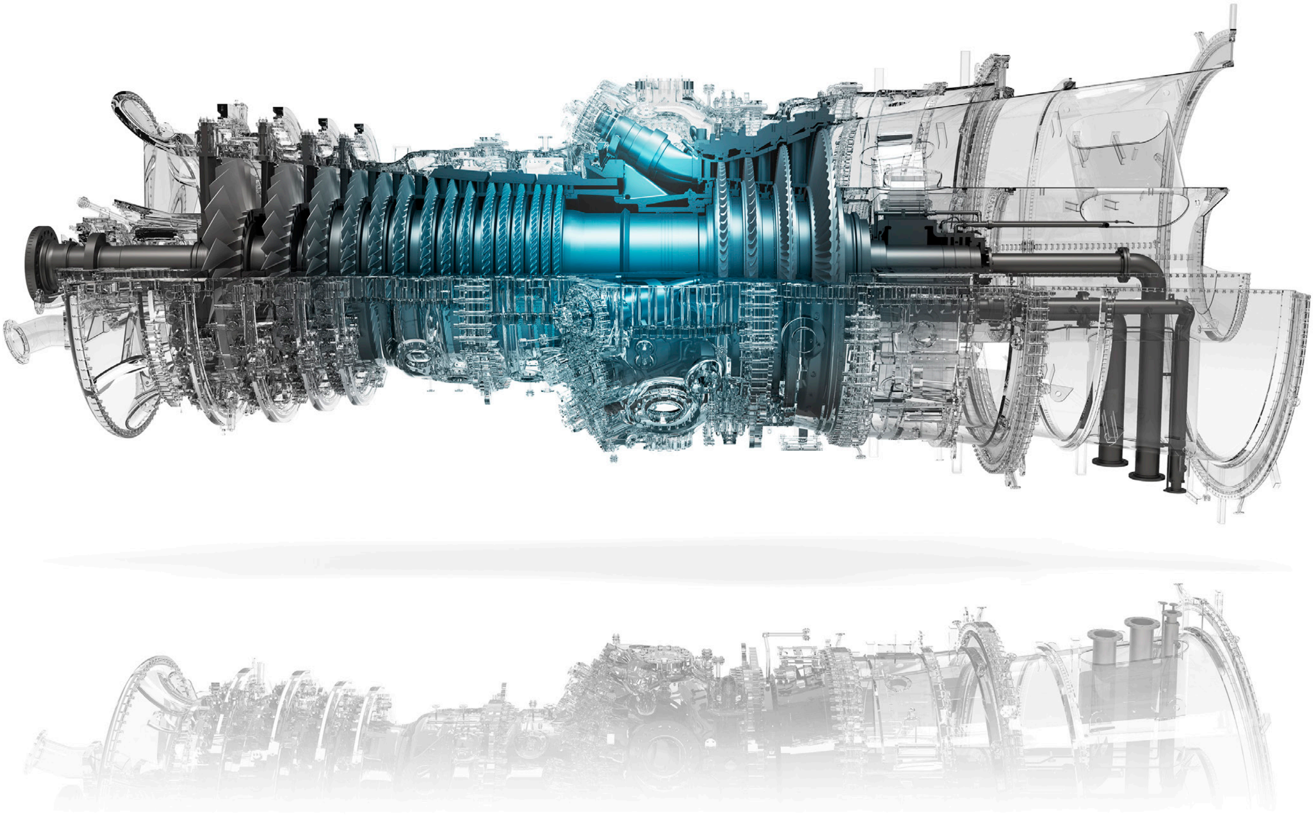
Multi-criteria Assessment of Alternative Fuels for Peak Power Generation

Applying the AHP method for the selection of an alternative fuel for gas turbines in Rotterdam



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Multi-criteria Assessment of Alternative Fuels for Peak Power Generation in Rotterdam

by

Youssef Saba

in partial fulfilment of the requirements for the degree of Master of Science in Complex Systems Engineering and Management at Delft University of Technology. To be defended publicly on Tuesday September 9, 2019.

