| E-Hydrogen | 0.09 | 0.13 | 0.18 | 0.08 | 0.12 | 0.15 | [13] [33] [100] |
| E-Methanol | 0.12 | 0.17 | 0.22 | 0.08 | 0.11 | 0.14 | [13] [33] [1] |
| E-Ammonia | 0.14 | 0.20 | 0.27 | 0.05 | 0.08 | 0.10 | [13] [33] [45] |
| Thorium | 6.19E-06 | 1.58E-05 | 2.55E-05 | 6.19E-06 | 1.58E-05 | 2.55E-05 | [58] |
| Uranium | 1.04E-04 | 2.67E-04 | 4.30E-04 | 1.04E-04 | 2.67E-04 | 4.30E-04 | [58] |

$^a$ *This MGO price does not include future ETS costs.*

The high and low expected fuel price developments are presented together in figure 6.2.

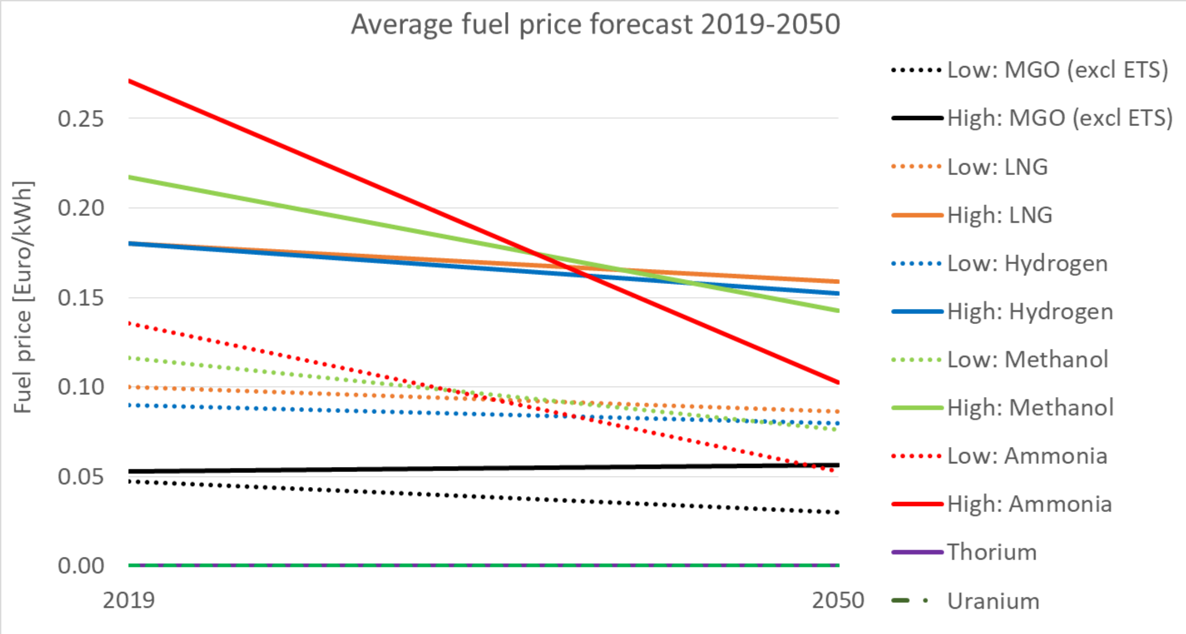


**Figure 6.2:** Average expected fuel price development until 2050

Since the required energy stored as a fuel differs per system due to variations in efficiencies, the fuel costs are sized per system to facilitate comparison. The costs are depicted in figure 6.3.

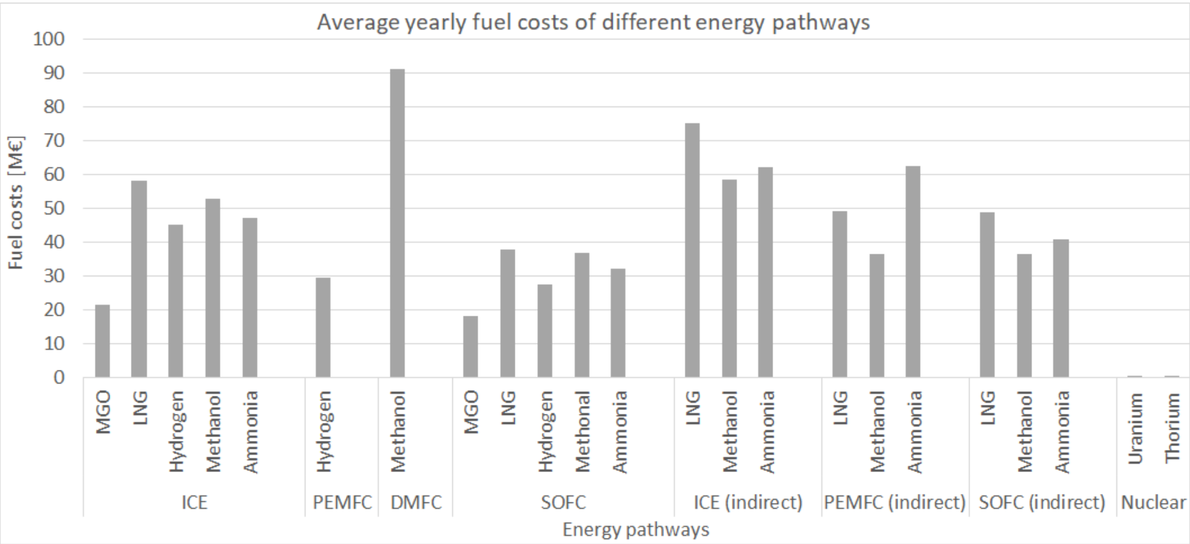


**Figure 6.3:** Average yearly fuel costs of different energy pathways [$10^6$ Euro]

## 6.2.2. Operation and maintenance costs

The second part of the OPEX is the operation and maintenance costs (O&M costs). These costs include all costs for the continuous operation of the system throughout the year, excluding fuel costs. A common approximation of the yearly O&M cost is expressing it as a percentage of the initial CAPEX of the specific system. The operation and maintenance costs of the conversion units are presented as [% of CAPEX / year] in table 6.4, and the general O&M costs of the storage facilities are presented in table 6.5. Again there are no O&M costs considered for the storage facility of nuclear reactors since the fuel is stored inside the conversion unit.

**Table 6.4:** Operational and maintenance cost per energy conversion unit

| | Cost [% of CAPEX / Year] | Source |
|---|---|---|
| **ICE** | | |
| MGO | 2% | [19] |
| E-LNG | 3% | [19] |
| Hydrogen | 3% | [19] |
| Methanol | 3% | [19] |
| Ammonia | 3% | [19] |
| **PEMFC** | | |
| Hydrogen | 5% | [18] |
| **DMFC** | | |
| Methanol | 5% | [18] |
| **SOFC** | | |
| MGO | 1% | [80] |
| E-LNG | 1% | [80] |
| Hydrogen | 1% | [80] |
| Methanol | 1% | [80] |
| Ammonia | 1% | [80] |
| **Nuclear** | | |
| Nuclear MSR | 5% | [58] |
| Nuclear VHSR | 5% | [58] |
| **Additional** | | |
| Steam Methane Ref. | 1% | [21] |
| Ammonia Cracker | 1% | [21] |

**Table 6.5:** Operational and maintenance cost of storage facility per fuel

| | Cost [% of CAPEX/ Year] | Source |
|---|---|---|
| MGO | 1% | [21] [51] |
| LNG | 2% | [21] [51] |
| Hydrogen | 2% | [21] [51] |
| Methanol | 2% | [21] [51] |
| Ammonia | 2% | [21] [51] |

In figure 6.4 the operational and maintenance costs for the sized systems are presented.

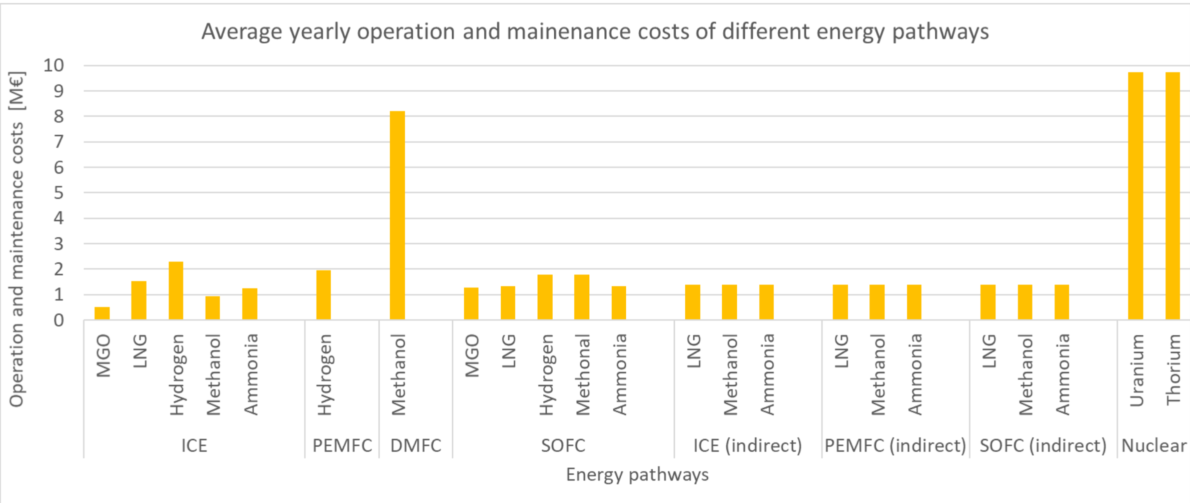


**Figure 6.4:** Average yearly operation and maintenance costs of different energy pathways [$10^6$ Euro]

The cumulative OPEX components have been sized for each energy pathway within the context of the SSCV's operational profile. The specific OPEXs are presented in figure 6.5.

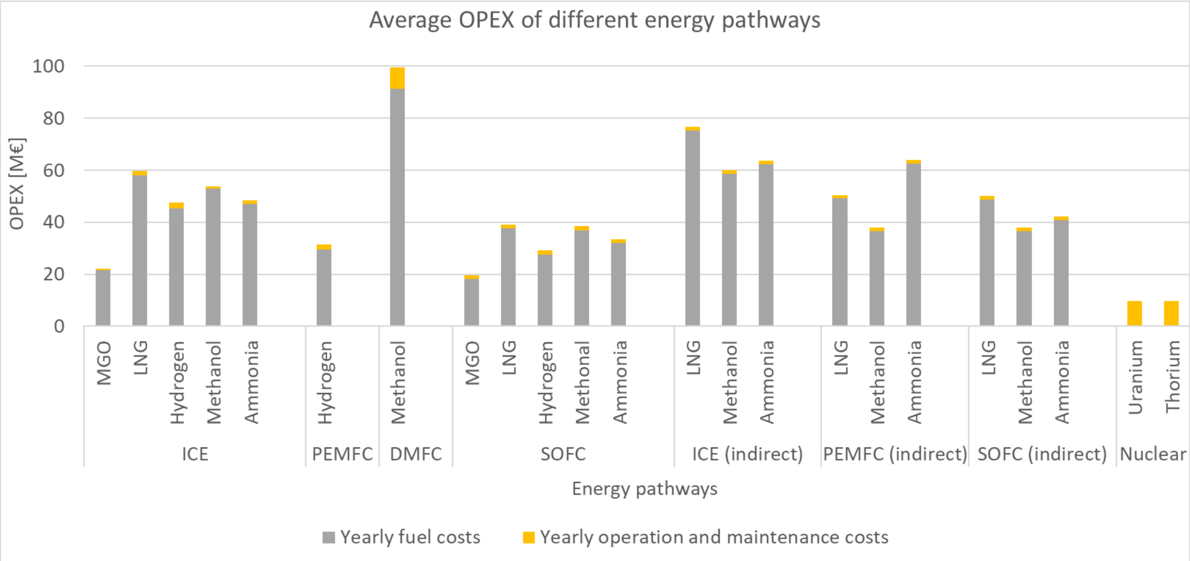


**Figure 6.5:** Average OPEX of different energy pathways [$10^6$ Euro]

## 6.3. LCOE

The concept of levelized cost of energy (LCOE) is used to evaluate and compare the price of producing electricity from various sources throughout the lifetime of an energy supply. It considers all costs associated with developing, constructing, operating, and maintaining an energy source, including fuel requirements. Apart from the costs, the concept of LCOE considers all energy produced over the lifetime of the energy supply. LCOE expresses the cost of energy in [price/amount of energy]. This way it facilitates a comparison of the cost of energy originating from different energy supplies. The formula of LCOE is depicted below in formula 6.1 to formula 6.3 [66].

$$LCOE = \frac{Total\ lifetime\ costs}{Total\ lifetime\ electricity\ generation} \tag{6.1}$$

$$Total\ lifetime\ costs = \sum_{t=1}^{n} \frac{I_t + M_t + F_t}{(1+r)^t} \tag{6.2}$$

$$Total\ lifetime\ electricity\ generation = \sum_{t=1}^{n} \frac{E_t}{(1+r)^t} \tag{6.3}$$

- $I_t$ = Investment costs for the year (t)
- $M_t$ = Operational and maintenance costs for the year (t)
- $F_t$ = Fuel costs for the year (t)
- $E_t$ = Electricity generations for the year (t)
- $r$ = Discount Rate
- $n$ = Lifetime of the energy supply

The calculated LCOE of different energy sources is depicted in table 6.6 and in figure 6.6. The expected LCOEs are described in a "low-", "medium-" and "high-" scenario. The pathways where the fuel is converted from hydrogen carrier to hydrogen, through a methane steam reformer or an ammonia cracker, before entering the conversion system are described as indirect pathways.

**Table 6.6:** LCOE of different energy pathways in [Euro/kWh]

| | LCOE [Euro/kWh] | | | | LCOE [Euro/kWh] | | |
|---|---|---|---|---|---|---|---|
| | **Low** | **Mid** | **High** | | **Low** | **Mid** | **High** |
| **ICE** | | | | ***ICE (indirect)*** | | | |
| MGO | 0.12 | 0.14 | 0.15 | LNG | 0.27 | 0.47 | 0.66 |
| LNG | 0.19 | 0.34 | 0.49 | Methanol | 0.22 | 0.38 | 0.53 |
| Hydrogen | 0.18 | 0.30 | 0.42 | Ammonia | 0.20 | 0.41 | 0.61 |
| Methanol | 0.18 | 0.31 | 0.40 | ***PEMFC (indirect)*** | | | |
| Ammonia | 0.14 | 0.29 | 0.45 | LNG | 0.20 | 0.34 | 0.47 |
| **PEMFC** | | | | Methanol | 0.16 | 0.26 | 0.36 |
| Hydrogen | 0.14 | 0.22 | 0.30 | Ammonia | 0.14 | 0.28 | 0.42 |
| **DMFC** | | | | ***SOFC (indirect)*** | | | |
| Methanol | 0.38 | 0.63 | 0.88 | LNG | 0.20 | 0.33 | 0.46 |
| **SOFC** | | | | Methanol | 0.16 | 0.26 | 0.36 |
| MGO | 0.15 | 0.18 | 0.20 | Ammonia | 0.14 | 0.28 | 0.42 |
| LNG | 0.17 | 0.28 | 0.38 | | | | |
| Hydrogen | 0.15 | 0.23 | 0.32 | **Nuclear** | | | |
| Methonal | 0.17 | 0.27 | 0.38 | Uranium | 0.31 | 0.41 | 0.51 |
| Ammonia | 0.14 | 0.26 | 0.37 | Thorium | 0.29 | 0.36 | 0.42 |

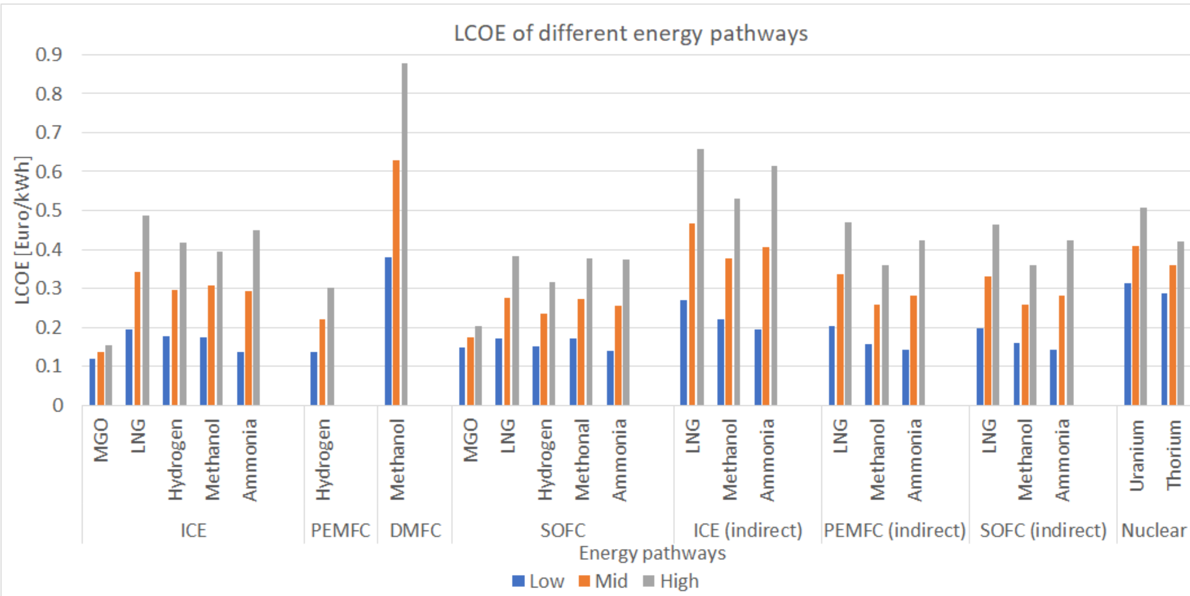


**Figure 6.6:** LCOE of different energy pathways [Euro/kWh]

## 6.4. Chapter conclusion

Comparing the OPEX multiplied by the system's lifetime, to the CAPEX of this specific system, one can conclude that the OPEX has the dominant financial impact. Furthermore, it can be stated that the efficiency of the system is of great influence on the financial impact. For example, it can be seen that the DMFC has high OPEX and CAPEX. Due to the low efficiency of the system, both the fuel capacity and the installed initial power have to be significantly oversized. This incurs costs. Finally, it can be seen that for all pathways, fuel costs are dominant within the OPEX approach, except for nuclear. Here fuel costs are significantly lower than for the other pathways. Meanwhile, operation and maintenance costs for nuclear are relatively high. Figure 6.6 shows that energy supplies on MGO have an attractive LCOE. This is partly due to the low fuel costs. Keep in mind that in the future reality, these fuel costs will be accompanied by ETS. This financial impact is not included in this analysis. The pathways that include direct SOFCs and direct PEMFCs are financially attractive. This can be traced to SOFCs' low maintenance costs and high efficiency, thus low fuel costs.

# 7

# Model Phase A: Criteria selection and weights

This chapter describes the approach and results regarding the obtained criteria weights. First, section 7.1 describes the approach of selecting categories and criteria, gathering the preferences of the decision-makers, and, finally, assigning preference weights to each criterion. Secondly, Section 7.2 presents and describes the obtained criteria weight. Finally, Section 7.3 concludes some takeaways regarding the criteria weights.

## 7.1. Approach: Criteria selection and weights

This section describes the approach to obtaining the selection weights. First, the selection of the criteria taken into account during the decision-making process is described in 7.1.1. Secondly, the process of gathering the preferences of the decision-makers within Heerema is described in 7.1.2. Finally, the processing of the preferences into criteria weights is described in 7.1.3. A schematic overview of this approach is presented in Figure 7.1. Additional explanations can be found throughout the section.

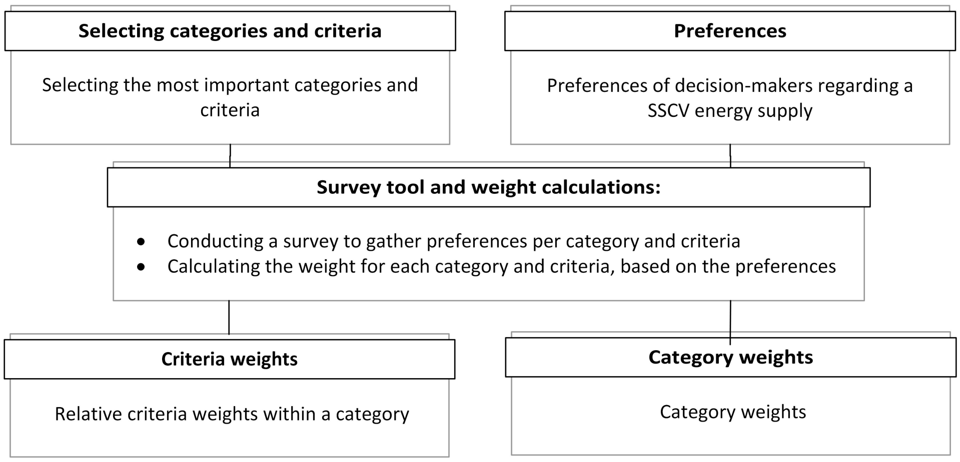


**Figure 7.1:** A schematic overview of the approach of obtaining the criteria weights.

### 7.1.1. Selecting criteria

First, the most important criteria in the decision-making process of an energy supply have to be identified. This is done based on the conducted literature study described in chapter 3 to 6 and by consulting ship design experts within Heerema Marine Contractors. The criteria are divided into categories. The categories used regard system design aspects, operational design aspects, financial impact aspects, safety aspects, emission aspects, regulation aspects, and ETS aspects. The selected categories and accompanying criteria for the decision model are depicted in table 7.1. ETS is included as a criterion to gain insight into the preference priority of the decision-makers regarding this aspect. It is important to note that ETS is not included in the financial assessment of the energy supplies.

**Table 7.1:** Selected decision criteria divided into categories

| Category | System design | System operation | Financial impact | Emissions | Safety | Regulations | ETS |
|---|---|---|---|---|---|---|---|
| ***Criteria 1*** | TRL | SSCV-specific efficiencies | LCOE$^a$ | $CO_{2eq}$ emissions | Health hazard | Regulatory framework clarity | ETS impact |
| ***Criteria 2*** | Weight | Conversion steps | CAPEX | | Flammability hazard | | |
| ***Criteria 3*** | Volume | Maintenance requirements | OPEX | | Risk during navigation | | |
| ***Criteria 4*** | Storage temperature | Bunker period limitation | | | Safety nuclear | | |
| ***Criteria 5*** | Storage pressure | | | | Security nuclear | | |

[a] *The LCOE criteria scores consist of low-, mid-, and high scenario variants*

## 7.1.2. Gathering the criteria preferences

A survey tool is used to gather criteria preferences from decision-makers within Heermema concerning the energy supply design for a new-built SSCV. Firstly, the reasoning for the selection of interview participants is provided. Secondly, the implementation of the survey tool is explained. An overview of the survey tool, including the survey questions, is presented in Appendix A.

### Interview participants

The group of interview participants consists of 9 Heerema employees currently engaged in the orientation process for a new-built SSCV design. The decision-maker group includes a selection of stakeholders and experts from various backgrounds and roles within Heerema. This approach aims to gather preference data that provides a broad range of perspectives on design considerations. The roles and backgrounds of the interview participants are presented in table 7.2.

**Table 7.2:** Function description of interview participants

| Department | Function description |
|---|---|
| Product Development | Research & development lead #1<br>Research & development lead #2<br>Sustainable product developer |
| Health & Safety | Safety director<br>Safety advisor |
| Strategy | Strategy advisor |
| Operations | Project director<br>Vessel operation superintendent |
| Finance | Finance director |

### Implementation of the survey tool

The survey uses a question format that allows the decision-maker to rank criteria in a hierarchical order of preference. These criteria are organized into categories. During the survey, the decision-makers are initially asked to express their preferences among criteria within a specific category. Finally, participants are requested to, also, rank their preferences for each category in a hierarchical order. To increase the quality of the interview results, the decision-maker receives background information on each criterion. The decision-maker replies to the questions by hierarchically ordering the criteria based on experts' personal preferences for a new-built energy supply design process.

The design criteria requested to order hierarchically within the category during the survey are presented in table 7.3.

**Table 7.3:** Overview of criteria requested to order hierarchically per category during the survey.

| Question & Category | Criteria | Question & Category | Criteria |
|---|---|---|---|
| Q1. System design | TRL | Q4. Safety | Health risk |
| | System weight | | Flammability risk |
| | System volume | | Risk during navigation |
| | Storage temperature | | Nuclear safety |
| | Storage pressure | | Nuclear security |
| Q2. System operation | Efficiency | Q5. Emissions | 100% emission abatement |
| | Amount of conversion steps | | Partial emission abatement |
| | Maintenance requirements | | No abatement |
| | Minimal bunker period | Q6. Regulations | No regulation in near future |
| Q3. Financial impact | LCOE | | Regulations under development |
| | CAPEX | | Currently clear regulations |
| | OPEX | Q7. ETS | Willing to pay ETS |
| | | | Not willing to pay ETS |

Some questions deviate from the usual question format. Some questions are adjusted to add more nuance, while others are adjusted to prevent unclear interpretation of the subject. For safety, for example, there is an option to rate one or more criteria as equally important when desired rather than a hierarchical classification. Moreover, given that this research does not quantify the financial impact of ETS due to reasons stated in section 1.5, the assessment of the impact of ETS on the decision process is approached through the following question format. Regarding the ETS criterion, the survey provides decision-makers with only two answer options regarding their willingness to pay for ETS, creating a binary format where they can choose between ”agree” or ”disagree”. This format is used to gain insight into the significance of the ETS impact regarding the decision problem, as perceived by the decision-makers.

After the hierarchical ordering of the criteria, the decision-maker is asked to order the overarching categories hierarchically. Table 7.4 presents an overview of the categories the decision-maker is requested to order.

**Table 7.4:** Overview of categories requested to order hierarchically during the survey.

| Question & Category | Criteria |
|---|---|
| Q 8. Categories | System design |
| | System operation |
| | Emissions |
| | Financial impact |
| | Regulations |
| | Safety |
| | ETS |

The output of the survey yields a set of numerical scores per category and per criteria. The category or criterion placed at the highest rank receive the highest numerical score. The next step is converting these scores into criteria weights that can be used for the decision tool. The processing of the data is done following the AHP method described in section 2.1.