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An electronic version of this thesis is available at `http://repository.tudelft.nl/`.

Preface

This thesis is the final product of my master's degree in Complex Systems Engineering and Management. This six-month-long project was the perfect way to end my academic journey at TU Delft. One that tested my existing knowledge and allowed me to gain new skills. The topic proved to be very relevant and challenging, allowing me to apply a multitude of skills from design, modeling, critical thinking and communication with industry experts.

This all could not have been possible without the motivation, help and guidance of many people. First and foremost, I would like to express my gratitude for my family for their constant support and motivation for as long as I have existed. I am really grateful for all four of you.

I would also like to thank my graduation committee for all their guidance throughout this thesis. Thank you Lydia for your patience and making yourself available for regular meetings. Your patience and knowledge helped guide me throughout the whole research, and made me ask the right questions. Margot, thank you for continuing to challenge me every step of the way. Your remarks helped in contributing to a much more meaningful research. Daniel, your feedback was always clear and to the point, which allowed me to shape my entire thesis.

Finally, I would like to thank the team at ZEF for allowing me to be a part of their team during this internship. You have created a wonderful working environment which has made my experience unforgettable. I would like to give special thanks to Hessel, you are a true role model for success, support and motivation. You played a huge role in the formulating stage, system design and connecting me to people in the industry. I would also like to thank Ulrich for keeping track of my progress and his support in the final stages. Finally, I would like to thank Jan for contributing to the technical dimension, and his input during the planning meetings.

Enjoy the read!

Youssef Saba

Delft, August 2019

Executive Summary

This research focuses on the selection of a sustainable alternative gas turbine fuel for peak power generation in Rotterdam. The interest is in identifying the preferred alternative fuel by key stakeholders for locations where no pre-existing geological structures can be utilized for energy storage. Little research has been carried for other alternative fuels for power generation in The Netherlands. Hydrogen fuel is being proposed by many as the future alternative fuel for gas turbines, however its handling, compression and storage is very challenging. Liquid organic hydrogen carriers, such as methanol, represent a convenient way for hydrogen transportation, long-term storage and utilization in current gas turbines and should also be part of the discussion for gas turbine alternative fuels. This research identifies hydrogen and methanol as two possible alternatives, and is built around the following research question:

> "What alternative fuel is most preferred by key decision-makers for peak power generation in Rotterdam?"

A few underlying assumptions and conditions are set for the analysis of both alternative fuels. The technologies selected for fuel production, handling and utilization are either commercially available, or undergoing current investment, research and experimentation. The system boundaries include the entire life-cycle phases of fuels from "well to wheel", covering production, transport, storage to utilization.

Since this is essentially a decision making question, a multi-criteria decision making method (MCDM) is applied for a variety of reasons. MCDM's are computational tools that are common for multidimensional problems which involving a number of different, often contradictory criteria. According to existing literature on MCDM studies in sustainable energy development, all relevant decision making criteria can fall under one of four major criteria which are the environmental, social, economic and technical dimensions. A literature review is carried, and 9 sub-criteria are identified to be relevant for the selected systems. These are the CAPEX, OPEX, global warming potential, NOx emissions, system efficiency, technological maturity, job creation, security of supply and system safety. The AHP method is identified as the preferred tool to handle both quantitative and qualitative criteria and analyse their conflicts for decision makers. The tool allows a decision maker to select between to select between fuels that vary in terms of safety, cost and social impact. For example, would a decision maker chose a more expensive fuel that offers better security of supply. What if an alternative fuel is cheaper yet relies on import? What if one of them is more environmentally benign compared to the other? The proposed Analytical Hierarchy Process (AHP) method facilitates such decisions.