To demonstrate the calculation process, the preferences of the financial manager within the financial impact category are chosen for illustration. The particularly preference outcomes from the financial manager are presented in Table 7.5.

**Table 7.5:** Survey output preference ratings concerning the criteria within the financial impact category, based on the preferences of Heerema’s financial manager.

| Criteria | Score |
|---|---|
| LCOE | 1.00 |
| CAPEX | 3.00 |
| OPEX | 2.00 |

### 7.1.3. Processing survey results into category and criteria weights

The survey results are transformed into criterion weights for each decision-maker. The interrelation of preferences is mapped by comparing each preference per criterion within a category. Similarly, the preferences regarding each category are compared against one another. This results in weights expressing the relative preference per criterion compared to another. The weights assigned during this comparing process range from the minimum priority weight of 1 to the maximum priority weight of 9. Table 7.6 demonstrates this comparison process for the financial impact category as an example. The weights indicate the level of preference for the criteria in the row relative to the criteria in the column. These weights are unaffected by preferences among the overarching categories. When the criterion weight is not adjusted according to the preferences of the parent category, it can be referred to as a separate criterion weight. The process of obtaining these weights is identical to that of the separate criteria weights. The process of combining the separate criterion weight with the parent category weight will be explained and applied in the procedures outlined in Chapter 9.1.

**Table 7.6:** Criteria preferences balanced against one another, based on the preferences of Heerema's financial manager

| | **LCOE** | **CAPEX** | **OPEX** |
|---|---|---|---|
| **LCOE** | 1.00 | 9.00 | 6.00 |
| **CAPEX** | 0.11 | 1.00 | 0.22 |
| **OPEX** | 0.17 | 4.50 | 1.00 |

The inter-relationships among the criterion must be converted into a preference weight expressed in a percentage per criterion for further use in the decision-making tool. This is achieved by normalizing the values across the columns, followed by taking the average of the values for each row. The preference weight percentage of the criterion within the example category is presented in table 7.7. The preference weight percentage of a criterion will be referred to as $W_{criterion}$. The preference weight percentage of the parent categories will be referred to as $W_{category}$.

**Table 7.7:** The preference weight percentage of Heerema's financial manager concerning the criteria within the financial impact category.

| **Criteria** | **Criteria weight [%]** |
|---|---|
| LCOE | 75 |
| CAPEX | 6 |
| OPEX | 19 |

## 7.2. Results: Category and criteria weights

This section presents the criteria weights based on the preferences of the decision-makers. As stated, the preference data is retrieved from the survey tool and expressed in a criteria weight. Keep in mind that the structure of the criteria ranking consists of two layers. The first layer consists of the decision-maker's preference concerning the criteria category. The second layer consists of the preference of the decision-maker regarding each specific criterion. In subsection 7.2.1, first, the distribution of the category preferences of the individual decision-makers is presented. Secondly, the average preference of the decision-maker group concerning the different categories is presented and discussed. In subsection 7.2.2 , first, the distribution of the criteria preferences of the individual decision-makers is presented. Secondly, the average of the preferences regarding the criteria is presented and discussed. The category weight [%] describes the rate of preference for a certain category compared to the other categories. The criteria weight [%] express the rate of preference for certain criteria within its parent category compared to the other criteria.

### 7.2.1. Category weights

Figure 7.2 shows the way individual decision-makers have distributed their preferences among different categories. What's particularly noticeable is that 33% of the decision-makers have chosen the system design category as their top priority, emphasizing its importance. This places system design as the category with the highest quantity of first-priority selections. Furthermore, it is clear that 100% of the decision-makers have chosen ETS as the least important category.


**Figure 7.2:** Percentage of decision-maker group who have chosen a specific priority for each category.

The individual preferences can be translated into an average preference distribution of the entire decision-maker group. Figure 7.5 shows that the system design criteria category is found to be the most important by the decision-makers on average. The system operation category and the safety category are found to be the second most important criteria categories. The lowest rating of importance is assigned to the ETS impact, followed by the clarity of the regulations.

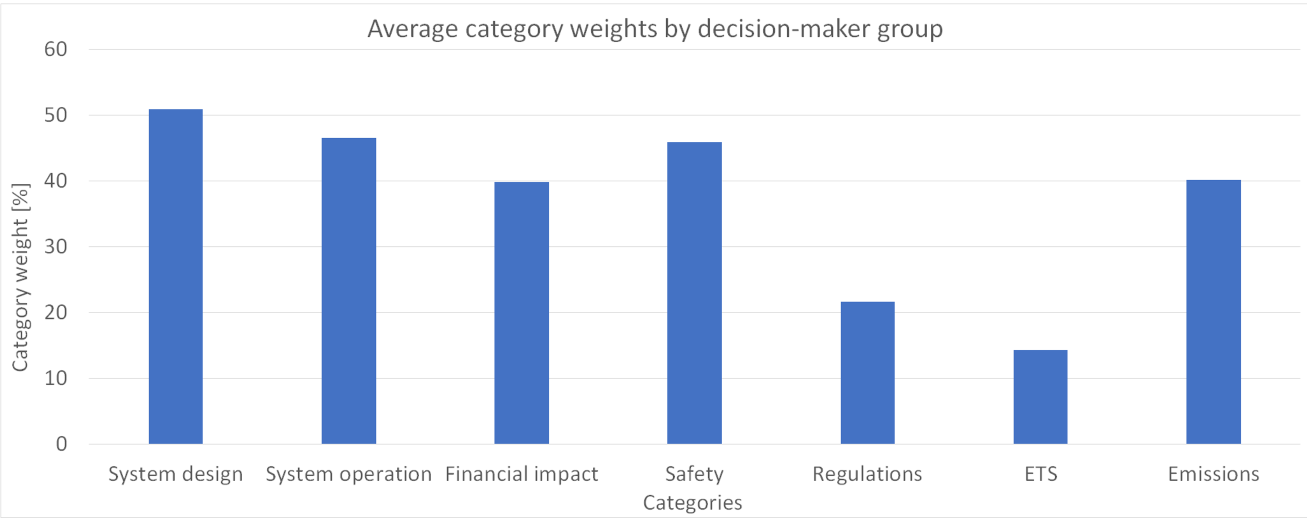


**Figure 7.3:** Average preferences concerning the different criteria categories by the decision-maker group.

### 7.2.2. Criteria weights

To illustrate the distribution of preferences within the decision-maker group, figure 7.4 displays the percentage of decision-makers who have chosen a specific priority for each criterion within the different categories. From this data can be concluded that the preferences hierarchy of the individual decision-maker varies from one another. Nevertheless, a pattern can be detected of more and less important criteria. For example, 100% of the decision-makers selected TRL as the most important criterion within the system design category. Figure 7.5 shows the average criteria preference by the decision-makers scaled on the rate of importance assigned to the overarching categories.

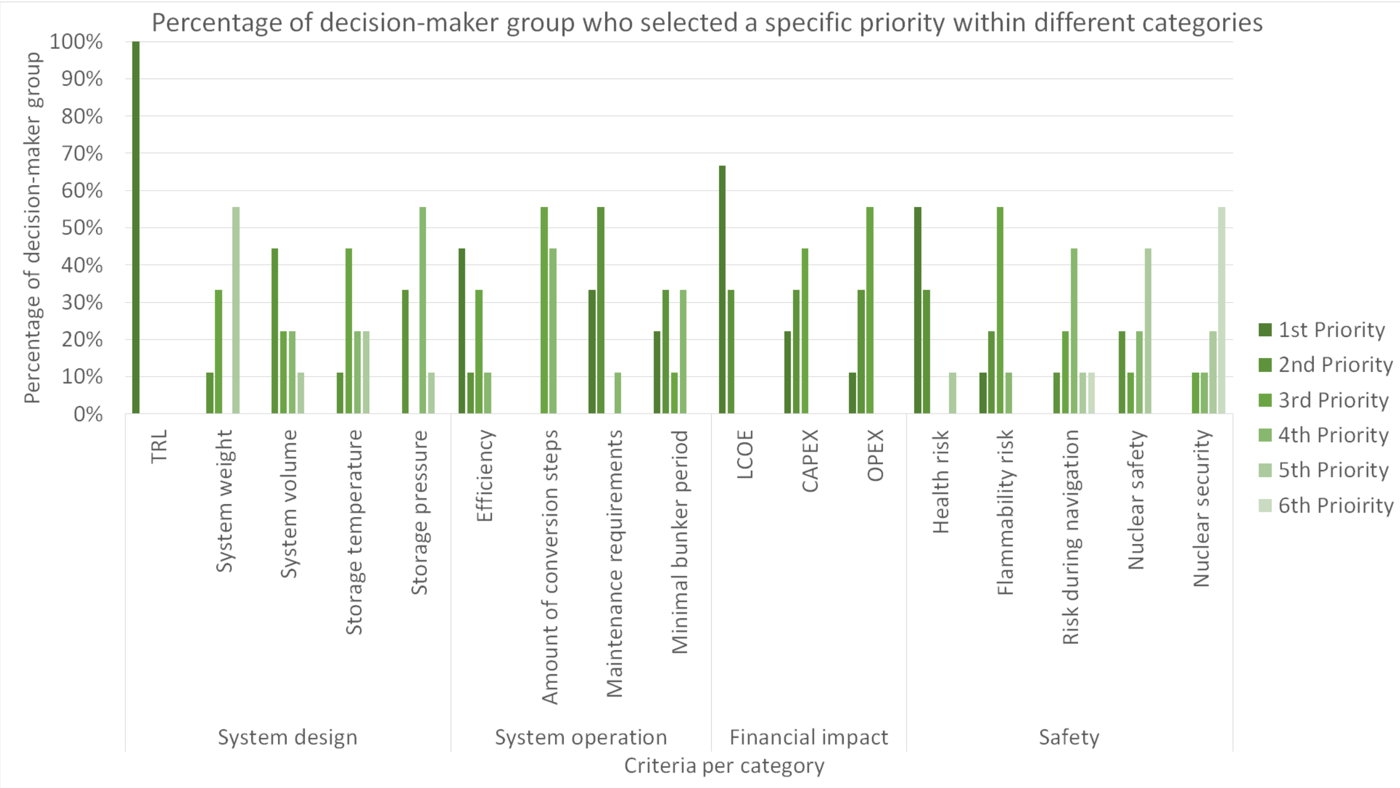


**Figure 7.4:** Percentage of decision-maker group who have chosen a specific priority for each criterion within the different categories.

*Categories consisting of only a single criterion have been omitted from this graph, as their preference weight is allocated during the assignment of category weights.*

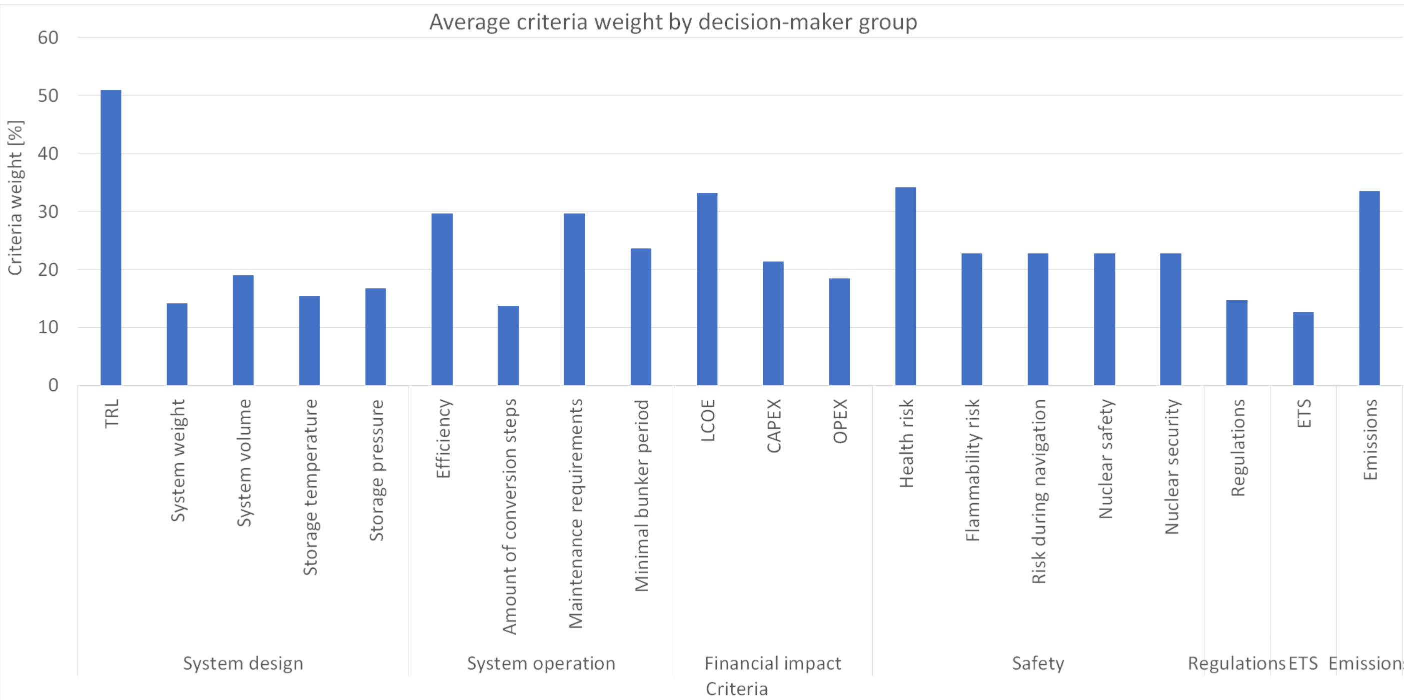


**Figure 7.5:** Average preferences concerning the different criteria by the decision-maker group. These criteria preferences are scaled to the overarching criteria category preferences.

### System design criteria
All decision-makers placed TRL on the highest rank of importance within the system design category. Since the system design category is also rated the most important category, TRL is the overall highest-rated criterion by the decision-maker group. The system weight is found to be the least important criterion within the system design category since 5 of the decision-makers placed it in the lowest order of importance.

### System operation criteria
In the context of system operation, efficiency, and maintenance requirements share the highest average rank of importance. The constraint related to the bunker period is identified as the second most significant aspect within the category of system operation. Notably, lagging behind in priority, the criterion found the least important within the category is the number of conversion steps within a system. The conversion step criterion is found overall the be the second-least important criterion.

### Financial impact
Within the financial impact category, the LCOE criterion is, by a distance, found to be the most important criterion. LCOE occupies a shared third position in the hierarchy of overall most important criteria. Although for most systems, OPEX has a dominant financial impact over CAPEX, the decision-maker group found CAPEX to be slightly more important during the decision process than OPEX.

### Safety
A clear priority within the safety category goes out to the health risk criterion. The health risk criterion is rated overall as the second-most important criterion. With a reduced level of priority, the remaining safety criteria are rated as equally important.

### Regulations
The importance of clear international regulations is found to be of relatively low significance by the decision-maker group.

### ETS
The criterion that implies the concept and impact of ETS is relatively found to be the overall least important criterion. Keep in mind, that ETS is incorporated as a criterion within the decision-making methodology to provide an understanding of the perceived importance of the impact of ETS as a concept, by the decision-makers. However, the impact of ETS is not integrated into the financial assessment.

### Emissions
The criterion that implies the importance of the general reduction of emissions occupies a shared third position in the hierarchy of overall most important criteria, according to the decision-makers.

## 7.3. Chapter conclusion
This chapter explains the procedure of collecting and processing preference weights for the criteria provided by the Heerema decision-maker group.

The criteria with the highest preference rate on average within the Heerema decision-maker group are presented in table 7.8.

**Table 7.8:** The six highest-scoring criteria in terms of preference weight that fall within a distinguished upper range.

| Criteria | Criteria weight [%] |
|---|---|
| TRL | 50.93 |
| Health risk | 34.19 |
| Emissions | 33.49 |
| LCOE | 33.18 |
| Maintenance requirements | 29.70 |
| Efficiency | 29.70 |

# 8

# Model Phase B: Alternative scores

This chapter describes the performance of different alternatives regarding each criterion. This performance is expressed in a score. The score of each alternative is determined per criteria when sized to the considered SSCV operational profile. Initially, the scoring methodology for each criterion is introduced, followed by a demonstration of how such scores are derived in Section 8.1. The process of scoring the alternatives will be illustrated by explaining the scoring process for three specific alternatives. The results of the alternative scoring process are visualized by presenting the average scores per category in Section 8.2. An overview of the alternative scores for each criterion is available in Appendix C. Finally, Section 8.3 concludes some take-aways regarding the alternative scores.

## 8.1. Approach: Alternative scoring

As explained in section 2.1, all alternative energy supplies must be rated with scores per criterion. These scores are based on data gathered during the literature study in chapter 3 to 6. The conversion from this data to scores from 1 to 9 for each criterion is done through specific calculations per criterion. The calculation method can be separated into two types. These two different approaches are presented in Figure 8.1.

The first type regards data from literature directly applicable to the SSCV operational profile. The second type regards data from the literature that needs to be converted into SSCV operational profile-specific data. Table 8.1 indicates the type of scoring method applicable for each criterion.

The table also defines the data on which the scores are based, followed by the chapter that discusses this data.

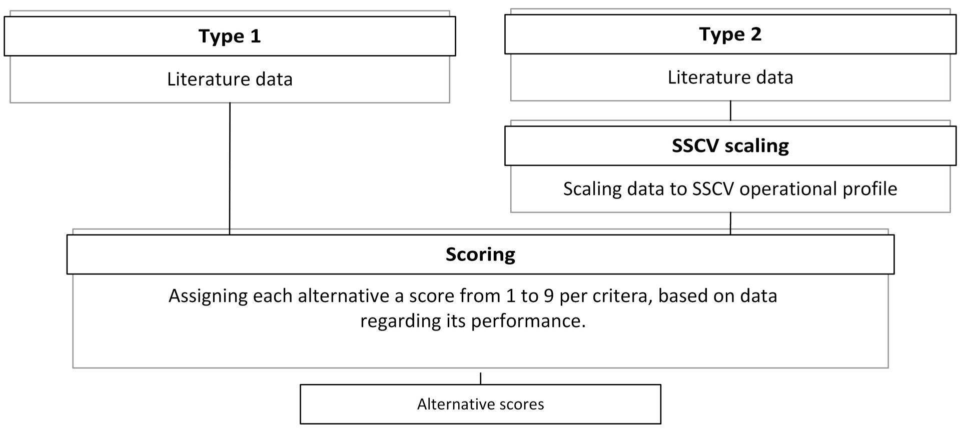


**Figure 8.1:** A schematic overview of the approach of obtaining the alternative scores.

**Table 8.1**

| Type 1: Scores directly translated from literature | | | Type 2: Scores scaled to SSCV operational profile | | |
|---|---|---|---|---|---|
| **Criteria** | **Based on** | **Chapter** | **Criteria** | **Based on** | **Chapter** |
| TRL | TRL values | 4, 5 | Weight | Storage and system weight | 4, 5 |
| Temperature | Temperature values | 4 | Volume | Storage and system volume | 4, 5 |
| Pressure | Pressure values | 4 | Efficiency | SSCV-specific efficiency | 5 |
| Conversion steps | Quantity of conversion steps | 5 | Maintenance requirements | Yearly maintenance costs | 5, 6 |
| Health hazard | NFPA safety index | 4 | Bunkering limit | Extend of exceeding weight or volume limit | 5 |
| Flammability hazard | NFPA safety index | 4 | LCOE | Financial assessment | 6 |
| Risk during navigation | NFPA safety index | 5 | CAPEX | Financial assessment | 6 |
| Safety nuclear | NIRO safety index | 4 | OPEX | Financial assessment | 6 |
| Security nuclear | Niro Safety index | 4 | | | |
| Regulation framework clarity | Assumptions based on literature | 5 | | | . |
| Subjected to ETS | Assumptions based on literature | 5 | | | |
| $CO2_{eq}$ emissions | Energy supply specific emissions | 5 | | | |

Both methods are illustrated in this section. To illustrate the first type, where scores are directly translated from literature, the scoring process of the regulatory framework clarity criterion is described. To illustrate the second type, the calculations for the SSCV-specific efficiencies and bunker period limitation are described.

### 8.1.1. Regulatory framework clarity scoring method

The scoring of the regulatory framework clarity consists of two steps. Step one is identifying the data from the literature. Step two is translating this data into scores from 1 to 9.

1. *Identifying the data from the literature.*

Three states of regulatory framework clarity were identified during the literature study. First, clear and mature international regulatory frameworks. Secondly, regulatory frameworks which are currently under development for future application. Thirdly, frameworks that are currently unclear with no signs of improvement in the near future are identified. In this study, only the frameworks considering the use of a certain fuel are taken into consideration without addressing energy supply-specific frameworks. Therefore, the clarity of the energy supply frameworks is assumed based on the clarity of the corresponding fuel frameworks.

2. *Translating the data into scores from 1 to 9.*

Clear and available frameworks are considered the most favorable. Therefore, energy supplies for which these frameworks are applicable will receive the highest score of 9. The least favorable scenario is identified for currently unclear frameworks with no signs of improvement in the near future. Energy supplies governed by these frameworks will be assigned a score of 1. The energy supplies subjected to frameworks that are currently under development are rated with a score of 4.5, representing a rating between the most and least favorable states. This value has been rounded to 5 in the table formatting. The scores for each energy supply are presented in table 8.2. Note that the same clarity score of the framework of a specific fuel is assumed for all energy supplies utilizing this specific fuel during this study.

**Table 8.2:** Regulatory framework clarity scores

| | ICE | PEMFC | SOFC | DMFC | Ref-ICE | Ref-PEMFC | Ref-SOFC | MSR | VHTR |
|---|---|---|---|---|---|---|---|---|---|
| **MGO** | 9 | - | 9 | - | - | - | - | - | - |
| **E-LNG** | 9 | - | 9 | - | 9 | 9 | 9 | - | - |
| **LH2** | 5 | 5 | 5 | - | - | - | - | - | - |
| **CH2** | 5 | 5 | 5 | - | - | - | - | - | - |
| **Methanol** | 9 | - | 9 | 9 | 9 | 9 | 9 | - | - |
| **Ammonia** | 5 | - | 5 | - | 5 | 5 | 5 | - | - |
| **Uranium** | - | - | - | - | - | - | - | 1 | 1 |
| **Thorium** | - | - | - | - | - | - | - | 1 | 1 |

*Note that during this research, these scores are based on regulatory framework clarity per fuel and are not energy supply specific.*

### 8.1.2. SSCV-specific efficiencies scoring method

The approximation of all energy supply efficiencies associated with the specific operational profile of the SSCV Sleipnir, as outlined in section 3, consists of five steps. These steps are presented below.

1. *Find specific efficiency per operational mode of each conversion system.*

It is necessary to convert the engine capacity factor of each mode into corresponding efficiency values for the specific energy converters. These efficiencies will be based on the general efficiency load profiles per conversion system shown in figure 5.7. The presented efficiency profile assumes the use of the most common fuel regarding this conversion system. When combining the general efficiency load profiles with the loads demanded during each operational mode, the specific mode efficiency of the conversion system can be determined. The specific mode efficiencies per conversion system are depicted in table 8.3. Keep in mind the engine capacity factor, only describes the laod requested from the engines that are online during this mode, rather than from the complete installed power.

**Table 8.3:** Specific efficiency of conversion systems-, and occurrence percentage per operational mode

| Operational mode | MOB | WORK | SAIL | IDLE | R&M | Unit |
|---|---|---|---|---|---|---|
| **Engine capacity factor** | [redacted] | | | | | [%] |
| **Occurence** | | | | | | [%] |
| **ICE** using MGO | | | | | | [%] |
| **PEMFC** using $H_2$ | | | | | | [%] |
| **SOFC** using $H_2$ | | | | | | [%] |
| **DMFC** using methanol | | | | | | [%] |
| **Nuclear** using uranium/thorium | | | | | | [%] |

2. *Find the average efficiency of a conversion system for the SSCV operational profile.*

The average system efficiency can be determined by summing up the efficiencies of each mode per energy conversion system and multiplying it by the occurrence percentage. This average efficiency takes the fluctuating efficiencies during a period of operation into account and is, therefore, specific to the operational profile of the considered SSCV. The formula for the average efficiency calculation is presented in equation 8.1. The average efficiencies of each conversion system subjected to the SSCV operational profile are presented in table 8.4. The system efficiencies are fuel dependent. Table 8.4 shows on what fuel the efficiencies are based per conversion system

$$\eta_{system} = \sum_{modes}^{system} \eta_{specific} * occurrence \tag{8.1}$$

$\eta_{system}$ = *Average efficiency of a conversion system subjected to the SSCV operational profile [%]*
$\eta_{specific}$ = *The efficiency of a specific energy converter in a specific work mode [%] (see table 8.3)*
$occurrence$ = *Occurrence per mode presented as a percentage of the total operational time [%]*

**Table 8.4:** Average efficiencies of conversion systems subjected to the SSCV operational profile ($\eta_{system}$).

| Conversion system | Average system efficiency [%] | Fuel used |
|---|---|---|
| **ICE** | [redacted] | MGO |
| **PEMFC** | | Hydrogen |
| **SOFC** | | Hydrogen |
| **DMFC** | | Methanol |
| **Nuclear** | | Uranium / Thorium |

3. *Find the ratio of the average conversion system efficiency and the efficiencies from the literature.*

The conversion system efficiency differs for each fuel. Therefore the ratio between the SSCV-specific efficiencies and the conversion efficiency found in the literature system will be used to scale the other fuel efficiencies. The objective is to adjust fuel efficiency for each energy supply to the unique characteristics of the SSCV. The formula for the ratio calculation is presented in 8.2.

$$efficiency\,ratio = \frac{\eta_{system}}{\eta_{literature}} \tag{8.2}$$

$efficiencyratio$ = *Ratio between SSCV-specific efficiency and efficiency retrieved from literature [-]*
$\eta_{literature}$ = *Efficiency retrieved from literature [%]*

**Table 8.5:** Ratio between operational profile specific efficiencies and literature efficiencies. ($efficiencyratio$)

| Conversion system | Efficiency Ratio |
|---|---|
| ICE | 0.90 |
| PEMFC | 0.96 |
| SOFC | 0.95 |
| DMFC | 1.04 |
| Nuclear | 1.09 |

4. *Multiply literature efficiencies by the conversion system efficiency ratio.*

This step is taken in order to make the efficiencies of all considered energy supplies SSCV specific. The efficiency ratio is used to scale all energy supply efficiencies found in literature, to efficiencies occurring during the operational profile of the considered SSCV. The formula to scale the other supply efficiencies is presented in equation 8.3. These sized specific efficiencies are depicted in table 8.6.

$$\eta_{SSCV} = efficiency\,ratio * \eta_{literature} \tag{8.3}$$

$\eta_{SSCV}$ = *SSCV operational profile-specific efficiencies for specific energy supply [%]*

**Table 8.6:** SSCV operational profile-specific efficiencies of different energy energy supplies [%]

| | ICE | PEMFC | SOFC | DMFC | Ref-ICE | Ref-PEMFC | Ref-SOFC | MSR | VHTR |
|---|---|---|---|---|---|---|---|---|---|
| **MGO** | [redacted] | | | | | | | | |
| **E-LNG** | | | | | | | | | |
| **LH2** | | | | | | | | | |
| **CH2** | | | | | | | | | |
| **Methanol** | | | | | | | | | |
| **Ammonia** | | | | | | | | | |
| **Uranium** | | | | | | | | | |
| **Thorium** | | | | | | | | | |

5. *Translate the efficiency values into a score of 1 to 9.*

To use the efficiency data for the decision-making tool, the efficiency values have to be translated into a score from 1 to 9. During this translation, the low efficiencies will receive a low score and the high efficiencies will receive a high score. The scores are presented in table 8.7.

**Table 8.7:** Efficiency scores, based on SSCV operational profile specific efficiencies

| | ICE | PEMFC | SOFC | DMFC | Ref-ICE | Ref-PEMFC | Ref-SOFC | MSR | VHTR |
|---|---|---|---|---|---|---|---|---|---|
| MGO | 6 | - | 7 | - | - | - | - | - | - |
| E-LNG | 5 | - | 8 | - | 4 | 6 | 6 | - | - |
| LH2 | 5 | 8 | 9 | - | - | - | - | - | - |
| CH2 | 5 | 8 | 9 | - | - | - | - | - | - |
| Methanol | 5 | - | 7 | 3 | 5 | 8 | 8 | - | - |
| Ammonia | 5 | - | 8 | - | 4 | 6 | 6 | - | - |
| Uranium | - | - | - | - | - | - | - | 5 | 5 |
| Thorium | - | - | - | - | - | - | - | 5 | 5 |

### 8.1.3. Bunker period limitations scoring method

The volume and weight of a system may limit the maximum bunker period of the vessel. To calculate the bunkering period limitation, the volume and weight of the energy supplies need to be considered. Each energy supply is made up of two parts. The first part is the energy converter and auxiliary system, referred to as the conversion system. The second part is the fuel storage facility. Each energy supply will receive a score to what extent they may exceed the static volume and weight limit stated in section 3.

”bunkering period limitation” scoring consists of three steps. The first step is considering the installed power and calculating the required quantity of energy stored in fuel per bunker period of each energy supply. After This step, the accompanying energy supply volume and weight can be determined. The third step is comparing the energy supply weight and volume with the SSCV Sleipnirs static limits stated in 3.

1. *Consider the installed power and find the required energy per bunker period of each energy supply.*

The required installed power required to meet the operational profile of the SSCV is stated in 3. The required installed power for the SSCV case study is 96 MW. The installed power will be referred to $P_{installed}$

The required quantity of energy stored in fuel during the bunker period is determined for each energy supply using the equation 8.4. The required quantity of stored energy per bunker period for each energy supply is presented in table 8.8.

$$E_{bunker\ period} = \frac{E_{effective}}{\eta_{SSCV}} \tag{8.4}$$

$E_{bunker\ period}$ = *Required energy stored in fuel per bunker period of each energy supply [MWh]*
$E_{effective}$ = *Required effective energy per bunker period to comply with SSCV operational profile [MWh]*

**Table 8.8:** Required energy stored in fuel per bunker period for each energy supply [MWh]

| | ICE | PEMFC | SOFC | DMFC | Ref-ICE | Ref-PEMFC | Ref-SOFC | MSR | VHTR |
|---|---|---|---|---|---|---|---|---|---|
| MGO | [redacted] | | | | | | | | |
| E-LNG | | | | | | | | | |
| LH2 | | | | | | | | | |
| CH2 | | | | | | | | | |
| Methanol | | | | | | | | | |
| Ammonia | | | | | | | | | |
| Uranium | | | | | | | | | |
| Thorium | | | | | | | | | |

2. *Find the volume and weight of each energy supply.*

The energy converter system and storage facility need to be scaled to the effective energy and power requirements of the SSCV. This scaling is done using equations 8.5 to 8.7. The volume of each energy supply is presented in table 8.9.

$$V_{energy\ supply} = V_{conversion} + V_{storage} \tag{8.5}$$

$$V_{conversion} = \rho_{P_V} * P_{installed} \tag{8.6}$$

$$V_{storage} = \rho_{E_V} * E_{bunker\ period} * storage\ volume\ ratio \tag{8.7}$$

$V_{energy\ supply}$ = *Volume of the energy supply, compliant to SSCV power and energy requirement [m$^3$]*
$V_{conversion}$ = *Volume of conversion system [m$^3$]*
$V_{storage}$ = *Volume of the storage facility [m$^3$]*
$\rho_{P_V}$ = *Volumetric power density of conversion system [m$^3$/MW]*
$\rho_{E_V}$ = *Volumetric energy density of fuel [m$^3$/MWh]*
$storage\ volume\ ratio$ = *Volume storage ratio, between fuel volume and additional storage facility volume [-]*

**Table 8.9:** Volume of each energy supply, compliant to the SSCV operational profile [m$^3$]

| | ICE | PEMFC | SOFC | DMFC | Ref-ICE | Ref-PEMFC | Ref-SOFC | MSR | VHTR |
|---|---|---|---|---|---|---|---|---|---|
| **MGO** | [redacted] | | | | | | | | |
| **E-LNG** | | | | | | | | | |
| **LH2** | | | | | | | | | |
| **CH2** | | | | | | | | | |
| **Methanol** | | | | | | | | | |
| **Ammonia** | | | | | | | | | |
| **Uranium** | | | | | | | | | |
| **Thorium** | | | | | | | | | |

*A similar approximation can be made for the weight of the energy supply. Equation 8.8 to 8.10 is used to determine the weights depicted in table 8.10.*

$$M_{energy\ supply} = M_{conversion} + M_{storage} \tag{8.8}$$

$$M_{conversion} = \rho_{P_M} * P_{installed} \tag{8.9}$$

$$M_{storage} = \rho_{E_M} * E_{bunker\ period} * storage\ weight\ ratio \tag{8.10}$$

$M_{energy\ supply}$ = *Weight of the energy supply, compliant to SSCV power and energy requirement [tonnes]*
$M_{conversion}$ = *Weight of conversion system [tonnes]*
$M_{storage}$ = *Weight of the storage facility [tonnes]*
$\rho_{P_M}$ = *Volumetric power density of conversion system [tonnes/MW]*
$\rho_{E_M}$ = *Volumetric energy density of fuel [tonnes/MWh]*
$storage\ weight\ ratio$ = *Volume storage ratio, between fuel volume and additional storage facility volume [-]*

**Table 8.10:** Weight of each energy supply, compliant to the SSCV operational profile [tonnes]

| | ICE | PEMFC | SOFC | DMFC | Ref-ICE | Ref-PEMFC | Ref-SOFC | MSR | VHTR |
|---|---|---|---|---|---|---|---|---|---|
| **MGO** | [redacted] | | | | | | | | |
| **E-LNG** | | | | | | | | | |
| **LH2** | | | | | | | | | |
| **CH2** | | | | | | | | | |
| **Methanol** | | | | | | | | | |
| **Ammonia** | | | | | | | | | |
| **Uranium** | | | | | | | | | |
| **Thorium** | | | | | | | | | |

3. *Compare the energy supply volume and weight to the SSCV's static limits and translate into scores from 1 to 9.*

The volume and weight approximations are compared to the SSCV's static limits stated in 3. All energy supplies that are within these limits will receive a score of 9. Energy sources exceeding these limits will be assigned a reduced score based on the extent of their excess. First, the volume and weight are evaluated independently and assigned separate scores. Secondly, these individual scores are combined into a comprehensive score that accounts for the degree of exceeding the bunkering limits in both volume and weight. The scores for the energy supplies are presented in table 8.11.

**Table 8.11:** Bunkering period limitation score of each energy supply

| | ICE | PEMFC | SOFC | DMFC | Ref-ICE | Ref-PEMFC | Ref-SOFC | MSR | VHTR |
|---|---|---|---|---|---|---|---|---|---|
| **MGO** | 9 | - | 9 | - | - | - | - | - | - |
| **E-LNG** | 9 | - | 6 | - | 5 | 9 | 6 | - | - |
| **LH2** | 5 | 5 | 5 | - | - | - | - | - | - |
| **CH2** | 1 | 5 | 5 | - | - | - | - | - | - |
| **Methanol** | 9 | - | 9 | 2 | 5 | 9 | 9 | - | - |
| **Ammonia** | 6 | - | 5 | - | 1 | 5 | 1 | - | - |
| **Uranium** | - | - | - | - | - | - | - | 9 | 9 |
| **Thorium** | - | - | - | - | - | - | - | 9 | 9 |

## 8.2. Results: Alternative scoring

In this section, the results of the alternative energy supply scoring will be discussed. These system scores represent the relative impact on the SSCV of each alternative energy supply per criterion. Therefore, scores will be used as input for the decision tool but also facilitate a comparison of the different energy supplies. Since, during this research, 20 criteria are considered for all 28 energy supplies, not all alternative scores will be presented in this section. First, the scoring table concerning the ICE energy supplies will be used as an example and discussed, in 8.2.1, to illustrate the criteria scores. Secondly, the scores of the criteria with the highest preference rate discussed in chapter 7, will be presented. Finally, the average system scores of each of the seven criteria categories will be presented for visualization of the impact of the different energy supplies and discussed in 8.2.2. For an overview of the detailed alternative score tables for each criterion for all energy supplies, please view Appendix D. The data on which the scores are based are shown in Appendix C.

### 8.2.1. Criteria scoring results

This subsection describes the scoring results of the alternatives. First, the alternative scoring table regarding the ICE energy supplies is presented and described to illustrate the layout of these tables. Secondly, the alternative scores of the energy supplies regarding the criteria with the highest preference weight are presented.

#### Scoring table

Table D.1 presents the scores and, therefore, the impact of an ICE conversion system in combination with different fuels on the SSCV criteria. Detailed information can be derived from such tables.

These scores are based on the comparison between all considered options during this research. Since different scenarios are used for the financial impact, a range of relative scores is presented in the table for the LCOE and OPEX criteria. These scenarios are also considered for the CAPEX criteria, but the relative score of the energy supply CAPEX within the high and the low scenarios is comparable. Therefore, the table shows a negligible range for the CAPEX criteria per scenario. Other detailed information can be derived from such a table. For example, MGO generally has relatively high system scores, with an exception for ETS and emission criteria. Another example is the low system scores concerning the volume of the hydrogen. The depicted table shows rounded values of the data used for the decision tool calculations. The system data on which the relative scores are based is presented in Appendix C.

**Table 8.12:** Alternative score table per criteria of the ICE energy supplies. This table shows rounded values.

| | | MGO | LNG | LH2 | CH2 | Methanol | Ammonia |
|---|---|---|---|---|---|---|---|
| System design | TRL | 9 | 9 | 6 | 6 | 7 | 5 |
| | System weight | 9 | 8 | 4 | 3 | 5 | 4 |
| | System volume | 6 | 3 | 2 | 2 | 4 | 3 |
| | Storage temperature | 9 | 4 | 1 | 9 | 9 | 7 |
| | Storage pressure | 9 | 9 | 9 | 1 | 9 | 9 |
| System operation | Efficiency | 6 | 5 | 5 | 5 | 5 | 5 |
| | Amount of conversion steps | 9 | 9 | 9 | 9 | 9 | 9 |
| | Maintenance requirements | 9 | 4 | 3 | 3 | 5 | 4 |
| | Minimal bunker period | 9 | 9 | 5 | 1 | 9 | 6 |
| Financial impact | LCOE | 9-9 | 6-3 | 6-3 | 6-3 | 6-4 | 8-3 |
| | CAPEX | 9-9 | 5-5 | 3-3 | 3-3 | 8-8 | 6-6 |
| | OPEX | 5-4 | 3-2 | 4-2 | 4-2 | 3-2 | 4-2 |
| Safety | Health risk | 5 | 2 | 9 | 9 | 3 | 2 |
| | Flammability risk | 6 | 4 | 4 | 4 | 5 | 9 |
| | Risk during navigation | 8 | 9 | 9 | 9 | 9 | 7 |
| | Nuclear safety | 9 | 9 | 9 | 9 | 9 | 9 |
| | Nuclear security | 9 | 9 | 9 | 9 | 9 | 9 |
| Regulations | Regulations | 9 | 9 | 5 | 5 | 9 | 5 |
| ETS | ETS | 1 | 9 | 9 | 9 | 9 | 9 |
| Emissions | Emissions | 1 | 8 | 9 | 9 | 9 | 8 |

### Alternative scores of the criteria with the highest preference weights

Figure 8.2 shows the alternative scores of the criteria with the highest preference weights as discussed in chapter 7. The gradient of color darkness within each bin in the figure represents the magnitude of the preference weights associated with the criteria.

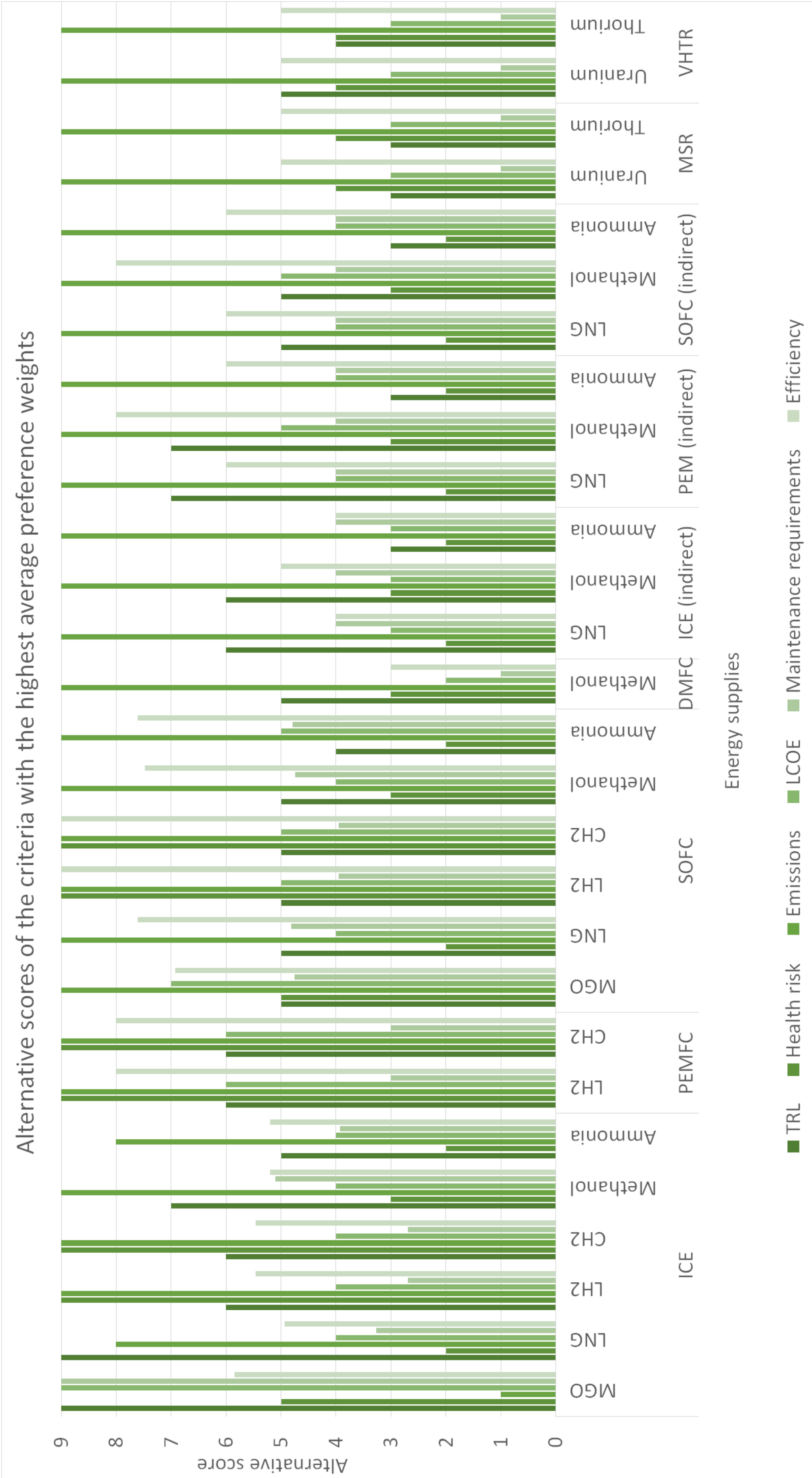


**Figure 8.2:** Alternative scores of the criteria with the highest average criteria weights

### 8.2.2. Category scoring results

To facilitate the visual comparison of the scores and the impact on the SSCV by the different energy supplies, the average alternative scores per criteria category are presented in table 8.3 to 8.9. The significant takeaways per category graph will be discussed below.

*Note that these scores are strictly used to visualize the average impact per criteria category. This visualization of average alternative scores per category can facilitate insights regarding the relative characteristics of the energy supplies. The alternative scores per criteria can vary significantly within their parent categories. For analysis of the detailed scores on the criteria level, please see Appendix D. The calculations by the decision tool make use of the alternative scores on a criteria level to facilitate a more nuanced outcome.*

#### System design category

Figure 8.3 shows a high score for the ICE - MGO energy supply and the nuclear energy supplies. For MGO this can be traced to the high TRL and the favorable storage temperature and pressure. Despite their low TRLs, the high system design scores of the nuclear systems can be traced to the favorable system volume. The lowest system design scores are assigned to the systems that include hydrogen as a fuel. This is due to the high, and therefore inconvenient, volume and weight of the systems.

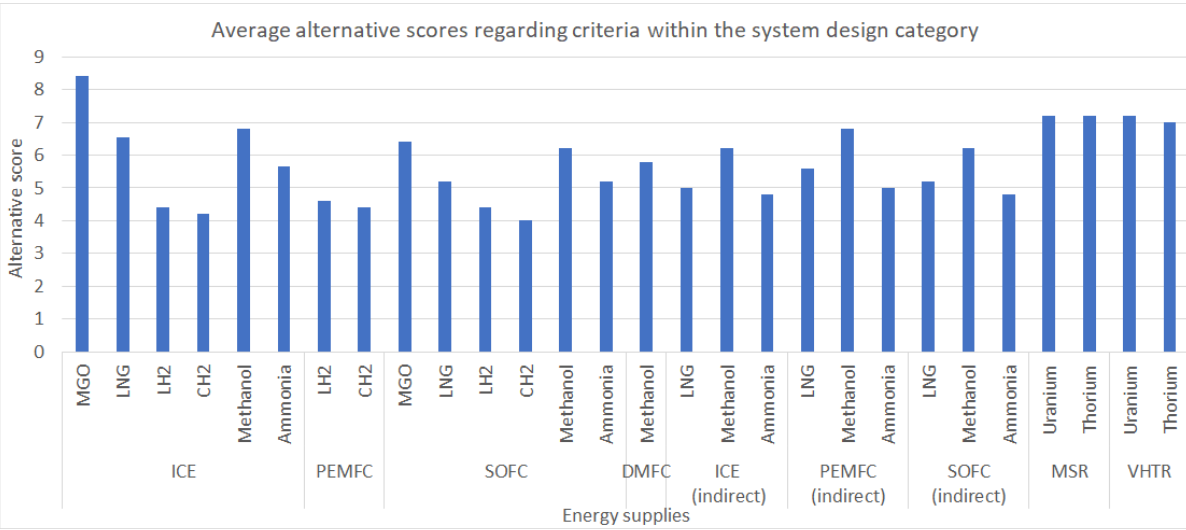


**Figure 8.3:** Average impact of energy supplies on the system design criteria, expressed in system scores 1 to 9. 1 being the least favorable impact and 9 being the most favorable impact.

#### System operation category

Figure 8.4 shows a high score for the ICE-MGO, ICE-methanol, and overall high scores for all direct PEMFC and SOFC energy supplies. The high scores for ICE-MGO and ICE-Methanol systems can be attributed to the absence of constraints on the required bunker period due to their system volume and weight. For the PEMFC and SOFC energy supplies, the high scores can be explained by their high efficiency and low maintenance requirements. The lowest system operation scores are assigned to the systems that have indirect energy pathways, including both MSR energy supplies. The low scores for these systems are due to their low score on the ”amount of conversion steps” criteria.

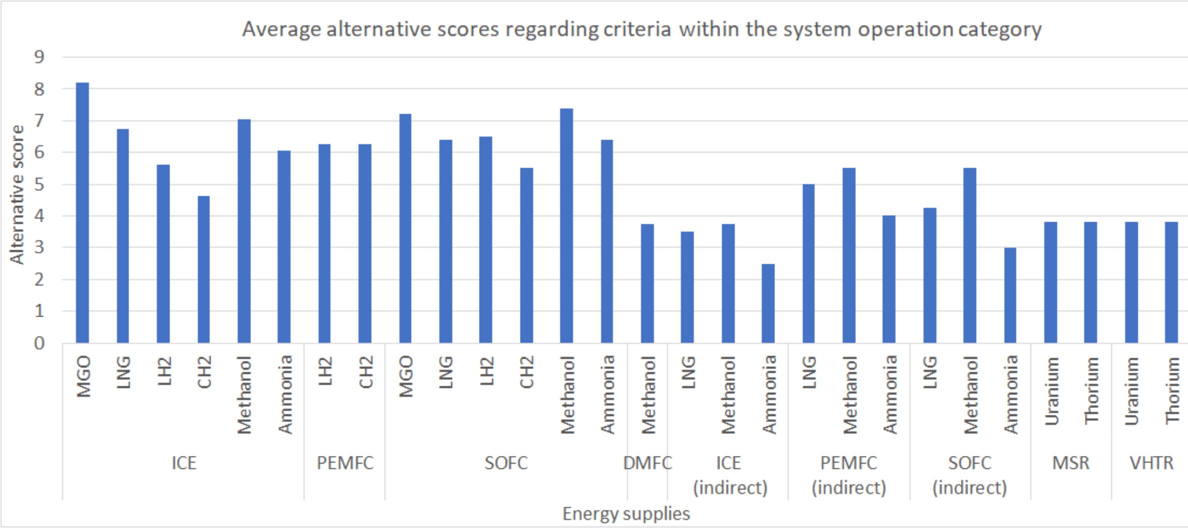


**Figure 8.4:** Average impact of energy supplies on the system operations criteria, expressed in system scores 1 to 9. 1 being the least favorable impact and 9 being the most favorable impact.

### Financial impact category

Figure 8.5 shows the relative system scores of each energy supply concerning different scenarios of the financial impact criteria. ICE-MGO is the most favorable during all cost scenarios. Note that some energy supplies are more sensitive to the difference in cost scenarios than others. furthermore, Note that the order of the most financially favorable energy supplies also varies across different scenarios. This is due to the fact that the cost increase between the low and high scenarios is relatively moderate for this energy supply compared to others. Finally, the unfavorable financial impact scores of DMFC-methanol stand out. This is due to the low efficiency of the system, which translates into a more costly, oversized system and high fuel costs.

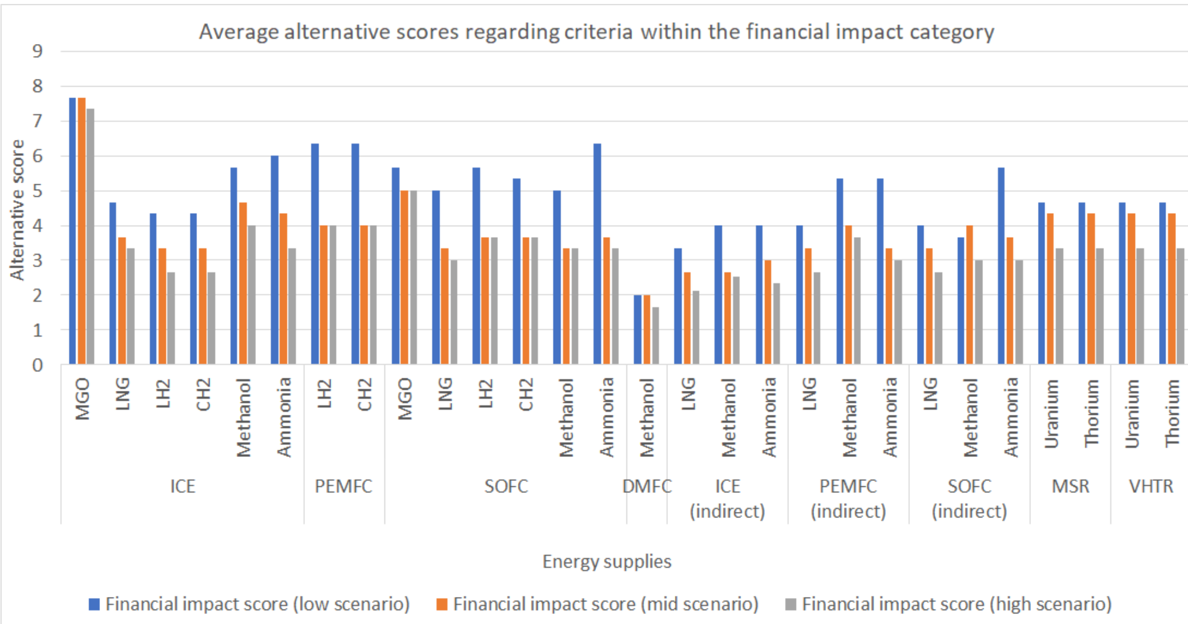


**Figure 8.5:** Average impact of energy supplies on the financial impact criteria, expressed in system scores 1 to 9. 1 being the least favorable impact and 9 being the most favorable impact.