A variety of methods are incorporated to assess each fuel's performance against the four major criteria. An environmental assessment is performed through an LCA using Sima-pro software. The entire value chain from production to utilization is evaluated on two major impact categories, the global warming potential measured in Kg CO_2 equivalent, and for ozone formation (NO_x equivalent). The economic assessment is based on present estimates for CAPEX and OPEX costs obtained from literature. The social implications of both alternative fuels were also compared by analysing the fuel safety, resulting job creation and security of supply. The final assessment carried analyzed the technical criteria. The technology readiness level (TRL) ranking method developed by NASA was incorporated for the first time within the AHP framework in this research. This represents a contribution to multi-criteria decision making tools, by adding a dimension that is often overlooked in existing sustainable energy assessment studies.

The AHP method relies on input from these four assessments, as well as criteria weighting to indicate the relative importance of each sub-criterion in the selection of an alternative fuel. This research proposes analysing the criteria weightings of multiple stakeholder perspectives that will be needed for a successful fuel development and adoption. Four stakeholder groups are identified, which are the energy companies, equipment manufacturers, energy policy makers and investors. Interviews are carried with representatives of each group, where they are asked to perform pair-wise comparisons between the selected criteria to indicate each criterion's global weight. The results are synthesized to identify the preferred fuel for each stakeholder, and infer further conclusions.

The aforementioned criteria and methods are applied to a base case of utilizing 100# renewable fuels to operate a peak power plant in Rotterdam. The AHP method was used to evaluate the preference of the four key stakeholders (equipment manufacturers, policy-makers, fuel producers and energy investor) according to the performance of both alternative fuels for all criteria, and the priority given to each criterion by each stakeholder. Based on the outcomes of the stakeholder interviews, a sensitivity analysis was performed to test the robustness of the results for two scenarios. The first scenario focused on the economic criteria by estimating the effect of cost reductions on the fuel scores, and the second scenario analyzed the effect of fuel blending with 50% fossil based fuels. The following bullet-points summarize the outcome of this research with regards to the selection of an alternative fuel for peak power generation in Rotterdam:

- For the short-term, hydrogen fuel blending with natural gas can significantly reduce the negative environmental impact of current natural gas peak power plants. Hydrogen-fuel blend outperforms a 50-50 green-grey methanol blend on the technology readiness level, total system energy efficiency and global warming potential. Gas turbines operating on high hydrogen fuel blends are commercially available, and can handle hydrogen percentages of 10-70%. By varying the amount of hydrogen in the fuel blend, the overall fuel costs and environmental impact can be controlled to meet power plant targets. The biggest challenge for the hydrogen fuel utilization in Rotterdam will be large scale storage, and should be addressed by stakeholders the Dutch energy sector.
- For the long-term, future of peak power plant fuel where the goal would be 100% renewable fuel, both hydrogen and methanol can play a role as an alternative fuel. With current technology and economic criteria in mind, methanol slightly outperforms hydrogen as the preferred alternative for most stakeholders. When future costs projections for the different sub-components of both systems are incorporated, stakeholders are divided in terms of their alternative fuel of choice.
- Natural gas will continue to power gas turbines due to economical reasons, even with the carbon emission floor price implemented by the Dutch government on electricity producers. At current technology costs, hydrogen fuel is more than 6 times more expensive than natural gas, and green methanol is around 4 times more expensive. Policy-makers should seek other measures to shift investor behaviour in favour of alternative fuels, especially with regards to the long-term future alternative fuels since there is no clear preference among stakeholders.

The underlying motivation behind the research method applied stems from systems engineering thinking of considering the entire life-cycle and the wide perspectives of stakeholders required. For an alternative fuel to be adopted, a thorough understanding of the implications of the entire life-cycle from production to utilization is necessary. Just as important is recognizing the positions of all stakeholders with regards to the same problem. The flexibility of the AHP method allows for qualitative and quantitative data to be incorporated from the different fuel assessments, and for the different stakeholders' views to be incorporated in the decision making process.