### Safety criteria

Figure 8.6 shows high scores for hydrogen. This is due to their favorable scores concerning health safety risks. Furthermore, the nuclear pathways score low due to the specific additional risks accompanied by the use of onboard nuclear reactors. MSR systems are more exposed to those risks than VHTR systems.

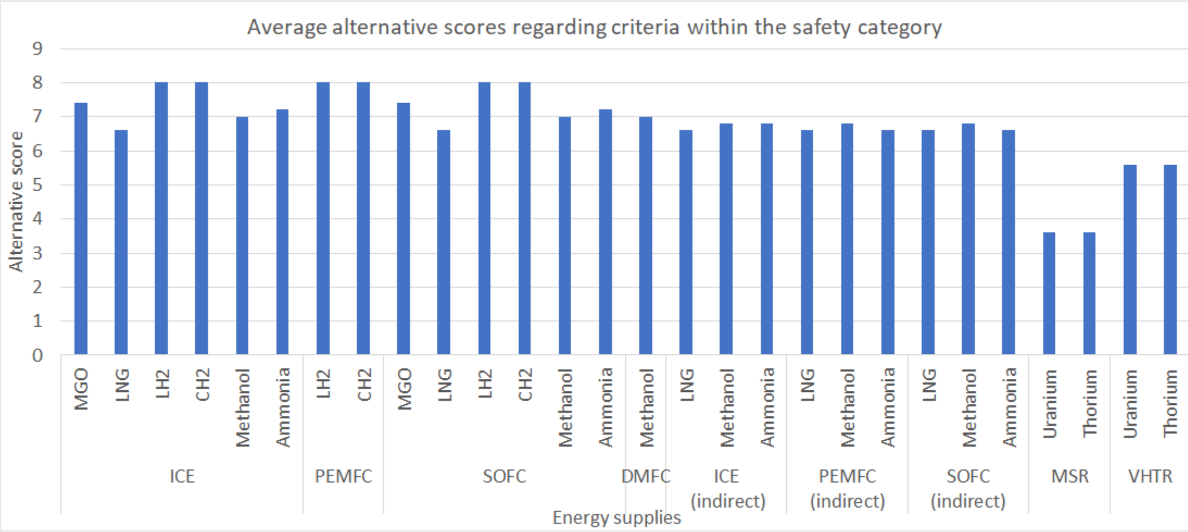


**Figure 8.6:** Average impact of energy supplies on the safety criteria, expressed in system scores 1 to 9. 1 being the least favorable impact and 9 being the most favorable impact.

### Regulations category

Given that the regulation category solely regards the criterion concerning the maturity of international regulations for the utilization of the specific system, the scoring consists of three options. The energy supplies with the highest scores in figure 8.7 are subject to present and developed regulations. For the energy supplies with the mid-range score, regulations are under development and will be available in the near future. The nuclear energy supply receives a low score regarding regulations, as there are currently no ongoing developments or prospects for international regulations.

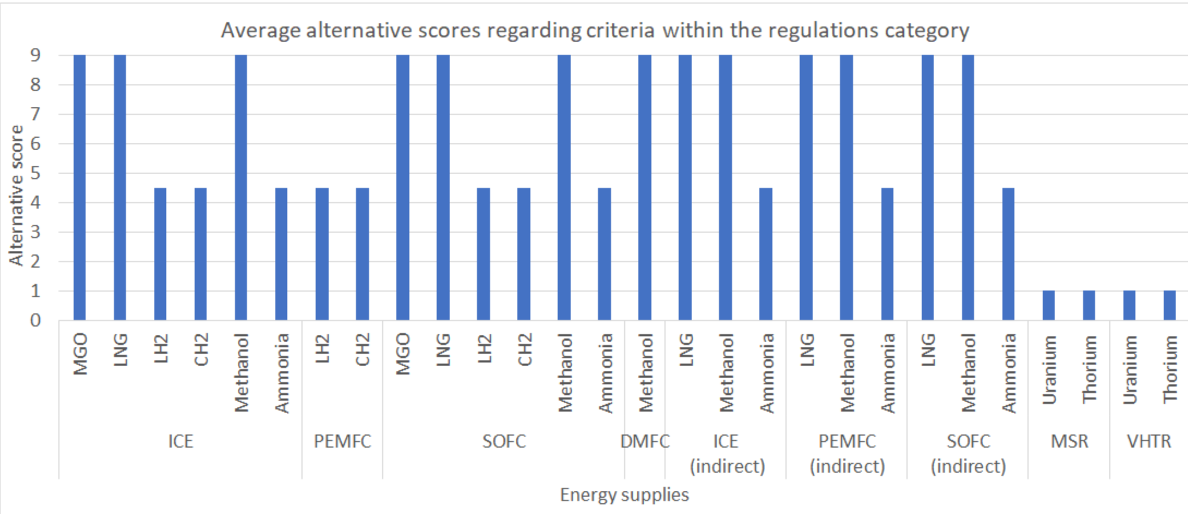


**Figure 8.7:** Average impact of energy supplies on the regulations criteria, expressed in system scores 1 to 9. 1 being the least favorable impact and 9 being the most favorable impact.

### ETS category

The results in 8.8, show that only the ICE-MGO energy supply is considered subjected to the impact of ETS within the scoring model.

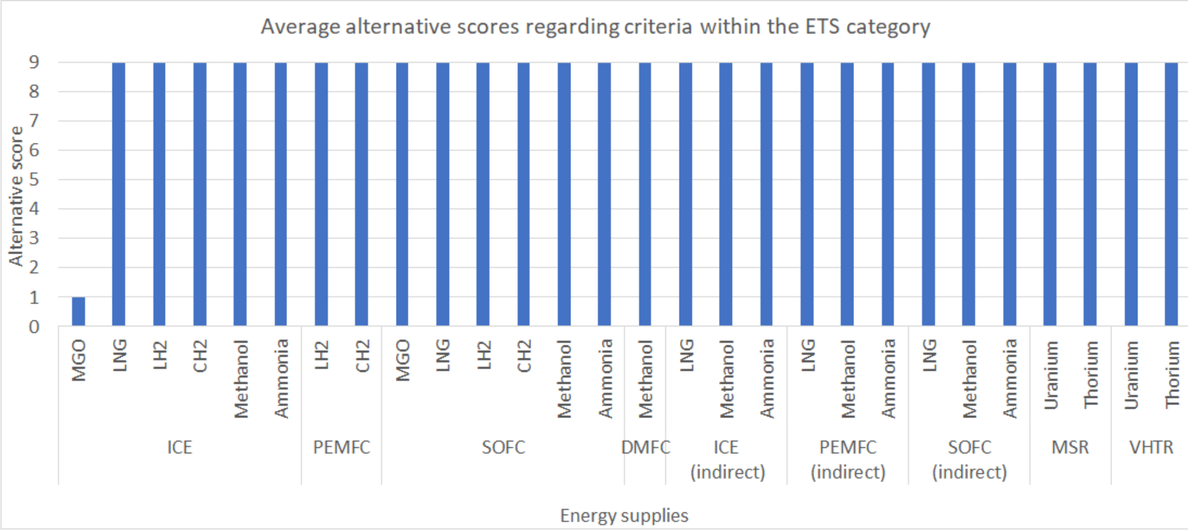


**Figure 8.8:** Average impact of energy supplies on the ETS criteria, expressed in system scores 1 to 9. 1 being the least favorable impact and 9 being the most favorable impact.

### Emissions category

Figure 8.9 shows the impact in terms of emissions on the SSCV, as included in this study. MGO has the largest emissions, followed by LNG and Ammonia. The other fuels are considered GHG emission-free.

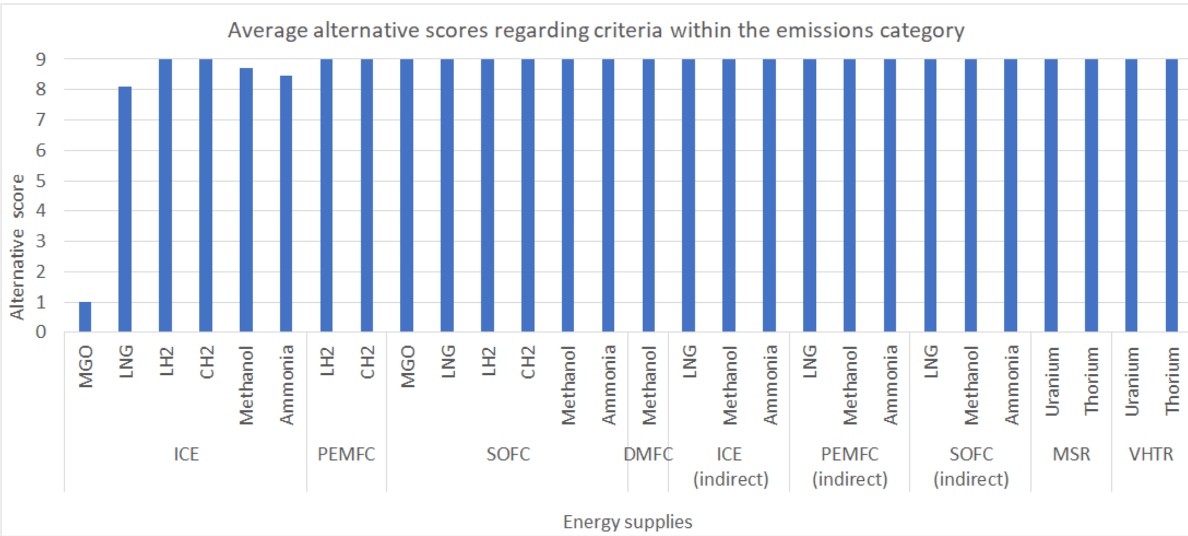


**Figure 8.9:** Average impact of energy supplies on the emissions criteria, expressed in system scores 1 to 9. 1 being the least favorable impact and 9 being the most favorable impact.

## 8.3. Chapter conclusion

The calculations and the results of the alternative scoring of the different energy supplies are explained and presented. The results are presented for the criteria assigned the highest weight and by the visualization of the average score per category. For all alternative scores, please see Appendix D.

Table 8.13 presents the scores of the alternative energy supplies for the criteria with the highest preference weights.

**Table 8.13:** Overview of alternative scores of the alternatives regarding the criteria with the highest weights. This table shows rounded values.

| | **ICE** | | | | | | **PEMFC** | | **SOFC** | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | MGO | LNG | LH2 | CH2 | Methanol | Ammonia | LH2 | CH2 | MGO | LNG | LH2 | CH2 | Methanol | Ammonia |
| **TRL** | 9 | 9 | 6 | 6 | 7 | 5 | 6 | 6 | 5 | 5 | 5 | 5 | 5 | 4 |
| **Health risk** | 5 | 2 | 9 | 9 | 3 | 2 | 9 | 9 | 5 | 2 | 9 | 9 | 3 | 2 |
| **Emissions** | 1 | 8 | 9 | 9 | 9 | 8 | 9 | 9 | 9 | 9 | 9 | 9 | 9 | 9 |
| **LCOE** | 9 | 4 | 4 | 4 | 4 | 4 | 6 | 6 | 7 | 4 | 5 | 5 | 4 | 5 |
| **Maintenance** | 9 | 3 | 3 | 3 | 5 | 4 | 3 | 3 | 5 | 5 | 4 | 4 | 5 | 5 |
| **Efficiency** | 6 | 5 | 5 | 5 | 5 | 5 | 8 | 8 | 7 | 8 | 9 | 9 | 7 | 8 |

| | **DMFC** | **ICE (indirect)** | | | **PEM (indirect)** | | | **SOFC (indirect)** | | | **MSR** | | **VHTR** | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Methanol | LNG | Methanol | Ammonia | LNG | Methanol | Ammonia | LNG | Methanol | Ammonia | Uranium | Thorium | Uranium | Thorium |
| **TRL** | 5 | 6 | 6 | 3 | 7 | 7 | 3 | 5 | 5 | 3 | 3 | 3 | 5 | 4 |
| **Health risk** | 3 | 2 | 3 | 2 | 2 | 3 | 2 | 2 | 3 | 2 | 4 | 4 | 4 | 4 |
| **Emissions** | 9 | 9 | 9 | 9 | 9 | 9 | 9 | 9 | 9 | 9 | 9 | 9 | 9 | 9 |
| **LCOE** | 2 | 3 | 3 | 3 | 4 | 5 | 4 | 4 | 5 | 4 | 3 | 3 | 3 | 3 |
| **Maintenance** | 1 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 1 | 1 | 1 | 1 |
| **Efficiency** | 3 | 4 | 5 | 4 | 6 | 8 | 6 | 6 | 8 | 6 | 5 | 5 | 5 | 5 |

Table 8.14 shows the highest scoring energy supplies within a distinguished upper range, per criteria category.

**Table 8.14:** The highest scoring energy supplies within a distinguished upper range, per criteria category.

| **System design** | | | **Safety** | | |
|---|---|---|---|---|---|
| ICE | MGO | 8.40 | SOFC | LH2 | 8.00 |
| MSR | Uranium | 7.80 | ICE | LH2 | 8.00 |
| MSR | Thorium | 7.80 | ICE | CH2 | 8.00 |
| VHTR | Uranium | 7.80 | PEMFC | LH2 | 8.00 |
| VHTR | Thorium | 7.60 | PEMFC | CH2 | 8.00 |
| **System operation** | | | SOFC | CH2 | 8.00 |
| ICE | MGO | 8.21 | **Regulations** | | |
| SOFC | Methanol | 7.37 | (all converters) | MGO | 9.00 |
| SOFC | MGO | 7.23 | (all converters) | LNG | 9.00 |
| ICE | Methanol | 7.05 | (all converters) | Methanol | 9.00 |
| **Financial impact** | | | **ETS** | | |
| ICE | MGO | 7.56 | All energy supplies excluding: | | |
| MSR | Uranium | 5.67 | ICE | MGO | |
| MSR | Thorium | 5.67 | **Emissions** | | |
| VHTR | Uranium | 5.67 | All energy supplies excluding: | | |
| VHTR | Thorium | 5.67 | ICE | IGO, LNG, Ammonia | |

*Note that table 8.14 shows average alternative scores per category. The alternative scores per criteria within a category can vary significantly.*

# 9 Model Phase C: Energy supply suitability

This chapter describes the approach to obtaining the best-suited energy supply in Section 9.1. The results regarding the suitability of each energy supply are presented and discussed in 9.2. The extent of the suitability of an energy supply to the preferences of the decision-maker is expressed as ”suitability score”. A suitability score higher than 3.5 percent indicates an above-average suitability.

## 9.1. Approach: Energy supply suitability

Firstly, this section shortly explains the definition of the term suitability score in 9.1.1

Secondly, this section describes the process of determining the suitability scores of each energy supply according to the individual decision-maker’s preferences. This is achieved by integrating alternative scores with criteria weights, resulting in suitability scores for each energy supply. These steps are detailed in Section 9.1.2.

Finally, 9.1.3 shows how the suitability scores for energy supplies, based on individual decision-makers’ preferences, will be aggregated into overall suitability scores. These overall suitability scores illustrate the energy supplies’ suitability regarding the combined preferences of the decision-maker group. The best-suiting energy supply can then be identified from this collection of overall suitability scores.

A schematic overview of this process is presented in Figure 9.1

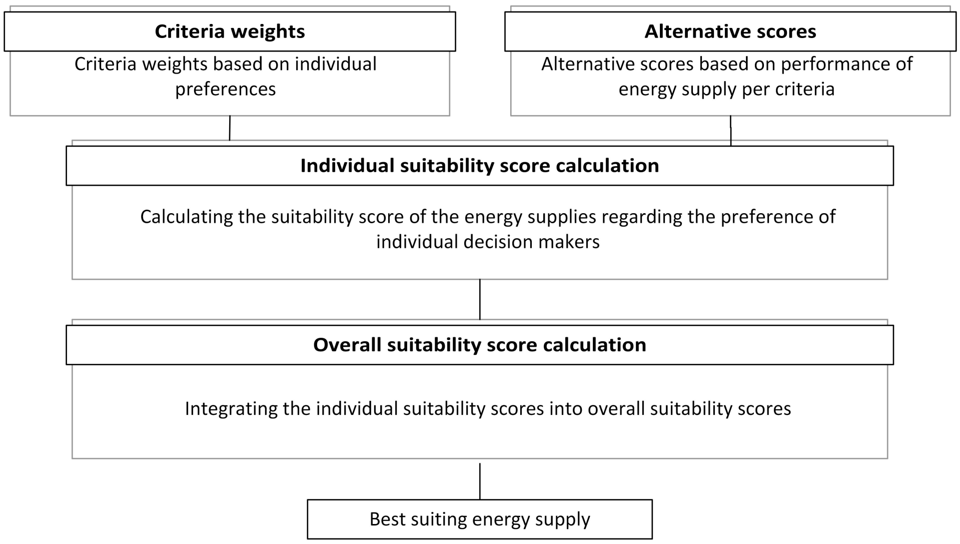


**Figure 9.1:** A schematic overview of the approach of obtaining the suitability scores.

### 9.1.1. Suitability score definition

The definition of the suitability score is the extent to which an energy supply is suitable relative to other energy supplies, based on the preferences of the decision-maker and the impact of the energy supply on the criteria. With this study containing a total of 28 energy supplies, the mean suitability score amounts to 3.57 percent. When assessing the suitability scores, it is important to note that any energy supply with a suitability score exceeding 3.57 percent is considered to be above the average level of suitability.

### 9.1.2. Determining the suitability scores based on an individual decision-maker

As said, first, the decision-maker preferences for each criterion are converted into criteria weights ($W_{criterion}$), as described in Section 7.1. Secondly, The alternatives were assigned scores per criteria, as described in section 8. These two variables are integrated to establish a suitability score for each energy supply, indicating the degree of alignment between the energy supply and the individual decision-makers preferences.

This process results in an overview of energy supply options ranked from the most suitable to the least suitable. The steps for this determination are described below. Due to the different financial scenarios considered in this study, the overview of suitability scores will include the impact of these three scenarios per energy supply.

#### Utilizing the alternative comparison matrix

The first step involves comparing and scoring the various alternative scores with each other regarding a specific criterion. This is done using a comparison matrix. This matrix will be referred to as $A_{comparison}$. Given the evaluation of 28 different energy supplies, this comparative scoring is organized into a 28x28 comparison matrix. A visual example of this matrix can be found in table 9.1. The scores within the comparison matrix reflect the degree of relative suitability of a particular energy supply with respect to Criterion A, as compared to another energy supply. Again, the values indicate to what degree the energy supply in the row is more fitting to the criterion than the energy supply in the column.

**Table 9.1:** Example of an alternative energy supply comparison matrix for criterion A.

| **Criterion A** | **Energy supply 1** | **Energy supply 2** | **...** | **Energy supply 28** |
|---|---|---|---|---|
| **Energy supply 1** | 1.00 | 3.00 | ... | 9 .00 |
| **Energy supply 2** | 0.33 | 1.00 | ... | 0.5 |
| **...** | ... | ... | ... | ... |
| **Energy supply 28** | 0.11 | 2.00 | ... | 1.00 |

#### Associating preferences with alternatives

In the second step, the decision-makers preferences are associated with the alternative scores by summing the values in each row of the alternative comparison matrix, followed by multiplying the result by the criteria weight. This corresponds to the suitability of a particular energy supply regarding a criterion multiplied by the criterion's weight provided by the decision-maker. This results in a decision-maker-specific score per energy supply for a criterion, which will be referred to as $S_{criterion}$. This step is illustrated in equation 9.1. This process is applied to all alternative comparison matrices and, therefore, to all criteria.

$$S_{criterion} = \sum A_{comparison} * W_{criterion} \tag{9.1}$$

$S_{criterion}$ = Suitability score for an energy supply regarding a specific criterion based on the preferences of the decision-maker.
$A_{comparison}$ = Relative suitability score between energy supplies concerning a criterion.
$W_{criterion}$ = Criteria weight based on the preference of the decision-maker [%]

#### Converting specific suitability scores into energy supply suitability score

The energy supply suitability can be determined by the sum of the criterion-specific suitability scores across the criteria within the different categories. To integrate the relative preference between the overarching categories, the sum of the criteria-specific suitability scores per category has to be multiplied by the category weight $W_{category}$. This results in a category-specific suitability score for each energy supply. This category-specific suitability score is referred to as $S_{category}$. Equation 9.2 illustrates this step.

$$S_{category} = \sum_{category} S_{criterion} * W_{category} \tag{9.2}$$

The final step to calculate the energy supply suitability score for an individual decision-maker, referred to as $S_{alternative}$ is illustrated in equation 9.3.

$$S_{alternative} = \sum S_{category} \tag{9.3}$$

The suitability score of a certain alternative energy supply can be expressed as a percentage using the normalized suitability scores. These normalized suitability scores will be referred to as $S_n$. This is done in equation 9.4.

$$S_n = \frac{S_{alternative}}{\sum S_{alternative}} \tag{9.4}$$

An example of an overview of the suitability scores of each alternative energy supply, considering the preference of an individual decision-maker, is presented in table 9.2. The suitability scores of each energy supply, based on the preferences of all decision-makers, will be discussed in chapter 9.2.

**Table 9.2:** Example of suitability scores of all energy supplies, based on the preferences of Heerema's financial manager [%].

| | ICE | PEMFC | SOFC | DMFC | Ref-ICE | Ref-PEMFC | Ref-SOFC | MSR | VHTR |
|---|---|---|---|---|---|---|---|---|---|
| **MGO** | 3.18 | - | 4.31 | - | - | - | - | - | - |
| **E-LNG** | 3.97 | - | 4.06 | - | 3.77 | 3.92 | 3.87 | - | - |
| **LH2** | 3.31 | 3.49 | 3.51 | - | - | - | - | - | - |
| **CH2** | 3.29 | 3.49 | 3.51 | - | - | - | - | - | - |
| **Methanol** | 4.09 | - | 4.08 | 3.60 | 3.84 | 4.05 | 3.81 | - | - |
| **Ammonia** | 3.48 | - | 3.59 | - | 3.20 | 3.35 | 3.35 | - | - |
| **Uranium** | - | - | - | - | - | - | - | 2.92 | 3.02 |
| **Thorium** | - | - | - | - | - | - | - | 2.93 | 3.02 |

### 9.1.3. Determining the suitability scores based on entire decision-maker group

Finally, all energy supply suitability scores of the decision-maker group will be combined into an overall most suitable energy supply design within the group of employees engaged in the decision-making of Heerema's new-build vessel. This is referred to as $S_{HMC}$. This is done by taking the average of all suitability scores of the different decision-makers. This step is illustrated in equation 9.5.

$$S_{HMC} = \sum S_n \tag{9.5}$$

The results of the decision tool, and therefore, the most suitable energy supplies to the preferences by Heerema for the considered SSCV, are presented in 9.2.

## 9.2. Results: Energy supply suitability

In this section, the results from the decision tool calculations will be described and discussed. First, the suitability scores of the financial director are presented to illustrate the impact of the different financial scenarios in 9.2.1. Secondly, the suitability scores of all decision-makers are combined and discussed 9.2.2. Finally, the most-, and the least-suiting energy supplies, based on the gathered criteria preference and energy supply impact, are presented and discussed in9.2.3.

### 9.2.1. Personal suitability scores in different financial scenarios

Figure 9.2 illustrates the alignment of the finance director's criteria preferences with how each energy supply performs regarding these criteria. The difference between the financial scenarios results in a difference between the energy supply suitability with the preferences of the decision-maker. To illustrate the effect of these different financial scenarios for each decision-maker, all three scenarios are considered. Appendix B presents all suitability scores per decision-maker, including the three different financial scenarios. Figure 9.2 illustrate the small impact of the difference in the financial scenarios on the suitability score per energy supply. This phenomenon is found to be present in the suitability scores for the entire decision-maker group. Firstly, this is due to the fact that there are a significant amount of other criteria that remain unchanged within different financial scenarios. Secondly, this is due to the fact that the financial impact is considered relatively between the different energy supplies. Therefore, in either the high, mid, or low financial scenarios, the relative relation between the financial impact per energy supply does not experience any dramatic changes. Finally, the financial impact criteria are overall not as highly rated in terms of priority, compared to other criteria, by the decision-makers. This also results in a lower impact on the suitability scores of the systems in different financial scenarios. Due to this low effect, the suitability scores of the "mid-financial scenario" for each energy supply are used for further analysis.

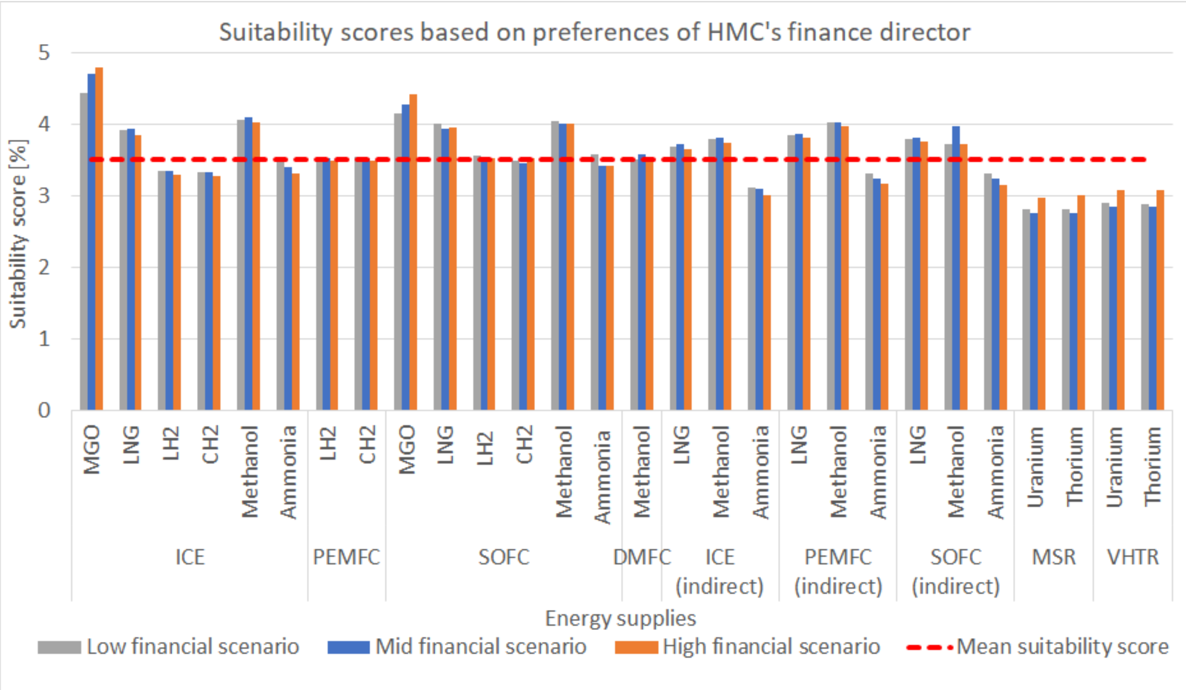


**Figure 9.2:** Suitability score of different energy supplies based on the survey responses of the finance director within Heerema, used to illustrate the impact of different financial scenarios.

### 9.2.2. suitability scores by Heerema's interviewee group

Figure 9.3 presents an overview of the suitability scores of each energy supply to the preferences of each decision-maker of Heerema. A clear pattern can be discovered regarding the more-, and less-suitable energy supplies. Overall a large part of the suitability scores are within a similar range per energy supply. The highest variation in suitability can be found regarding nuclear energy supplies. The research and developer lead, sustainable product developer, and safety advisor within Heerema, give a significantly higher preference to these options than the other interviewed decision-makers. For further analysis, the average suitability score per energy supply of the decision-maker group is considered and presented in figure 9.4.

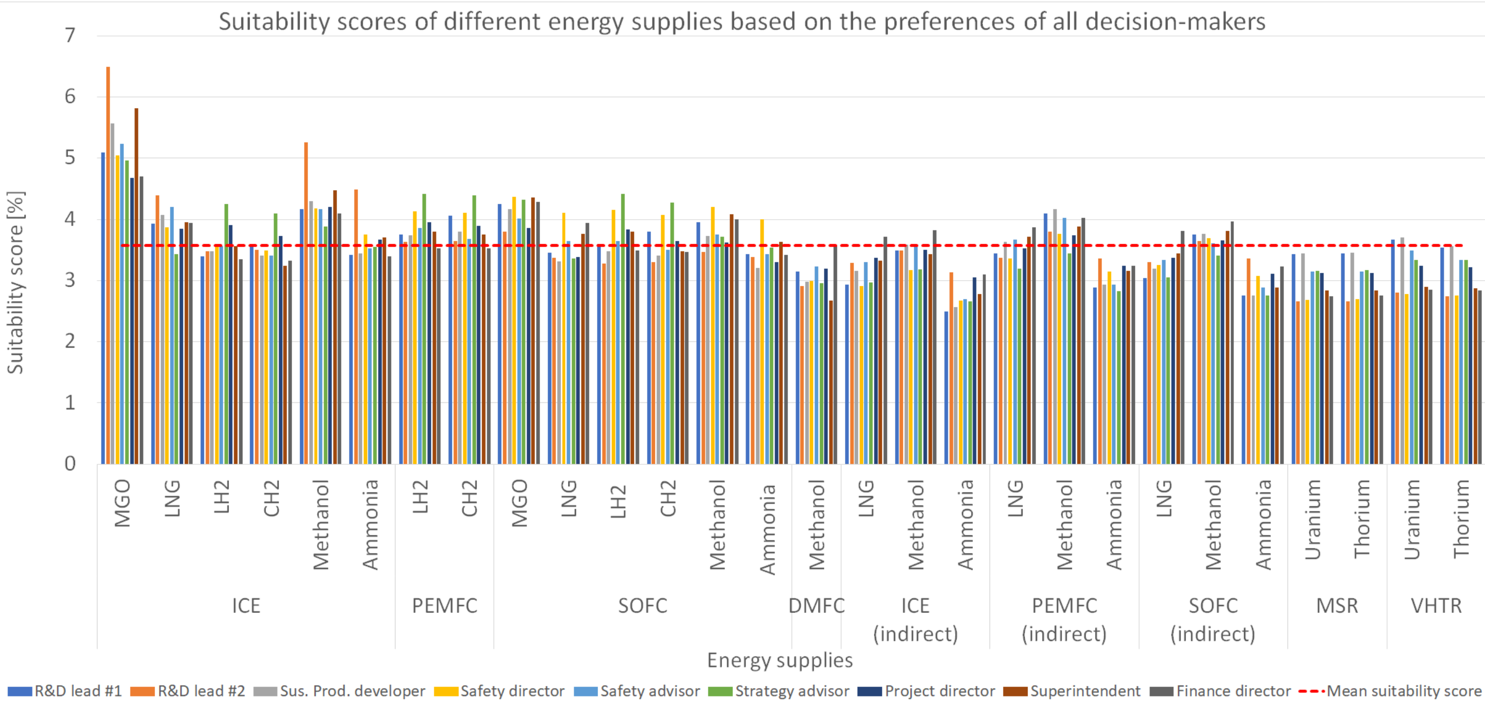


**Figure 9.3:** suitability score of different energy supplies based on the survey responses of all nine decision-makers within Heerema.

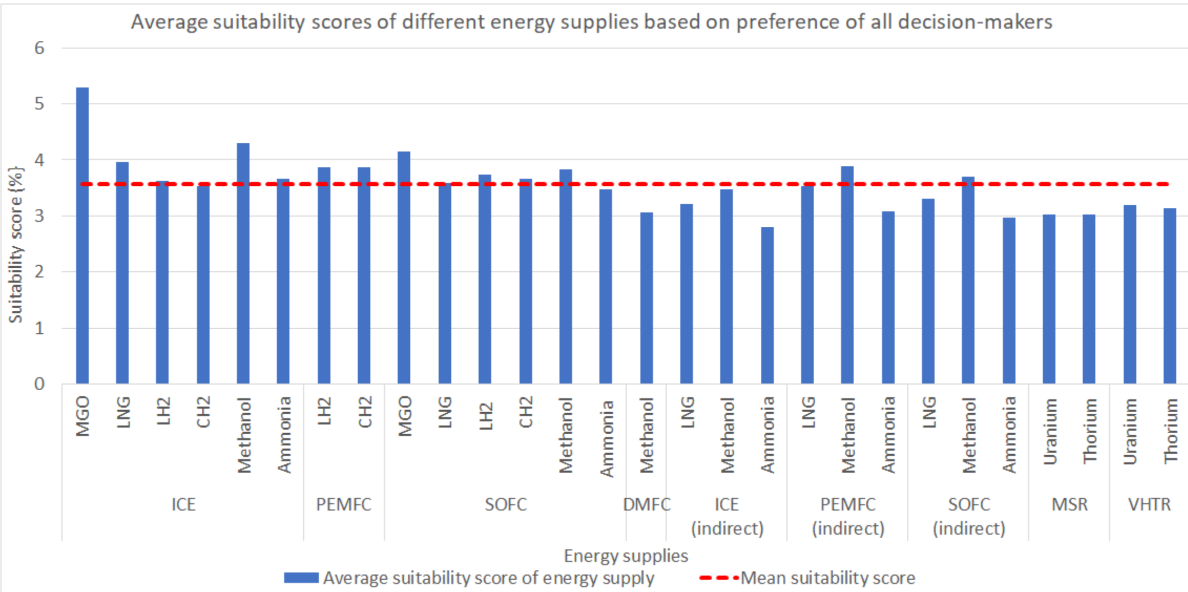


**Figure 9.4:** Suitability score of different energy supplies based on the survey responses of all nine decision-makers within Heerema.

### 9.2.3. The most- and least suiting energy supplies

Table 9.3 shows the energy supplies that are the most suitable with the preferences of the Heerema decision-maker group, as well as the energy supplies that are the least suitable with the preferences of the Heerema decision-maker group. The suitability scores of the energy supplies presented in this table will be discussed in this section.

**Table 9.3:** The energy supply with the highest (left) and lowest (right) suitability scores, based on the preferences of Heerema's decision-makers.

| Energy converter | Fuel | Suitability score [%] | Energy converter | Fuel | Suitability score [%] |
|---|---|---|---|---|---|
| ICE | MGO | 5.29 | ICE (indirect) | Ammonia | 2.79 |
| ICE | Methanol | 4.30 | SOFC (indirect) | Ammonia | 2.98 |
| SOFC | MGO | 4.16 | MSR | Uranium | 3.03 |
| ICE | LNG | 3.96 | MSR | Thorium | 3.03 |
| PEMFC (indirect) | Methanol | 3.88 | DMFC | Methanol | 3.07 |
| PEMFC | LH2 | 3.87 | PEMFC (indirect) | Ammonia | 3.08 |
| PEMFC | CH2 | 3.87 | | | |
| SOFC | Methanol | 3.84 | | | |
| SOFC | LH2 | 3.74 | | | |

### 9.2.4. The most suitable energy supplies

#### Exclusion of MGO

The most suitable energy supply to the preferences of Heerema's experts is, by distance, the Internal Combustion Engine running on MGO. This can be explained due to the combination of the highest-ranked criteria preference weights and the favorable alternative energy supply scores for these specific criteria. As an illustration, the criterion holding the top rank of preference and therefore exercising the most significant influence on the suitability score is TRL. The highest TRL system score is assigned to the ICE-MGO and ICE-LNG energy supply. A second reason for the high suitability is the favorable LCOE. The low system CAPEX and the low assumed fuel prices are the explanation for this. It is important to realize that the ETS costs are not included in this financial approximation. MGO used in a SOFC has a lower TRL but higher efficiency.

Given that the MGO energy supplies examined in this study serve solely as representations of a base-case scenario, they are not considered viable alternative energy supplies due to their non-compliance with emission reduction regulations outlined by the European Union. Consequently, all MGO energy supplies are excluded from the most suitable options presented in figure 9.5. This figure displays the eight highest-scoring energy supplies that fall within a comparable upper range.

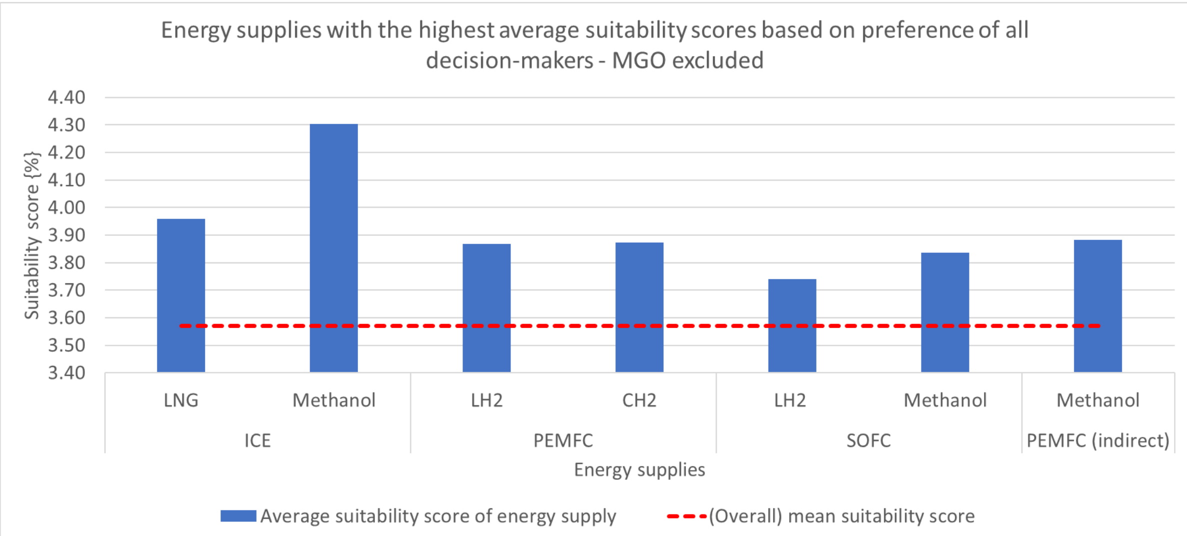


**Figure 9.5:** The eight highest scoring energy supplies in terms of suitability to the preferences of the Heerema interviewee group

#### Methanol in various energy converters

Among the energy supplies that align with the EU emission goals, methanol, used in an Internal Combustion Engine, stands out as the most suitable choice for Heerema's preferences. Methanol energy supplies do not necessarily have the highest scores on the criteria with the highest weight, but they have average upper-range scores over most criteria. The fact that ICE-methanol has a slightly higher TRL than the other energy supply has a big impact on the final suitability score of these systems. This combination causes it to be more suitable than energy supplies that possess high scores on specific criteria with significant weights but also exhibit low scores across a considerable number of criteria or low scores for criteria with substantial preference weights. This effect is also visible in the high score of methanol indirectly used in a PEMFC. Please be aware that methanol carries a relatively unfavorable health risk score; however, the presence of other favorable scores, like maintenance requirements, serves to compensate for this lower score.

#### LNG in an ICE

LNG usage within an Internal Combustion Engine acquires the second-highest suitability score. The system's technological readiness level of 9 enhances its appeal to the decision-makers. However, the criteria scores associated with other prominently weighted preferences do not exhibit notably high scores in relation to LNG-ICE. From a health risk perspective, LNG shows one of the lower scores, Nevertheless, the lower scores are compensated by the high TRL score and preference weight.

#### Hydrogen in various energy converters

In a shared third position range regarding the best-suiting energy supply hierarchy are various energy supplies with hydrogen as a fuel. The high position in the hierarchy can be explained by the high score considering health risks and emissions. Furthermore, the reasonable TRL and LCOE also contribute to this hierarchical position, The criteria where hydrogen has low scores are assigned with relatively low weights by the Heerema experts. These criteria are system volume, system weight, and bunker period limitation.

### 9.2.5. The least suiting energy supplies

#### Ammonia in indirect energy supplies

Some of the lowest suitability scores are assigned to ammonia used in indirect energy supplies. This is due to their low TRL and unfavorable health risk scores in combination with an overall lower range of scores,

#### Uranium and thorium in a MSR

The low scores of uranium and thorium in a MSR are due to the low TRL of the nuclear energy converter, the significantly high maintenance cost, and the unfavorable LCOE. The MSR is slightly less suitable than the VHTR due to the lower nuclear safety and security scores accompanied by the MSR.

#### Methanol in a DMFC

Methanol used in a Direct Methanol Fuel Cell is ranked among the lowest suitability scores. The efficiency of a system has an effect on a significant amount of criteria. Efficiency affects the scale and fuel use of a system. Since Direct Methanol Fuel Cells has the lowest efficiency, a lot of scores are influenced negatively.

## 9.3. Chapter conclusion

Based on the criteria analyzed in this study, the best-suiting energy supply for the new-build SSCV, as assessed in the case study and considering preferences from the interviewed experts at Heerema, is an Internal Combustion Engine utilizing methanol as its fuel. The following favorable energy supply, within the specified context, is an Internal Combustion Engine utilizing LNG. Subsequently following are several energy supply options that exhibit comparable levels of suitability: Methanol, when utilized indirectly in a PEMFC, as well as liquid and compressed hydrogen directly in a PEMFC. Concluding this range are liquid hydrogen and methanol utilized in a SOFC.

# 10 Discussion

In this chapter, a comprehensive discussion is presented concerning the implications of the results and the limits and strengths of the methodology. The discussion regarding the implications of the results is presented in section 10.1. Subsequently, the limitations of the methodology will be discussed in section 10.2.1. Finally, the strengths of the methodology will be appointed in section 10.3.

## 10.1. Results

In this section, the results of the research will be analyzed, and the implications will be discussed. The results will be discussed per model phase.

### 10.1.1. Model Phase A: Criteria and preference weights

#### Individual preferences

The comparison of individual preferences reveals that certain categories or criteria unanimously receive specific priority, while preferences for other categories and criteria show a discrepancy between the decision-makers.

The preferences for the categories that ultimately receive higher average scores show discrepancies when considering each decision-maker's individual preference. This implies that there is a set of categories that are considered important by the experts. Therefore the highest priority cannot be clearly attributed to a single category.

Regarding the criteria within these categories, it is noteworthy that TRL is unanimously assigned by the experts as the most important criterion in the context of system design, despite the relatively wide range of options within this category. The category, including TRL, also receives the highest overarching category preference. This implies that the experts find TRL by distance the most important criterion in a decision-making process for a new-build energy supply. This results in a preference weight that is nearly 1.5 times heavier than the weight of the next most significant criterion. Consequently, energy supplies with a high TRL value enjoy a proportionally significant advantage over other energy supplies. It could be suggested that this slightly decreases the nuance of the evaluation, as the outcomes are so dominated by a single criterion. The high TRL weight suggests that in the short term, MGO and Liquefied Natural Gas LNG in an Internal Combustion Engine are likely to remain the most preferred choices. Furthermore, this underscores that the pace of development of other systems will significantly impact their market share in the SSCV sector.

In the lower preference range, there is unanimous agreement that ETS holds the lowest priority in the decision-making process. The results imply that experts do not consider the payment of ETS to be relatively significant in a decision-making process. This implies that in a decision-making process for a new-build vessel, $CO2_eq$ emitting energy supplies will be relatively less constrained in their preference by the consequences of the ETS compared to the effect of other criteria.

#### Combined preferences of the decision-maker group

The results concerning the average criteria preferences imply the existence of a group of criteria that are evidently preferred by Heerema's experts. These favored criteria contain TRL, health risks, emissions, Levelized Cost of Energy (LCOE), maintenance requirements, and efficiency. These results imply that these criteria will be the dominant driving forces within the decision process for the group of experts. If the broader industry preferences align with those expressed by the decision-makers at Heerema, it implies the possibility that an energy supply excelling in these selected criteria could eventually gain prominence as a commonly favored option.

Finally, a cluster of criteria receives considerably less priority during the decision-making process. Examples of these include the impact of the Emissions Trading System (ETS), clear international regulations, system weight, and the number of conversion steps within the system. This suggests that systems performing poorly in these areas still have reasonable chances. The unanimous lowest priority of ETS renders it the most insignificant during the choice process.

### 10.1.2. Model Phase B: Alternative system scores

The results of the alternative scores imply the relative impact of an energy supply on the different criteria of an SSCV. These results could be used to gain insights into the impact of a certain energy supply regarding certain criteria on an SSCV.

#### Fuel and conversion system dominance

The results suggest a clear clustering of alternative scores that are dominated by the choice of fuel and alternative scores that are dominated by the choice of converter system. The fuel choice dominates the scores regarding storage temperature and pressure, safety, and regulations. The converter system choice dominates the scores regarding system weight, system volume, all criteria in the system operation category, and the financial impact.

The dominance of the converter system can be explained by considering the impact of the systems' efficiency. Efficiency determines the amount of fuel used, which affects the weight and volume scores, subsequently influencing the bunker period score. Lastly, efficiency significantly influences fuel costs, resulting in high OPEX and a high LCOE. An example of this is the generally low scores, combined with the low efficiency of the DMFC energy supply.

#### Financial scenario scores

The range of financial criteria scores provides insight into which energy supplies are relatively more sensitive to high and low financial scenarios. The scores for financial criteria suggest that MGO is the least affected by different financial scenarios. The most substantial variation in financial impact between energy supplies is apparent when examining the low financial scenario. The difference between the mid and high financial scenarios has a less pronounced effect. This implies that if the assumptions for the low scenario were to become reality, the influence of a financially favorable energy supply would become more dominant in the decision-making process.

#### Remarkable scoring patterns nuclear

Lastly, the scores suggest that nuclear energy exhibits distinct score patterns compared to other energy supplies. Particularly, nuclear energy demonstrates relatively favorable scores in terms of volume and OPEX, followed by negative scores for safety risks, maintenance requirements, and CAPEX.

### 10.1.3. Model Phase C: Energy supply suitability

#### Financial scenario impact

The difference in the financial scenarios implies a negligible impact on the relative magnitude of the suitability scores. This can be explained by the inclusion of a considerable amount of criteria in the decision-making process, indicating that a relatively minor shift in costs will not be decisive enough to alter the energy supply preference.

#### Unanimous suitability score pattern

When individual preferences are integrated with the system scores, the outcomes for the most appropriate energy supplies exhibit a similar pattern and hierarchy across all decision-makers. This suggests that there is a collective consensus regarding the most suitable energy supplies. Therefore, the best-suiting energy supply will optimally satisfy the preferences of all decision-makers individually.

#### The best-suitable energy supply validity

The results imply that if emissions were not a concern, MGO used in an ICE would be, by a considerable margin, the best-suiting energy supply according to the preferences of all decision-makers.

The results imply that considering the EU emission regulations, the most fitting energy supply would be methanol used in an ICE. This is primarily because ICE-Methanol boasts an attractive TRL coupled with no other significant low scores for crucial criteria, resulting in a high suitability score.

MGO-ICE stands far ahead with the highest score. The score of methanol-ICE is much closer to the scores of the other energy supplies. it is important to keep in mind that the method is sensitive to assumptions' uncertainty. A shift in these assumptions could substantially alter the ranking of the best-suited energy supplies. This is especially true for energy supplies with closely matched scores. This underscores that the statement that methanol-ICE is definitively the best-suited energy supply becomes invalid due to this sensitivity.

## 10.2. Limitations of the methodology

In this section, the limitations of the methodology will be named and discussed. The limitations will be analyzed per research phase.

### 10.2.1. Literature study

#### Scope of energy supplies

First of all, the scope of the energy supplies considered in this research needs to be addressed. A specific set of fuels and conversion systems is integrated into this scope. The selection of these subjects is largely based on literature and previous studies within Heerema. Nevertheless, the study does not include all possible energy supply options. For example, the use of dual-fuel engines, batteries, or biofuels is not integrated. Apart from fuels, conversion systems, and storage facilities, some available abatement options, like carbon capture and storage (CCS), are also not considered, although they could provide a suitable energy supply complaint to the EU emission targets.

#### SSCV specific efficiencies

During the study, the average efficiency of each energy supply for the SSCV has been made dependent on different operational modes and the extent to which they occur. These SSCV-specific efficiencies bring the tool's approaches closer to reality for SSCV vessels. For each mode, a specific energy capacity factor is considered, representing the requested load from the energy supplies that are online at that moment. However, there is room for improvement in this aspect. Some energy supplies experience an increase in efficiency with a higher load, while for others, it is the opposite. In reality, this can be utilized to the advantage of the ship owner. For instance, with an ICE and nuclear energy supply, achieving the highest possible engine capacity factor would be desirable, whereas, for PEMFC and SOFC, a lower engine capacity factor would be preferred. This can be achieved by having more or fewer energy supplies online per mode. This nuance could significantly impact the efficiency within this research, thereby strengthening the results.

#### Assumptions

During the literature phase, a significant amount of assumptions are made. An error within an assumption can lead to a significant misjudgment within the final selected best-suiting energy supply, especially when the assumptions regard criteria that are assigned the higher preference weights during this research. Some assumptions could be considered questionable and might have a reasonable impact on the final results. Assumptions regarding the SSCV operational requirements and static limits. Assumptions regarding the well-to-wake emissions of the e-fuels. But also, assumptions regarding safety scores and TRLs have a significant role in this research.

Assumptions related to maintenance requirements are exclusively based on expected maintenance costs. Throughout the study, it is assumed that the proportional maintenance requirements across various fuels are directly proportional to their respective maintenance costs. This supposition does not include factors such as man-hours and maintenance frequency. These excluded factors could significantly influence the operational boundaries of the SSCV.

#### Uncertainty

Certain chosen criteria within this research are sensitive to uncertainty. For instance, TRLs provide forecasts about system availability. However, the progress of systems can be accelerated or decelerated due to specific societal developments. Another criterion sensitive to uncertainty regards internationally available clear regulatory framework. A limitation of this research is not including different scenarios for these uncertain criteria.

### 10.2.2. Financial assessment

#### Exclusion of ETS

Throughout this research, ETS is excluded from the financial assessment, primarily due to the assumption that it exclusively applies to fossil fuels. These fossil fuels are not regarded as viable options for future energy supplies. Nevertheless, the inclusion and quantification of ETS in the financial assessment could provide a more realistic insight into the decision problem at hand.

Furthermore, the emissions of the e-fuels in this study are considered (close) to zero. Following the expected future frameworks, these fuels will not be subjective to the ETS system. In reality, these emissions might not be zero due to additional well-to-wake emissions or the use of pilot fuels and lubricants in combustion engines, These emissions, which are excluded during this research, might be subjected to the ETS regulations in reality. Depending on the ETS price, this could have a significant impact on the financial assessment of the energy supplies.

#### Exclusion of fuel availability

During this study is assumed that each considered (zero emission produced) fuel is available in all regions of the globe. In reality, this varies strongly for certain fuels. This does not only impact the local fuel price but also might limit the operational area of the SSCV considered.

#### Uncertainty

Although different scenario analyses have been used during this research, uncertainty remains a dominant factor within the financial assessment. Since this study aims to forecast the long-term financial effects of multiple future vessels' energy supply, it encounters a high amount of variables that can influence this financial outcome. Consequently, a considerable degree of uncertainty surrounds these assumptions and predictions.

### 10.2.3. Model Phase A: Criteria selection and preference Weights

#### Criteria selection

The selection of decision criteria is based on literature and extensive consulting experts within Heerema. Nevertheless, the choice of the selection of the criteria influences the final results. Furthermore, the criteria that are excluded during this research limit its validity. Finally, in some cases, the criteria selection results in difficult comparisons for the decision-makers. For example, the comparison of health risks to nuclear safety. This limits the validity of the results.

#### Sensitivity of interview to interpretation

Although the survey questions used to gather the preferences of the decision-makers are accompanied by a short background description, they remain sensitive to interpretation by the decision-maker. An example of this interpretation can be found in the noteworthy result of low criteria weight concerning OPEX but significant criteria weight concerning LCOE, even though the impact on LCOE for most energy supplies is primarily determined by OPEX. This sensitivity to interpretation limits the robustness of this data.

#### Selection of interviewees

The results of the survey are highly dependent on the selection of the interviewees. First of all, 9 interviewees participated in the survey. The validation of the results would be higher if more interviewees participated. A selection of interviewees with different backgrounds and functions within Heerema is made. This function/background can lead to subjective answers during the survey. Therefore the composition of this selection can have a significant effect on the results of the survey. Finally, only experts are interviewed within Heerema. This is also prone to subjective survey answers and limits the applicability of the research on the overall offshore sector.

#### Exclusion of consistency check

The AHP model describes a consistency check. This consistency check is used to verify the consistency of the answers provided by the individual decision-maker. Due to a large number of criteria and alternatives used in this research, it has been decided not to use the conventional interview method because the interview would be too time-consuming. The question format used in the survey is not suitable for integrating a consistency check. This limits the validity of the preference weights.

### 10.2.4. Model Phase B: Alternative system scores

#### Scaling methods: redundancy exclusion

Some values are scaled to the SSCV characteristics before being assigned a score. This increases the validity of the results regarding a specific SSCV energy supply. Nevertheless, assumptions in this scaling method may influence the scores significantly. The SSCV considered must comply in reality with the DP3 redundancy regulations, These regulations dictate that the SSCV needs to have a sufficient amount of energy supplies available to accommodate unexpected peak loads and remain resilient to unexpected failure of a certain part of the energy supply. During this research, the constraints regarding the redundancy regulations of the considered SSCV are not included. These regulations have a direct impact on the composition and size of the energy supply components. A difference in the composition or size of the energy supply components will have a direct impact on the scores assigned for each alternative. This decreases the validity of the results when specifically regarding a SSCV.

#### Scoring method: subjective scoring ranges and criteria interpretation

The research employs a scoring methodology grounded in existing literature. The conversion of this literature into numerical scores involves a careful process. it is essential to note that this translation process is sensitive to the interpretation by the person responsible for conducting it. This interpretation plays a role in determining which data qualifies for a high score (e.g., 9) and in what range data deserves a lower score. Consequently, such interpretation can potentially introduce unintended advantages, not only within a specific criterion but also across criteria, thereby influencing the overall advantages of one criterion compared to another.

Furthermore, the scoring of the alternatives is, in some cases, sensitive to the interpretation of the definition of the criteria. For example, the scores regarding the pressure of storage for nuclear systems are very favorable since only the storage environment of the fuel is considered, while in reality, someone could argue that there are high-pressure components in this energy supply, which are accompanied by the same or higher risks due to pressure. Cases like this make the scoring method sensitive to interpretation.

### 10.2.5. Model Pahse C: Suitable energy supply calculations

#### Misalignment suitability scores regarding safety

The safety category contains criteria regarding nuclear safety and security that are only applicable to specific alternatives. In the calculation of the suitability scores, all alternatives are measured on these criteria. This results in high scores for all alternatives that do not include nuclear energy. This excludes nuances regarding the safety impact. For example, the scores regarding the highly explosive hydrogen are relatively favorable compared to those of nuclear. This may result in a distorted and unrealistic view of the safety impact of each energy supply.

#### Financial impact

The model assesses the influence of a financial scenario on an energy supply. However, a limitation arises from the fact that the model only compares the low scenario of one energy supply with the low scenario of other energy supplies. This leads to relatively consistent ratios among the different scenarios. In reality, one energy supply might be subjective to the values of a high financial impact, while another energy supply might be subjective to favorable financial values. Comparing these energy supplies across different scenarios would provide a more meaningful and insightful perspective.

## 10.3. Strengths of the methodology

The strengths of the methodology and the application of the tool developed during this research are discussed below. The tool and the accompanying result provide insights into- and grip on the complex decision problem at hand. The method allows a deeper understanding of the multifaceted factors that influence the decision process. The exploratory consideration of a substantial number of criteria and alternatives improves the comprehensiveness of the analysis, offering a holistic view of the impact of a large number of potential energy supplies. Leveraging the expertise of industry professionals regarding information and preferences improves the credibility of the results. The results of this methodology can provide valuable guidance for directing more comprehensive future research efforts. The tool is the first-ever AHP tool designed specifically for SSCV energy supplies and contributes to the innovation toward the unique requirements of this industry. Finally, the tool's usability for strategic decision-making in the context of decarbonization makes it a valuable instrument in guiding sustainable future choices for companies like Heerema and might be applicable for more shipping sectors when the constraints within the tool are adjusted.

# 11 Conclusion

This chapter will address the answer to the main research question and propose recommendations for future studies.

To answer the main research question **”Which energy supply is best suited for a new-build SSCV, meeting the European Union emission targets, taking into account the preferences of experts?”** various aspects have been thoroughly examined.

Primarily, the use of employing an AHP model has proven effective in tackling such complex decision-making problems. Notably, the incorporation of criteria categorization within the model has proven advantageous, given the multitude of diverse criteria that must be considered during this type of decision-making challenge.

Subsequently, research and consultations with experts within Heerema suggest that the most significant requirements and limits concerning an SSCV fall into two categories. The first category relates to the operational profile of an SSCV, while the second category contains the vessel’s static limits. The requirements and limits associated with the operational profile are identified as the need to support five operational modes. Furthermore, careful attention must be given to constraints related to the vessel’s bunkering period. The static limits and requirements are identified as specific weight and volume parameters, ensuring the vessel’s operational capability at certain depths. However, this analysis is sensitive to insufficient assumptions regarding the selection and value assignment of these limits and requirements.

Furthermore, it can be concluded that the comprehensiveness of the choice concerning the included criteria significantly impacts the validity of the results. The results regarding the score determination of these characteristics and criteria provide an indication of the impact of various energy supplies on an SSCV. It is noteworthy that the assigned efficiency of an energy supply affects the score of a significant number of other criteria. Given that the scores, in some cases, regard future estimations, uncertainty must be considered in assessing this impact.

Regarding the financial impact of energy supplies on an SSCV, the research suggests that the financial effect is driven by OPEX for all conventional and e-fuels, while for nuclear, the dominant factor leans more toward CAPEX. The OPEX-dominated energy supplies are significantly influenced by the efficiency of the system, due to the impact on its fuel usage. The use of various financial scenarios provides insight into potential future uncertainty. MGO used in an ICE stands out as the financially most attractive energy supply. Note that in this assessment, the MGO fuel price does not include ETS. Furthermore, MGO is a non-compliant fuel regarding the EU emission goals and is, therefore, not considered a viable option. Regarding the EU emission goal-compliant fuels, direct SOFC and PEMFC energy supplies are financially favorable due to their low maintenance costs and high efficiency, resulting in lower fuel costs compared to other conversion systems. Finally, the research results suggest that the financial scenarios have a negligible impact on the relative suitability scores of the various energy supplies. This is because suitability scores rely on numerous criteria, so relatively small variations due to financial scenarios have limited impact. It is important to note that this assessment solely examined the financial effects of different energy supplies within the same scenario.

Insights gathered from interviews with Heerema experts suggest a strong priority for high TRLs when it comes to selecting a new energy supply. To a lesser extent, there is also substantial attention placed on health risks, emissions, LCOE, maintenance requirements, and efficiencies. The sequence of priority within this group of criteria varies among the decision-makers. On the other hand, survey results clearly suggest that experts consider the effect of the ETS the least significant in the decision-making process. Also, the clarity of the regulatory framework, the number of conversion steps, system weight, storage temperature, and storage pressure are considered less important than most other criteria. However, the reliability of this information is limited by the sensitivity of interpretation of the interview by the decision-makers.

The converted data from literature study into alternative scores provides insights into the impact of a certain energy supply on an SSCV regarding specific criteria. Nevertheless, it must be concluded that the scoring of these alternatives is, in some cases, subjective and based on assumptions.

Regarding addressing the main research question, it is important to note that this study is exploratory in nature and requires making several assumptions while selecting an extensive but still limited set of criteria. These factors could be further refined in future research. Additionally, the results are subject to uncertainty, partly due to a limited number of interviews conducted and the potential for future developments in techniques, finances, and regulations. Therefore, the results should not be interpreted as identifying a future energy supply, which should or should not be installed on a new-build SSCV, with absolute certainty. However, a ranking of energy supplies that seem most suitable based on this research can be identified. This set of energy supplies is interesting to focus on in future research. Finally, a set of energy supplies can be regarded as least suitable.

From the gathered preferences and alternative scores, it can be concluded that MGO in an ICE receives the highest suitability scores of all considered energy supplies. It is important to emphasize that the financial impact of ETS has not been included in this assessment. Furthermore, it is important to note that MGO energy supplies are assumed to be non-compliant with the EU emission goals. Therefore, MGO in an ICE is not considered a viable future energy supply for a new-build SSCV. MGO energy supplies are only used to illustrate a base-case scenario in this study.

Finally. the energy supplies that are compliant with the EU emission goals, and receive the highest suitability scores within this research are ranked and presented in descending order. This ranking can guide future research priorities. The energy supply with the highest suitability score is methanol used in an ICE. E-LNG used in an ICE follows in second place. Methanol when indirectly used in a PEMFC, as well as both liquid and compressed hydrogen in a PEMFC, follow within a similar range of suitability. Finally, methanol and liquid hydrogen in a SOFC conclude the ranking of energy supplies with high suitability scores. The least suitable energy supplies are identified as ammonia used in an ICE, uranium and thorium used in a MSR, and Methanol used in a DMFC.

In conclusion, creating a decision tool that incorporates various criteria for selecting a new-build SSCV energy supply, along with the consideration of a substantial number of energy supplies, can offer insights into a complex decision challenge. Particularly regarding to expert preferences and an indication of the impact of different energy supplies on a new-build SSCV. Furthermore, it can serve as a starting point for discussions among decision-makers, potentially leading to more informed and considered steps in the decision-making process's progression. Finally, energy supplies that align with EU emission goals and are considered the most suitable in this report can be the focus of more in-depth research to assess their impact and suitability. According to this research, methanol used in an ICE stands out as the most suitable energy supply for a new-build SSCV and could therefore be considered with priority. Conversely, the energy supplies deemed less suitable are of lesser interest for future research and decision-making considerations.

# 12 Recommendations

In this chapter, recommendations regarding further research are provided. These suggestions for further research seek to improve the methodology's reliability and robustness by addressing its current limitations. The suggested research will enhance the support concerning the decision-making process regarding the energy supply choices for new-build SSCVs, and potentially other shipping sectors.

### An in-depth study regarding the identified best-suiting energy supplies

Based on the research results, a ranking of energy supplies is identified as most suitable for a new-build SSCV. Conducting a more in-depth study, including comparisons regarding the implications of implementing this set of energy supplies can strengthen the evaluation of the optimal choice in terms of an EU emission goal-compliant energy supply for an SSCV. Since methanol used in an ICE is identified as the most suitable energy supply in this research, this energy supply could be of priority for further research. Nevertheless, it is not advisable to neglect the other reasonable scoring energy supplies, due to the uncertain, and, exploratory nature of this research.

### More nuance regarding the layout of the energy supplies

To obtain a more accurate assessment of the most suitable energy supply, it is essential to introduce more detailed and nuanced energy supply options within the decision-making methodology. Examples of these energy supplies are systems making use of dual-fuel engines, carbon capture and storage (CCS) systems, batteries, and biofuels. Also, energy supplies that comply with the EU emission goals in phased emission reduction steps are of interest.

### Expand and enhance the selection of criteria

A broader set of criteria could provide a more comprehensive view of the decision-making problem. Furthermore, providing more nuance regarding the selection and definition of the criteria could minimize ambiguity during the scoring of the alternative and assessing criteria weights, for example regarding safety and security risks.

### Increase nuance in the approach of assigning scores to alternative

Since, in some cases, the scoring of alternatives depends on assumptions, future research could involve a more detailed and nuanced scoring approach which will lead to more realistic scores for alternatives.

An example could be incorporating redundancy requirements for an SSCV compliant with DP3 regulations. In the current methodology, the sizing of the energy supply is based on a single engine room which provides the energy for the entire vessel. In reality, this layout is not compliant with the DP3 regulations that are mandatory for the considered SSCV.

Another example involves optimizing energy supply-specific efficiency through adjustments in the engine capacity factor. This optimization takes into account the unique efficiency characteristics of each energy supply across different load scenarios. By optimizing the engine capacity factor during various operational profiles and considering the "spinning reserve" requirements, it is possible to achieve the highest efficiency for each specific energy supply. This approach enhances the quality of the suitability scores by providing a more objective comparison.

### Compare energy supplies across financial scenarios

The research methodology utilizes three different financial scenarios to address financial forecast uncertainty. Assessing these scenarios provides insight into how sensitive an energy supply is to this financial uncertainty. However, in this research, energy supply comparisons were made under the assumption that they all faced the same scenario, such as a high fuel price scenario. In reality, this may not hold, as fuel price scenarios can differ among various fuels. For future research, it would be valuable to compare energy supplies under varying scenarios to gain a deeper understanding of uncertainty.

### Examine the financial impact of ETS

During this study, the financial impact of ETS is not included in the financial evaluation of the energy supplies. By including the financial impact of ETS regarding the MGO energy supplies, a more realistic base case can be created. Furthermore, during this research, the assumption is made that ETS is not applicable for the considered E-fuels and nuclear fuels. In reality, the future regulations regarding these fuels are uncertain. Therefore, it is interesting for further research, to include the possible financial impact of ETS on each energy supply.

### Enhance interview methodology

Expanding the pool of interviewees to include individuals with diverse backgrounds and roles can enhance the reliability of the interview results. Providing more context regarding the criteria and increasing the number of questions during the interviews can also lead to a more comprehensive understanding of the experts' preferences. Implementing an extended set of comparisons during the interviews allows for a consistency check in the Analytic Hierarchy Process to validate the reliability of decision-makers responses. Finally, presenting the interview results back to the participants could initiate discussions within this group regarding their different priorities, potentially leading to new insights and a more considered preference for the following stages of the decision-making process.

### Mitigate uncertainty

Develop methods to reduce uncertainty in the decision-making process by addressing factors like assumptions, limited criteria, and future developments. An example of such a method is creating realistic scenarios regarding regulatory framework development, fuel availability, and technological developments.

### Conduct a sensitivity analysis

Finally, it is advised to conduct a sensitivity analysis to validate the research results. This sensitivity analysis will provide valuable insights into how certain error margins regarding assumptions or misinterpretations can impact the outcomes. The reliability of the research results depends upon the method's sensitivity, making this analysis crucial for a comprehensive evaluation.

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# A
# Survey tool questions

The figures in this appendix show the questions in their original format, as conducted among the chosen group of Heerema decision-makers. The decision-makers are able to drag the different criteria, and this way, create a hierarchical ranking of importance. Questions 5 and 6 are an exception to this format. The values provided alongside each option represent the average preference among the decision-makers. A higher score reflects a stronger preference, while a lower score indicates a relatively weaker preference.

1

Q1 Tech. - Rank the technical design aspects of a new-build energy supply in order of...

| Veld | Gemiddelde |
|---|---|
| Technological Readiness Level: .... Rate this category high if you prefer a well-established technique that the industry has extensive knowledge and infrastructure about. | 1.00 |
| System weight: .... Rate this category high if you prefer a system that does not impact the weight limitations of your cargo. | 4.00 |
| System volume: .... Rate this category high if you prefer a system that does not impact the volume limitations of your cargo. | 3.00 |
| Storage temperature: .... Rate this category high if you prefer a fuel that can be stored under ambient temperature. (Extreme temperatures demand better-trained personnel and advanced fuel handling methods). | 3.56 |
| Storage pressure: .... Rate this category high if you prefer a fuel that can be stored under ambient pressure. (Extreme pressure demand better-trained personnel and advanced fuel handling methods.). | 3.44 |

Q2 Oper. - Rank the operational aspects of a new-build energy supply in order of prior...

| Veld | Gemiddelde |
|---|---|
| Efficiency: .... High efficiency maximizes storage volume and weight usage. | 2.11 |
| Amount of conversion steps: .... Prioritize low conversion steps; steam methane reformers or ammonia crackers may add more auxiliary systems. | 3.44 |
| Maintenance requirements: .... Rate high for a simple and cost-effective system maintenance. | 1.89 |
| Minimal bunker period .... Rate high if a minimal bunker period of 6 weeks is of high importance to you. | 2.56 |

**Figure A.1:** Survey questions 1 and 2 from the survey conducted among the chosen group of Heerema decision-makers.

2

## Q3 Eco. - Rank what economic aspect should be focused on during the decision making o...

| Veld | Gemiddelde |
|---|---|
| Levelized Cost Of Energy (LCOE): .... The financial decision-making should be focused on the cost per MWh over the whole lifetime of the vessel. Integrating CAPEX & OPEX of initial investment costs and OPEX of fuel costs. | 1.33 |
| Initial investment costs: .... Prioritize when the initial investment cost of the energy supply is of high importance | 2.22 |
| Fuel price & maintenance: .... Prioritize when the expected fuel price and maintenance for the system is of high importance | 2.44 |

## Q4 Safe. - Rank the safety aspects for the design of a new-build energy supply based o...

| Veld | Gemiddelde |
|---|---|
| Health risk: .... Focus on health risks related to the energy supply. | 1.78 |
| Flammability risk: .... Focus on flammability risks related to the energy supply. | 2.67 |
| Risks during navigation: .... Focus on risks during the navigation of the vessel caused by a specific energy supply. For example the risks during bunkering or a collision | 3.89 |
| Nuclear Safety: .... Prioritize when safety risks regarding nuclear power are highly concerning to you. | 3.89 |
| Nuclear security: .... Prioritize when the risk of sabotage and/or other harm by third parties is highly concerning to you. | 5.22 |
| The blocks below this one, are of equal importance to me | 3.56 |

**Figure A.2:** Survey questions 3 and 4 from the survey conducted among the chosen group of Heerema decision-makers.

Question 5 asks about a level of importance attributed to the need for well-defined international regulations. This significance is indicated on a scale from 0 to 100. Question 6 employs a binary format, posing a ”yes” or ”no” question. Decision-makers are asked to express their agreement or disagreement with the given statement.

3

## Q5 Regul._1 - Rate of preference

| Veld | Gemiddelde |
|---|---|
| Rate of preference | 68.00 |

## Q6 ETS - "I am prepared to pay for Emission Trade System (ETS), starting form 2026, when this will result in an overall more convenient energy supply." (Question 6 of 8)


## Q7 Emissions - Please indicate your priority regarding the abatement of CO2 equivalent emi...

| Veld | Gemiddelde |
|---|---|
| Partial emission abatement .... Install, when more convenient, a system that abates emissions conform to EU guidelines, but may need adjustments before 2050. | 1.33 |
| 100% emission-free .... Install a 100% emission-free system compatible with 2050 EU guidelines. | 1.67 |
| No abatement .... No action to abate emissions will be concidered. | 3.00 |

## Q8 Catog. - Please indicate your preference for the importance of the main categories b...

| Veld | Gemiddelde |
|---|---|
| System design .... (TRL, System Weight/Volume, Storage Temperature/Pressure) | 3.22 |
| System operation .... (Efficiency, Amount of conversion steps, Maintenance requirements) | 3.11 |
| Emissions .... (100% CO2 equivalent abatement) | 3.00 |
| Economics .... (LCOE, Initial investment costs, Fuel costs) | 3.22 |
| Regulations .... (Seamless internationally operational) | 5.22 |

**Figure A.3:** Survey questions 5, 6, 7 and 8 from the survey conducted among the chosen group of Heerema decision-makers.

| | | |
|---|---|---|
| | | 4 |
| Safety .... (Health-, Flammability-, Navigation risks, Nuclear safety/security) | 3.22 | |
| ETS .... (Prepared to pay for ETS) | 7.00 | |

# B
# suitability scores per decision-maker

The graphs in this Appendix show the suitability scores of the different alternatives, based on the preference weights provided by individual decision-makers. The graphs contain the suitability scores of the different financial scenarios.

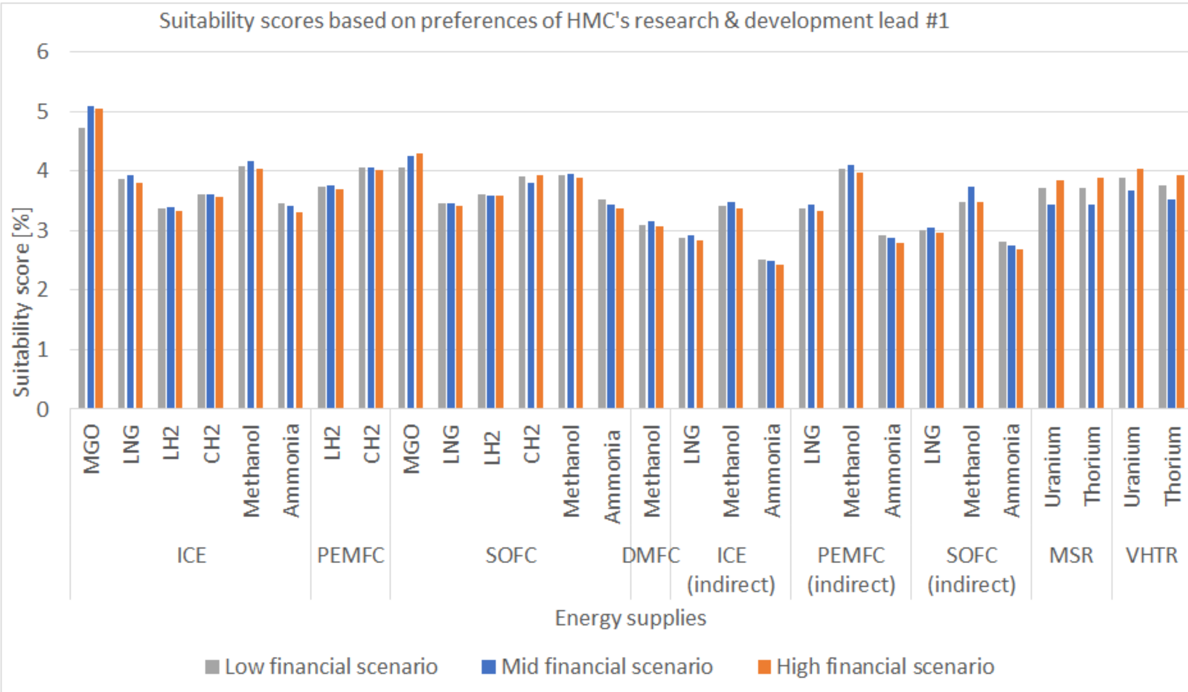


**Figure B.1:** suitability score of different energy supplies based on the survey responses of the first research & development lead within Heerema.

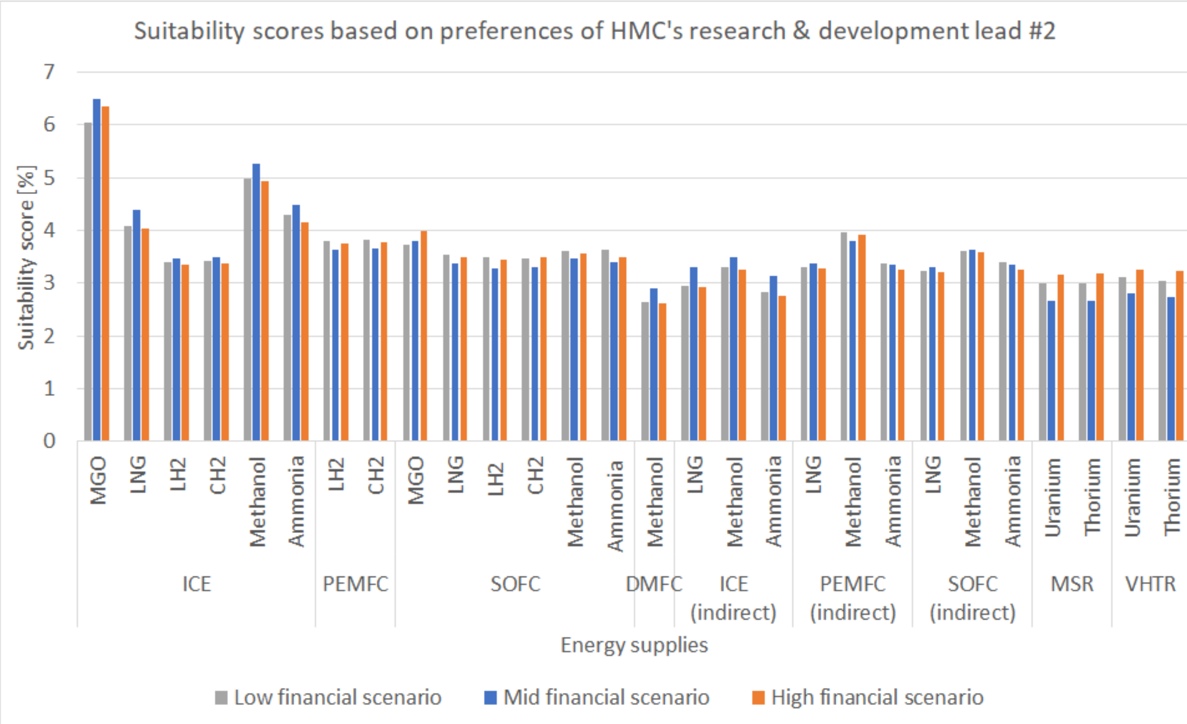


**Figure B.2:** suitability score of different energy supplies based on the survey responses of the second research & development lead within Heerema.

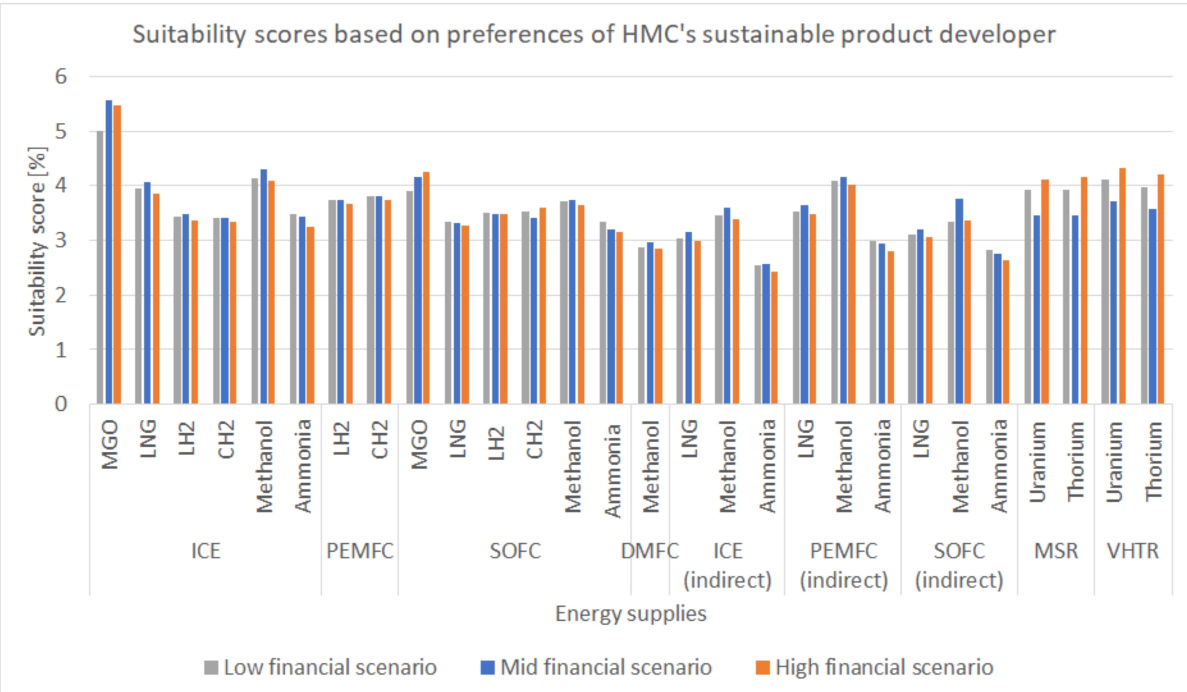


**Figure B.3:** suitability score of different energy supplies based on the survey responses of the sustainable product developer within Heerema.

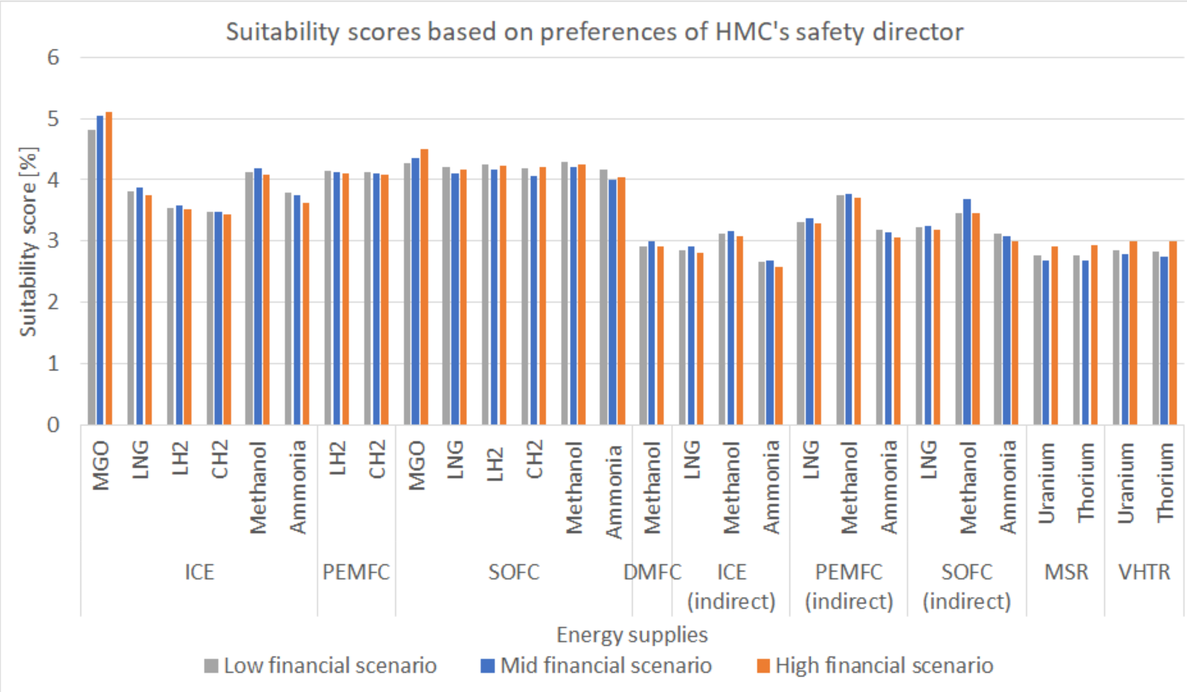


**Figure B.4:** suitability score of different energy supplies based on the survey responses of the safety director within Heerema.

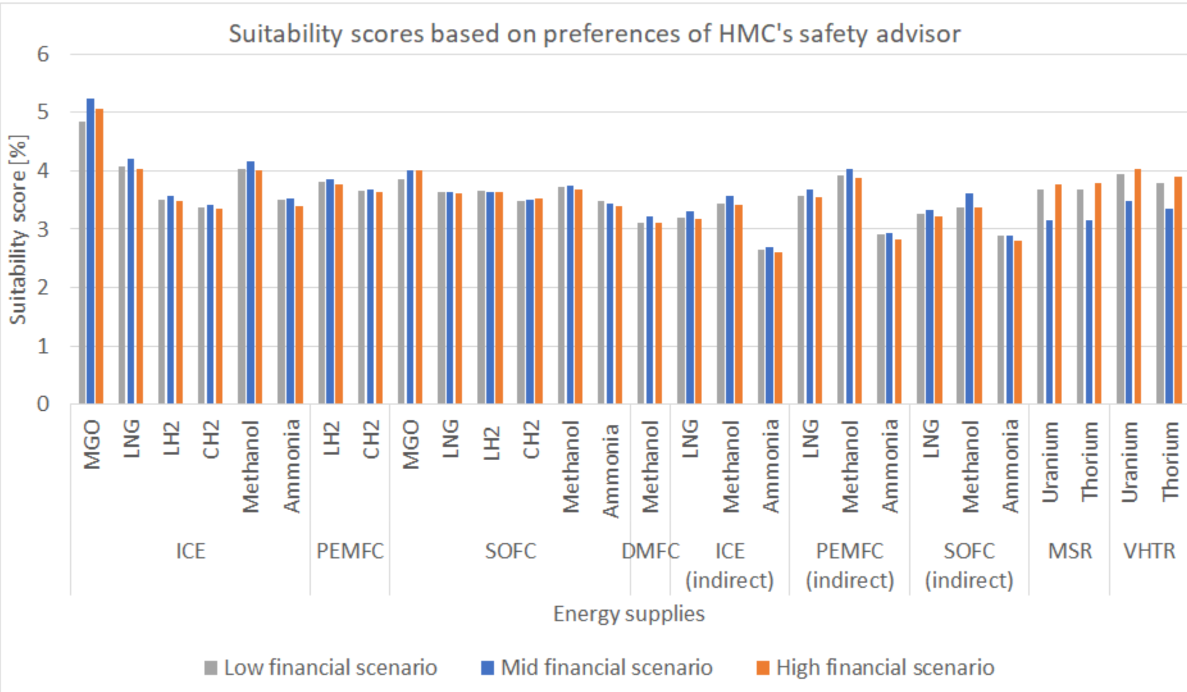


**Figure B.5:** suitability score of different energy supplies based on the survey responses of the safety advisor within Heerema.

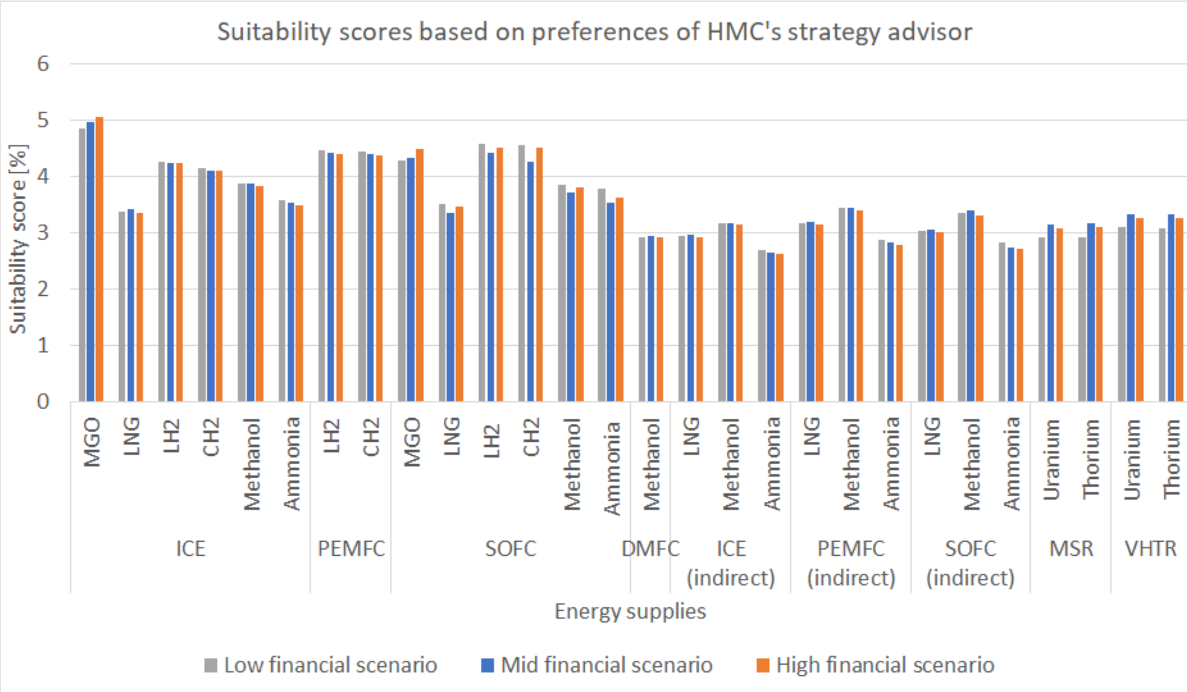


**Figure B.6:** suitability score of different energy supplies based on the survey responses of the strategy advisor within Heerema.

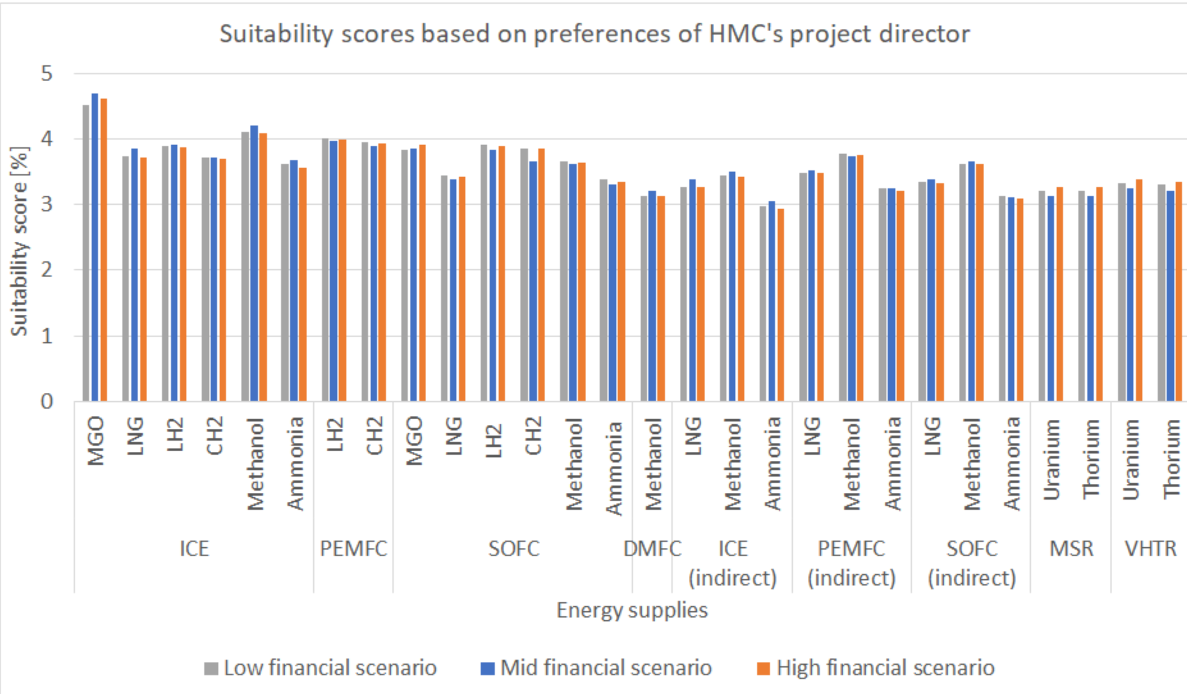


**Figure B.7:** suitability score of different energy supplies based on the survey responses of the project director within Heerema.

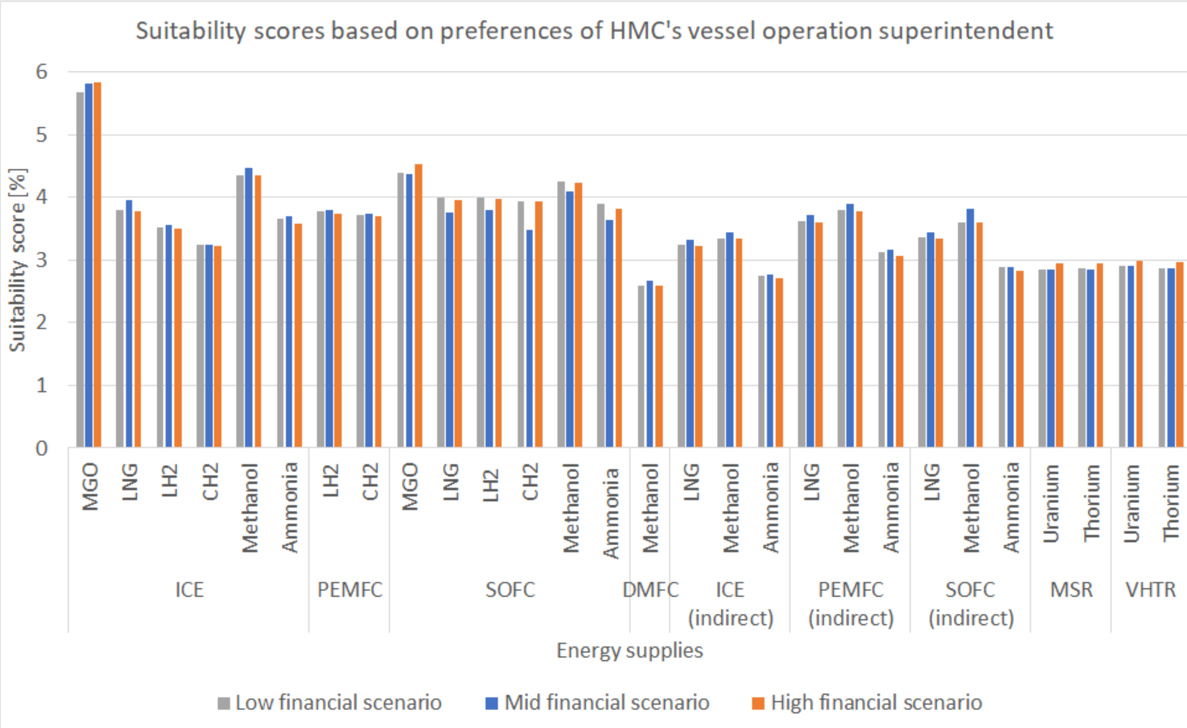


**Figure B.8:** suitability score of different energy supplies based on the survey responses of the vessel operation superintendent within Heerema.

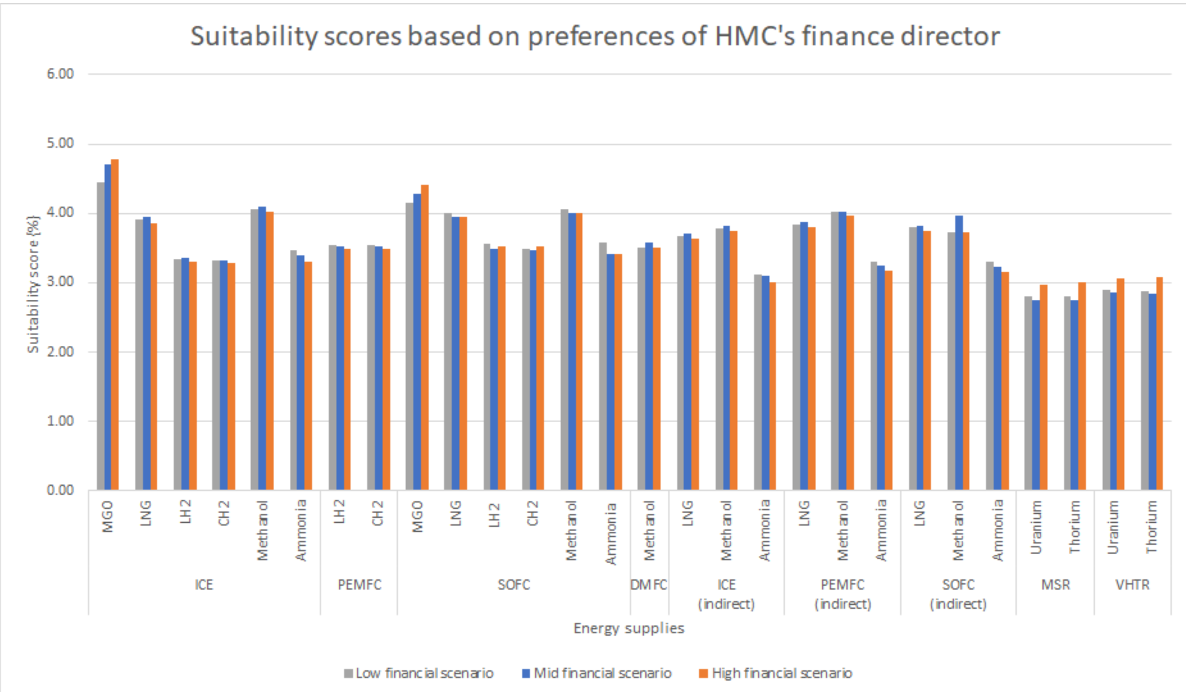


**Figure B.9:** suitability score of different energy supplies based on the survey responses of the finance director within Heerema.

# C

# Data utilized for scoring alternatives

The tables in this Appendix display the data used for assigning scores to each alternative. This data is collected either through literature research or by performing calculations to adapt it to the operational profile of the SSCV Sleipnir.

**Table C.1:** Data utilized for scoring of alternatives. [-]

| *TRL* | ICE | PEMFC | SOFC | DMFC | ICE (indirect) | PEMFC (indirect) | SOFC (indirect) | MSR | VHTR |
|---|---|---|---|---|---|---|---|---|---|
| **MGO** | 9 | | 5 | | | | | | |
| **LNG** | 9 | | 5 | | 6 | 7 | 5 | | |
| **$LH_2$** | 6 | 6 | 5 | | | | | | |
| **$CH_2$** | 6 | 6 | 5 | | | | | | |
| **Methanol** | 7 | | 5 | 5 | 6 | 7 | 5 | | |
| **Ammonia** | 5 | | 4 | | 3 | 3 | 3 | | |
| **Uranium** | | | | | | | | 3 | 5 |
| **Thorium** | | | | | | | | 3 | 4 |

**Table C.2:** Data utilized for scoring of alternatives. [tonnes]

| *Weight* | ICE | PEMFC | SOFC | DMFC | ICE (indirect) | PEMFC (indirect) | SOFC (indirect) | MSR | VHTR |
|---|---|---|---|---|---|---|---|---|---|
| **MGO** | [redacted] | | | | | | | | |
| **LNG** | | | | | | | | | |
| **$LH_2$** | | | | | | | | | |
| **$CH_2$** | | | | | | | | | |
| **Methanol** | | | | | | | | | |
| **Ammonia** | | | | | | | | | |
| **Uranium** | | | | | | | | | |
| **Thorium** | | | | | | | | | |

**Table C.3:** Data utilized for scoring of alternatives. [$m^3$]

| *Volume* | ICE | PEMFC | SOFC | DMFC | ICE (indirect) | PEMFC (indirect) | SOFC (indirect) | MSR | VHTR |
|---|---|---|---|---|---|---|---|---|---|
| **MGO** | [redacted] | | | | | | | | |
| **LNG** | | | | | | | | | |
| **$LH_2$** | | | | | | | | | |
| **$CH_2$** | | | | | | | | | |
| **Methanol** | | | | | | | | | |
| **Ammonia** | | | | | | | | | |
| **Uranium** | | | | | | | | | |
| **Thorium** | | | | | | | | | |

**Table C.4:** Data utilized for scoring of alternatives. [°C]

| *Temperature* | ICE | PEMFC | SOFC | DMFC | ICE (indirect) | PEMFC (indirect) | SOFC (indirect) | MSR | VHTR |
|---|---|---|---|---|---|---|---|---|---|
| **MGO** | 25 | | 25 | | | | | | |
| **LNG** | 162 | | 162 | | 162 | 162 | 162 | | |
| **$LH_2$** | 253 | 253 | 253 | | | | | | |
| **$CH_2$** | 25 | 25 | 25 | | | | | | |
| **Methanol** | 25 | 25 | 25 | 25 | 25 | 25 | 25 | | |
| **Ammonia** | 33 | | 33 | 33 | 33 | 33 | 33 | | |
| **Uranium** | | | | | | | | 25 | 25 |
| **Thorium** | | | | | | | | 25 | 25 |

**Table C.5:** Data utilized for scoring of alternatives. [Bar]

| ***Pressure*** | ICE | PEMFC | SOFC | DMFC | ICE (indirect) | PEMFC (indirect) | SOFC (indirect) | MSR | VHTR |
|---|---|---|---|---|---|---|---|---|---|
| **MGO** | 1 | | 1 | | | | | | |
| **LNG** | 1 | 1 | 1 | | 1 | 1 | 1 | | |
| **$LH_2$** | 1 | 1 | 1 | | | | | | |
| **$CH_2$** | 700 | 700 | 700 | | | | | | |
| **Methanol** | 1 | 1 | 1 | 1 | 1 | 1 | 1 | | |
| **Ammonia** | 1 | 1 | 1 | | 1 | 1 | 1 | | |
| **Uranium** | | | | | | | | 1 | 1 |
| **Thorium** | | | | | | | | 1 | 1 |

**Table C.6:** Data utilized for scoring of alternatives. [Quantity of conversion steps]

| *Conversion steps* | ICE | PEMFC | SOFC | DMFC | ICE (indirect) | PEMFC (indirect) | SOFC (indirect) | MSR | VHTR |
|---|---|---|---|---|---|---|---|---|---|
| **MGO** | 1 | | 1 | | | | | | |
| **LNG** | 1 | | 1 | | 2 | 2 | 2 | | |
| **$LH_2$** | 1 | 1 | 1 | | | | | | |
| **$CH_2$** | 1 | 1 | 1 | | | | | | |
| **Methanol** | 1 | | 1 | 1 | 2 | 2 | 2 | | |
| **Ammonia** | 1 | | 1 | | 2 | 2 | 2 | | |
| **Uranium** | | | | | | | | 2 | 2 |
| **Thorium** | | | | | | | | 2 | 2 |

**Table C.7:** Data utilized for scoring of alternatives. [M€]

| *Mainenance requirements* | ICE | PEMFC | SOFC | DMFC | ICE (indirect) | PEMFC (indirect) | SOFC (indirect) | MSR | VHTR |
|---|---|---|---|---|---|---|---|---|---|
| **MGO** | 0.50 | | 1.27 | | | | | | |
| **LNG** | 1.53 | | 1.34 | | 1.40 | 1.40 | 1.40 | | |
| **$LH_2$** | 2.29 | 1.96 | 1.79 | | | | | | |
| **$CH_2$** | 2.29 | 1.96 | 1.79 | | | | | | |
| **Methanol** | 0.93 | | 1.34 | 8.21 | 1.39 | 1.39 | 1.39 | | |
| **Ammonia** | 1.24 | | 1.35 | | 1.39 | 1.38 | 1.38 | | |
| **Uranium** | | | | | | | | 9.72 | 9.72 |
| **Thorium** | | | | | | | | 9.72 | 9.72 |

**Table C.8:** Data utilized for scoring of alternatives. [Euro]

| *LCOE High* | ICE | PEMFC | SOFC | DMFC | ICE (indirect) | PEMFC (indirect) | SOFC (indirect) | MSR | VHTR |
|---|---|---|---|---|---|---|---|---|---|
| **MGO** | 153.95 | | 203.48 | | | | | | |
| **LNG** | 488.32 | | 382.58 | | 659.33 | 468.83 | 464.53 | | |
| **$LH_2$** | 416.49 | 302.63 | 317.33 | | | | | | |
| **$CH_2$** | 416.49 | 302.63 | 317.33 | | | | | | |
| **Methanol** | 395.04 | | 378.31 | 877.79 | 530.01 | 360.09 | 359.77 | | |
| **Ammonia** | 450.15 | | 373.53 | | 613.70 | 422.43 | 423.01 | | |
| **Uranium** | | | | | | | | 432.00 | 432.00 |
| **Thorium** | | | | | | | | 420.27 | 420.27 |

**Table C.9:** Data utilized for scoring of alternatives. [Euro]

| *LCOE Average* | **ICE** | **PEMFC** | **SOFC** | **DMFC** | **ICE (indirect)** | **PEMFC (indirect)** | **SOFC (indirect)** | **MSR** | **VHTR** |
|---|---|---|---|---|---|---|---|---|---|
| **MGO** | 137.01 | | 175.95 | | | | | | |
| **LNG** | 341.23 | | 276.19 | | 465.42 | 336.20 | 331.61 | | |
| **$LH_2$** | 297.21 | 219.29 | 234.19 | | | | | | |
| **$CH_2$** | 297.21 | 219.29 | 234.19 | | | | | | |
| **Methanol** | 292.93 | | 274.06 | 629.20 | 375.62 | 259.11 | 259.74 | | |
| **Ammonia** | 294.00 | | 255.88 | | 404.86 | 281.89 | 282.37 | | |
| **Uranium** | | | | | | | | 359.75 | 359.75 |
| **Thorium** | | | | | | | | 355.51 | 355.51 |

**Table C.10:** Data utilized for scoring of alternatives. [Euro]

| *LCOE Low* | **ICE** | **PEMFC** | **SOFC** | **DMFC** | **ICE (indirect)** | **PEMFC (indirect)** | **SOFC (indirect)** | **MSR** | **VHTR** |
|---|---|---|---|---|---|---|---|---|---|
| **MGO** | 120.07 | | 149.07 | | | | | | |
| **LNG** | 194.14 | | 169.81 | | 270.91 | 203.58 | 198.68 | | |
| **$LH_2$** | 177.94 | 135.59 | 151.05 | | | | | | |
| **$CH_2$** | 175.52 | 135.59 | 169.82 | | | | | | |
| **Methanol** | 175.52 | | 169.82 | 380.60 | 221.23 | 158.13 | 160.61 | | |
| **Ammonia** | 137.85 | | 138.23 | | 195.52 | 141.35 | 141.74 | | |
| **Uranium** | | | | | | | | 287.49 | 287.49 |
| **Thorium** | | | | | | | | 287.22 | 287.22 |

**Table C.11:** Data utilized for scoring of alternatives. [M€]

| *CAPEX High* | **ICE** | **PEMFC** | **SOFC** | **DMFC** | **ICE (indirect)** | **PEMFC (indirect)** | **SOFC (indirect)** | **MSR** | **VHTR** |
|---|---|---|---|---|---|---|---|---|---|
| **MGO** | 33 | | 152 | | | | | | |
| **LNG** | 65 | | 154 | | 110 | 136 | 122 | | |
| **$LH_2$** | 110 | 121 | 181 | | | | | | |
| **$CH_2$** | 110 | 121 | 181 | | | | | | |
| **Methanol** | 40 | | 154 | 207 | 107 | 104 | 104 | | |
| **Ammonia** | 53 | | 155 | | 97 | 92 | 92 | | |
| **Uranium** | | | | | | | | 691 | 691 |
| **Thorium** | | | | | | | | 691 | 691 |

**Table C.12:** Data utilized for scoring of alternatives. [M€]

| *CAPEX Average* | **ICE** | **PEMFC** | **SOFC** | **DMFC** | **ICE (indirect)** | **PEMFC (indirect)** | **SOFC (indirect)** | **MSR** | **VHTR** |
|---|---|---|---|---|---|---|---|---|---|
| **MGO** | 27 | | 127 | | | | | | |
| **LNG** | 54 | | 129 | | 92 | 113 | 101 | | |
| **$LH_2$** | 92 | 101 | 151 | | | | | | |
| **$CH_2$** | 92 | 101 | 151 | | | | | | |
| **Methanol** | 34 | | 129 | 173 | 89 | 86 | 86 | | |
| **Ammonia** | 44 | | 129 | | 81 | 77 | 77 | | |
| **Uranium** | | | | | | | | 576 | 576 |
| **Thorium** | | | | | | | | 576 | 576 |

**Table C.13:** Data utilized for scoring of alternatives. [M€]

| *Capex Low* | **ICE** | **PEMFC** | **SOFC** | **DMFC** | **ICE (indirect)** | **PEMFC (indirect)** | **SOFC (indirect)** | **MSR** | **VHTR** |
|---|---|---|---|---|---|---|---|---|---|
| **MGO** | 22 | | 101 | | | | | | |
| **LNG** | 43 | | 103 | | 74 | 90 | 81 | | |
| **$LH_2$** | 73 | 80 | 121 | | | | | | |
| **$CH_2$** | 73 | 80 | 121 | | | | | | |
| **Methanol** | 27 | | 103 | 138 | 72 | 69 | 69 | | |
| **Ammonia** | 35 | | 103 | | 65 | 61 | 61 | | |
| **Uranium** | | | | | | | | 461 | 461 |
| **Thorium** | | | | | | | | 461 | 461 |

**Table C.14:** Data utilized for scoring of alternatives. [M€/yr]

| *Opex High* | **ICE** | **PEMFC** | **SOFC** | **DMFC** | **ICE (indirect)** | **PEMFC (indirect)** | **SOFC (indirect)** | **MSR** | **VHTR** |
|---|---|---|---|---|---|---|---|---|---|
| **MGO** | 25 | | 22 | | | | | | |
| **LNG** | 87 | | 57 | | 111 | 73 | 73 | | |
| **$LH_2$** | 69 | 45 | 42 | | | | | | |
| **$CH_2$** | 69 | 45 | 42 | | | | | | |
| **Methanol** | 78 | | 55 | 142 | 86 | 55 | 55 | | |
| **Ammonia** | 75 | | 52 | | 99 | 100 | 65 | | |
| **Uranium** | | | | | | | | 12 | 12 |
| **Thorium** | | | | | | | | 12 | 12 |

**Table C.15:** Data utilized for scoring of alternatives. [M€/yr]

| *OPEx average* | **ICE** | **PEMFC** | **SOFC** | **DMFC** | **ICE (indirect)** | **PEMFC (indirect)** | **SOFC (indirect)** | **MSR** | **VHTR** |
|---|---|---|---|---|---|---|---|---|---|
| **MGO** | 22 | | 20 | | DIV/0! | DIV/0! | DIV/0! | | |
| **LNG** | 60 | | 39 | | 77 | 51 | 50 | | |
| **$LH_2$** | 47 | 32 | 29 | | | | | | |
| **$CH_2$** | 47 | 32 | 29 | | | | | | |
| **Methanol** | 54 | | 38 | 99 | 60 | 38 | 38 | | |
| **Ammonia** | 48 | | 33 | | 64 | 64 | 42 | | |
| **Uranium** | | | | | | | | 10 | 10 |
| **Thorium** | | | | | | | | 10 | 10 |

**Table C.16:** Data utilized for scoring of alternatives. [M€/yr]

| *OPEX Low* | **ICE** | **PEMFC** | **SOFC** | **DMFC** | **ICE (indirect)** | **PEMFC (indirect)** | **SOFC (indirect)** | **MSR** | **VHTR** |
|---|---|---|---|---|---|---|---|---|---|
| **MGO** | 20 | | 17 | | | | | | |
| **LNG** | 33 | | 22 | | 42 | 28 | 28 | | |
| **$LH_2$** | 26 | 18 | 16 | | | | | | |
| **$CH_2$** | 26 | 18 | 16 | | | | | | |
| **Methanol** | 30 | | 21 | 57 | 33 | 21 | 21 | | |
| **Ammonia** | 22 | | 15 | | 28 | 28 | 19 | | |
| **Uranium** | | | | | | | | 8 | 8 |
| **Thorium** | | | | | | | | 8 | 8 |

**Table C.17:** Data utilized for scoring of alternatives. [$CO_2eq$/MJ]

| *Emissions* | **ICE** | **PEMFC** | **SOFC** | **DMFC** | **ICE (indirect)** | **PEMFC (indirect)** | **SOFC (indirect)** | **MSR** | **VHTR** |
|---|---|---|---|---|---|---|---|---|---|
| **MGO** | 201.5 | | | | | | | | |
| **LNG** | 201.8 | | | | | | | | |
| **LNG** | 22.6 | | | | 0.0 | 0.0 | 0.0 | | |
| **$LH_2$** | 0.0 | 0.0 | 0.0 | | | | | | |
| **$CH_2$** | 0.0 | 0.0 | 0.0 | | | | | | |
| **Methanol** | 7.7 | | | 0.0 | 0.0 | 0.0 | 0.0 | | |
| **Ammonia** | 13.3 | | | | 0.0 | 0.0 | 0.0 | | |
| **Uranium** | | | | | | | | 0.0 | 0.0 |
| **Thorium** | | | | | | | | 0.0 | 0.0 |

**Table C.18:** Data utilized for scoring of alternatives. [NFPA index]

| *Health* | ICE | PEMFC | SOFC | DMFC | ICE (indirect) | PEMFC (indirect) | SOFC (indirect) | MSR | VHTR |
|---|---|---|---|---|---|---|---|---|---|
| MGO | 2 | | 2 | | | | | | |
| LNG | 4 | | 4 | | 4 | 4 | 4 | | |
| $LH_2$ | 1 | 1 | 1 | | | | | | |
| $CH_2$ | 1 | 1 | 1 | | | | | | |
| Methanol | 3 | | 3 | 3 | 3 | 3 | 3 | | |
| Ammonia | 4 | | 4 | | 4 | 4 | 4 | | |
| Uranium | | | | | | | | 3 | 3 |
| Thorium | | | | | | | | 3 | 3 |

**Table C.19:** Data utilized for scoring of alternatives. [NFPA index]

| *Flamability* | ICE | PEMFC | SOFC | DMFC | ICE (indirect) | PEMFC (indirect) | SOFC (indirect) | MSR | VHTR |
|---|---|---|---|---|---|---|---|---|---|
| **MGO** | 3 | | 3 | | | | | | |
| **LNG** | 5 | | 5 | | 5 | 5 | 5 | | |
| **$LH_2$** | 5 | 5 | 5 | | | | | | |
| **$CH_2$** | 5 | 5 | 5 | | | | | | |
| **Methanol** | 4 | | 4 | 4 | 5 | 5 | 5 | | |
| **Ammonia** | 2 | | 2 | | 5 | 5 | 5 | | |
| **Uranium** | | | | | | | | 4 | 4 |
| **Thorium** | | | | | | | | 4 | 4 |

**Table C.20:** Data utilized for scoring of alternatives. [Navigation risk index]

| *Risk during navigation* | ICE | PEMFC | SOFC | DMFC | ICE (indirect) | PEMFC (indirect) | SOFC (indirect) | MSR | VHTR |
|---|---|---|---|---|---|---|---|---|---|
| **MGO** | 0.11 | | 0.11 | | | | | | |
| **LNG** | 0.11 | | 0.11 | | 0.11 | | 0.11 | | |
| **$LH_2$** | 0.11 | 0.11 | 0.11 | | | | | | |
| **$CH_2$** | 0.11 | 0.11 | 0.11 | | | | | | |
| **Methanol** | 0.12 | | 0.12 | 0.12 | 0.12 | 0.12 | 0.12 | | |
| **Ammonia** | 0.09 | | 0.09 | | 0.09 | | 0.09 | | |
| **Uranium** | | | | | | | | 0.11 | 0.11 |
| **Thorium** | | | | | | | | 0.11 | 0.11 |

**Table C.21:** Data utilized for scoring of alternatives. [NIRO index]

| *Safety nuclear* | ICE | PEMFC | SOFC | DMFC | ICE (indirect) | PEMFC (indirect) | SOFC (indirect) | MSR | VHTR |
|---|---|---|---|---|---|---|---|---|---|
| **MGO** | 9 | | 9 | | | | | | |
| **LNG** | 9 | | 9 | | 9 | 9 | 9 | | |
| **$LH_2$** | 9 | 9 | 9 | | | | | | |
| **$CH_2$** | 9 | 9 | 9 | | | | | | |
| **Methanol** | 9 | | 9 | 9 | 9 | 9 | 9 | | |
| **Ammonia** | 9 | | 9 | | 9 | 9 | 9 | | |
| **Uranium** | | | | | | | | 1 | 6 |
| **Thorium** | | | | | | | | 1 | 6 |

**Table C.22:** Data utilized for scoring of alternatives. [NIRO index]

| *Security nuclear* | ICE | PEMFC | SOFC | DMFC | ICE (indirect) | PEMFC (indirect) | SOFC (indirect) | MSR | VHTR |
|---|---|---|---|---|---|---|---|---|---|
| **MGO** | 9 | | 9 | | | | | | |
| **LNG** | 9 | | 9 | | 9 | 9 | 9 | | |
| **$LH_2$** | 9 | 9 | 9 | | | | | | |
| **$CH_2$** | 9 | 9 | 9 | | | | | | |
| **Methanol** | 9 | | 9 | 9 | 9 | 9 | 9 | | |
| **Ammonia** | 9 | | 9 | | 9 | 9 | 9 | | |
| **Uranium** | | | | | | | | 1 | 6 |
| **Thorium** | | | | | | | | 1 | 6 |

**Table C.23:** Data utilized for scoring of alternatives. [9 = yes, 4.5 = in development, 1 = no]

| *Clear Frameworks (yes/no)* | ICE | PEMFC | SOFC | DMFC | ICE (indirect) | PEMFC (indirect) | SOFC (indirect) | MSR | VHTR |
|---|---|---|---|---|---|---|---|---|---|
| **MGO** | 9.00 | | 9.00 | | | | | | |
| **LNG** | 9.00 | | 9.00 | | 9.00 | 9.00 | 9.00 | | |
| **$LH_2$** | 4.50 | 4.50 | 4.50 | | | | | | |
| **$CH_2$** | 4.50 | 4.50 | 4.50 | | | | | | |
| **Methanol** | 9.00 | | 9.00 | 9.00 | 9.00 | 9.00 | 9.00 | | |
| **Ammonia** | 4.50 | | 4.50 | | 4.50 | 4.50 | 4.50 | | |
| **Uranium** | | | | | | | | 1.00 | 1.00 |
| **Thorium** | | | | | | | | 1.00 | 1.00 |

**Table C.24:** Data utilized for scoring of alternatives. [9 = no, 1 = yes]

| *ETS Applicable (yes/no)* | **ICE** | **PEMFC** | **SOFC** | **DMFC** | | | | **MSR** | **VHTR** |
|---|---|---|---|---|---|---|---|---|---|
| **MGO** | 1.00 | | 9.00 | | | | | | |
| **E-LNG** | 9.00 | | 9.00 | | 9.00 | 9.00 | 9.00 | | |
| **LH$_2$** | 9.00 | 9.00 | 9.00 | | | | | | |
| **CH$_2$** | 9.00 | 9.00 | 9.00 | | | | | | |
| **Methanol** | 9.00 | | 9.00 | 9.00 | 9.00 | 9.00 | 9.00 | | |
| **Ammonia** | 9.00 | | 9.00 | | 9.00 | 9.00 | 9.00 | | |
| **Uranium** | | | | | | | | 9.00 | 9.00 |
| **Thorium** | | | | | | | | 9.00 | 9.00 |

# D
# Alternative scores

The tables in this Appendix display the scores assigned to each alternative per criteria. This data is collected either through scaling of the data represented in Appendix C. These scores are used to calculate the best-suiting energy supply.

ICE

**Table D.1:** System score table per criteria of the ICE energy supplies.

| | | MGO | LNG | LH2 | CH2 | Methanol | Ammonia |
|---|---|---|---|---|---|---|---|
| System design | TRL | 9 | 9 | 6 | 6 | 7 | 5 |
| | System weight | 9 | 8 | 4 | 3 | 5 | 4 |
| | System volume | 6 | 3 | 2 | 2 | 4 | 3 |
| | Storage temperature | 9 | 4 | 1 | 9 | 9 | 7 |
| | Storage pressure | 9 | 9 | 9 | 1 | 9 | 9 |
| System operation | Efficiency | 6 | 5 | 5 | 5 | 5 | 5 |
| | Amount of conversion steps | 9 | 9 | 9 | 9 | 9 | 9 |
| | Maintenance requirements | 9 | 4 | 3 | 3 | 5 | 4 |
| | Minimal bunker period | 9 | 9 | 5 | 1 | 9 | 6 |
| Financial impact | LCOE | 9-9 | 6-3 | 6-3 | 6-3 | 6-4 | 8-3 |
| | CAPEX | 9-9 | 5-5 | 3-3 | 3-3 | 8-8 | 6-6 |
| | OPEX | 5-4 | 3-2 | 4-2 | 4-2 | 3-2 | 4-2 |
| Safety | Health risk | 5 | 2 | 9 | 9 | 3 | 2 |
| | Flammability risk | 6 | 4 | 4 | 4 | 5 | 9 |
| | Risk during navigation | 8 | 9 | 9 | 9 | 9 | 7 |
| | Nuclear safety | 9 | 9 | 9 | 9 | 9 | 9 |
| | Nuclear security | 9 | 9 | 9 | 9 | 9 | 9 |
| Regulations | Regulations | 9 | 9 | 5 | 5 | 9 | 5 |
| ETS | ETS | 1 | 9 | 9 | 9 | 9 | 9 |
| Emissions | Emissions | 1 | 8 | 9 | 9 | 9 | 8 |

PEMFC

**Table D.2:** System score table per criteria of the PEMFC energy supplies.

| | | LH2 | CH2 |
|---|---|---|---|
| **System design** | TRL | 6 | 6 |
| | System weight | 5 | 4 |
| | System volume | 2 | 2 |
| | Storage temperature | 1 | 9 |
| | Storage pressure | 9 | 1 |
| **System operation** | Efficiency | 8 | 8 |
| | Amount of conversion steps | 9 | 9 |
| | Maintenance requirements | 3 | 3 |
| | Minimal bunker period | 5 | 5 |
| **Financial impact** | LCOE | 6 | 6 |
| | CAPEX | 3 | 3 |
| | OPEX | 3 | 3 |
| **Safety** | Health risk | 9 | 9 |
| | Flammability risk | 4 | 4 |
| | Risk during navigation | 9 | 9 |
| | Nuclear safety | 9 | 9 |
| | Nuclear security | 9 | 9 |
| **Regulations** | Regulations | 5 | 5 |
| **ETS** | ETS | 9 | 9 |
| **Emissions** | Emissions | 9 | 9 |

SOFC

**Table D.3:** System score table per criteria of the SOFC energy supplies.

| | | MGO | LNG | LH2 | CH2 | Methanol | Ammonia |
|---|---|---|---|---|---|---|---|
| **System design** | TRL | 5 | 5 | 5 | 5 | 5 | 4 |
| | System weight | 6 | 6 | 5 | 3 | 5 | 4 |
| | System volume | 3 | 2 | 2 | 2 | 3 | 2 |
| | Storage temperature | 9 | 4 | 1 | 9 | 9 | 7 |
| | Storage pressure | 9 | 9 | 9 | 1 | 9 | 9 |
| **System operation** | Efficiency | 7 | 8 | 9 | 9 | 7 | 8 |
| | Amount of conversion steps | 9 | 9 | 9 | 9 | 9 | 9 |
| | Maintenance requirements | 4 | 4 | 3 | 3 | 4 | 4 |
| | Minimal bunker period | 9 | 5 | 5 | 1 | 9 | 5 |
| **Financial impact** | LCOE | 7 | 4 | 5 | 5 | 4 | 5 |
| | CAPEX | 3 | 3 | 2 | 2 | 3 | 3 |
| | OPEX | 5 | 3 | 4 | 4 | 3 | 3 |
| **Safety** | Health risk | 5 | 2 | 9 | 9 | 3 | 2 |
| | Flammability risk | 6 | 4 | 4 | 4 | 5 | 9 |
| | Risk during navigation | 8 | 9 | 9 | 9 | 9 | 7 |
| | Nuclear safety | 9 | 9 | 9 | 9 | 9 | 9 |
| | Nuclear security | 9 | 9 | 9 | 9 | 9 | 9 |
| **Regulations** | Regulations | 9 | 9 | 5 | 5 | 9 | 5 |
| **ETS** | ETS | 9 | 9 | 9 | 9 | 9 | 9 |
| **Emissions** | Emissions | 9 | 9 | 9 | 9 | 9 | 9 |

DMFC

**Table D.4:** System score table per criteria of the DMFC energy supply.

| | | Methanol |
|---|---|---|
| **System design** | TRL | 5 |
| | System weight | 3 |
| | System volume | 3 |
| | Storage temperature | 9 |
| | Storage pressure | 9 |
| **System operation** | Efficiency | 3 |
| | Amount of conversion steps | 9 |
| | Maintenance requirements | 1 |
| | Minimal bunker period | 2 |
| **Financial impact** | LCOE | 2 |
| | CAPEX | 2 |
| | OPEX | 2 |
| **Safety** | Health risk | 3 |
| | Flammability risk | 5 |
| | Risk during navigation | 9 |
| | Nuclear safety | 9 |
| | Nuclear security | 9 |
| **Regulations** | Regulations | 9 |
| **ETS** | ETS | 9 |
| **Emissions** | Emissions | 9 |

ICE (indirect)

**Table D.5:** System score table per criteria of the indirect ICE energy supplies.

| | | LNG | Methanol | Ammonia |
|---|---|---|---|---|
| **System design** | TRL | 6 | 6 | 3 |
| | System weight | 4 | 3 | 3 |
| | System volume | 2 | 4 | 2 |
| | Storage temperature | 4 | 9 | 7 |
| | Storage pressure | 9 | 9 | 9 |
| **System operation** | Efficiency | 4 | 5 | 4 |
| | Amount of conversion steps | 1 | 1 | 1 |
| | Maintenance requirements | 4 | 4 | 4 |
| | Minimal bunker period | 5 | 5 | 1 |
| **Financial impact** | LCOE | 3 | 3 | 3 |
| | CAPEX | 3 | 3 | 4 |
| | OPEX | 2 | 2 | 2 |
| **Safety** | Health risk | 2 | 3 | 2 |
| | Flammability risk | 4 | 4 | 5 |
| | Risk during navigation | 9 | 9 | 9 |
| | Nuclear safety | 9 | 9 | 9 |
| | Nuclear security | 9 | 9 | 9 |
| **Regulations** | Regulations | 9 | 9 | 5 |
| **ETS** | ETS | 9 | 9 | 9 |
| **Emissions** | Emissions | 9 | 9 | 9 |

PEMFC (indirect)

**Table D.6:** System score table per criteria of the indirect PEMFC energy supplies.

| | | LNG | Methanol | Ammonia |
|---|---|---|---|---|
| **System design** | TRL | 7 | 7 | 3 |
| | System weight | 5 | 4 | 3 |
| | System volume | 3 | 5 | 3 |
| | Storage temperature | 4 | 9 | 7 |
| | Storage pressure | 9 | 9 | 9 |
| **System operation** | Efficiency | 6 | 8 | 6 |
| | Amount of conversion steps | 1 | 1 | 1 |
| | Maintenance requirements | 4 | 4 | 4 |
| | Minimal bunker period | 9 | 9 | 5 |
| **Financial impact** | LCOE | 4 | 5 | 4 |
| | CAPEX | 3 | 4 | 4 |
| | OPEX | 3 | 3 | 2 |
| **Safety** | Health risk | 2 | 3 | 2 |
| | Flammability risk | 4 | 4 | 4 |
| | Risk during navigation | 9 | 9 | 9 |
| | Nuclear safety | 9 | 9 | 9 |
| | Nuclear security | 9 | 9 | 9 |
| **Regulations** | Regulations | 9 | 9 | 5 |
| **ETS** | ETS | 9 | 9 | 9 |
| **Emissions** | Emissions | 9 | 9 | 9 |

SOFC (indirect)

**Table D.7:** System score table per criteria of the indirect SOFC energy supplies.

| | | LNG | Methanol | Ammonia |
|---|---|---|---|---|
| **System design** | TRL | 5 | 5 | 3 |
| | System weight | 5 | 4 | 3 |
| | System volume | 3 | 4 | 2 |
| | Storage temperature | 4 | 9 | 7 |
| | Storage pressure | 9 | 9 | 9 |
| **System operation** | Efficiency | 6 | 8 | 6 |
| | Amount of conversion steps | 1 | 1 | 1 |
| | Maintenance requirements | 4 | 4 | 4 |
| | Minimal bunker period | 6 | 9 | 1 |
| **Financial impact** | LCOE | 4 | 5 | 4 |
| | CAPEX | 3 | 4 | 4 |
| | OPEX | 3 | 3 | 3 |
| **Safety** | Health risk | 2 | 3 | 2 |
| | Flammability risk | 4 | 4 | 4 |
| | Risk during navigation | 9 | 9 | 9 |
| | Nuclear safety | 9 | 9 | 9 |
| | Nuclear security | 9 | 9 | 9 |
| **Regulations** | Regulations | 9 | 9 | 5 |
| **ETS** | ETS | 9 | 9 | 9 |
| **Emissions** | Emissions | 9 | 9 | 9 |

MSR

**Table D.8:** System score table per criteria of the MSR energy supplies.

| | | Uranium | Thorium |
|---|---|---|---|
| **System design** | TRL | 3 | 3 |
| | System weight | 6 | 6 |
| | System volume | 9 | 9 |
| | Storage temperature | 9 | 9 |
| | Storage pressure | 9 | 9 |
| **System operation** | Efficiency | 5 | 5 |
| | Amount of conversion steps | 1 | 1 |
| | Maintenance requirements | 1 | 1 |
| | Minimal bunker period | 9 | 9 |
| **Financial impact** | LCOE | 3 | 3 |
| | CAPEX | 1 | 1 |
| | OPEX | 9 | 9 |
| **Safety** | Health risk | 4 | 4 |
| | Flammability risk | 4 | 4 |
| | Risk during navigation | 8 | 8 |
| | Nuclear safety | 1 | 1 |
| | Nuclear security | 1 | 1 |
| **Regulations** | Regulations | 1 | 1 |
| **ETS** | ETS | 9 | 9 |
| **Emissions** | Emissions | 9 | 9 |

VHTR

**Table D.9:** System score table per criteria of the VHTR energy supplies.

| | | Uranium | Thorium |
|---|---|---|---|
| **System design** | TRL | 5 | 4 |
| | System weight | 5 | 5 |
| | System volume | 8 | 8 |
| | Storage temperature | 9 | 9 |
| | Storage pressure | 9 | 9 |
| **System operation** | Efficiency | 5 | 5 |
| | Amount of conversion steps | 1 | 1 |
| | Maintenance requirements | 1 | 1 |
| | Minimal bunker period | 9 | 9 |
| **Financial impact** | LCOE | 3 | 3 |
| | CAPEX | 1 | 1 |
| | OPEX | 9 | 9 |
| **Safety** | Health risk | 4 | 4 |
| | Flammability risk | 4 | 4 |
| | Risk during navigation | 8 | 8 |
| | Nuclear safety | 6 | 6 |
| | Nuclear security | 6 | 6 |
| **Regulations** | Regulations | 1 | 1 |
| **ETS** | ETS | 9 | 9 |
| **Emissions** | Emissions | 9 | 9 |