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List of Abbreviations

AHP	Analytical Hierarchy Process
BOS	Balance of System
CAPEX	Capital Expenditure
CD	Direct Current
CH_3COH	Methanol
CO	Carbon monoxide
CO_2	Carbon Dioxide
DAC	Direct Air Capture
GWP	Global Warming Potential
HHV	Higher Heating Value
LCA	Life Cycle Assessment
LCOE	Levelized Cost of Energy
LHV	Lower Heating Value
LOHC	Liquid Organic Hydrogen Carrier
MJ	Megajoule
MW	Megawatt
MWh	Megawatt hour
MWh_{th}	Megawatt hour thermal
NO_x	Nitrogen oxides
OCGT	Open Cycle Gas Turbine
OPEX	Operational Expenditure
PEM	Polymer Electrolyte Membrane electrolysers
SC	Simple Cycle Turbine
TRL	Technology Readiness Level
ZEF	Zero Emission Fuel

1 Introduction

As the energy transition continues to evolve, decision-makers are continuously faced with puzzling trade-offs when supporting renewable energy initiatives (Park et al., 2014). In The Netherlands, coal and fossil based power plants are increasingly being replaced with renewable energy sources. By 2030, all coal-fired base-load power plants will be shut down starting with the two oldest plants (1245 MW Amer and 630 MW Hemweg) as soon as 2024 (Meijer, 2018). While dispatchable base-load power generation from coal is being retired, more intermittent renewable energy sources are being introduced in the Dutch energy mix. In the period leading to 2026, tenders have been issued for offshore projects totalling 6800 MW in Hollandse Kust, Ten Noorden van de Waddeneilanden and Ijmuiden Ver (RVO, 2019). Consequently, ensuring reliable electricity supply, especially during peak hours, will become more challenging with increased renewable energy penetration (Eid et al., 2016). While demand side management will be needed to reduce or shift peak demand, implementation in Europe faces some challenges such as the significant initial technology investment, coordination problems and in some cases even increased emissions (Eid et al., 2016).

Peak power plants play a vital role in meeting high demand during peak hours. Peak power supply is required to be highly responsive, therefore it is conventionally fulfilled with gas or diesel turbines (Lin & Damato, 2011). Several renewable energy alternative technologies that are highly responsive exist, however they are typically geologically dependant. Some examples are compressed air energy storage (CAES) which requires the existence of salt caverns or aquifers, and pumped hydro which requires the existence of elevated water reservoirs (Hadjipaschalis et al., 2009). Storage of renewable electricity in batteries is still economically challenging at large scale and faces technical challenges when dealing with intermittent nature of renewable energy. Frequent charging, recharging or deep discharge leads to significantly reduced operational lifetime and depending on the type of battery, energy self-discharge rates can reach 10% per month (Faunce et al., 2018; Liu et al., 2013; Hadjipaschalis et al., 2009).

Gas turbines offer much needed flexibility in generation, independent of the presence of special geological structures. Renewable alternative fuels can be fired in existing gas turbines to offer dispatchable electricity generation on demand, independent of the presence of special geological structures. Gas turbines are available for a wide range of power plant generating capacities and current gas turbines can be reconfigured to operate on hydrogen rich fuels, bio-fuels, methanol and other alternative fuels (Gökalp & Lebas, 2004; Goldmeer, 2018a; Murray & Furlonge, 2009). Peak power plants typically run for much fewer hours compared to base-load plants, with the exact operational duration dependent on conditions of the local electricity grid. At these times, electricity prices per KWh are much higher than during base-load hours, therefore this research is focused on the use of the "currently expensive" alternative fuels for electricity generation from gas turbines.

Hydrogen is being widely considered as a gas turbine fuel in the Netherlands. The Dutch ministry of Economic Affairs has granted a 0.5 million euro subsidy to six partners from academia and industry (Ansaldo Thomassen, Delft University of Technology, OPRA Turbines, Vattenfall, Nouryon and EMMTEC) to experiment with hydrogen utilization in gas turbines (Koeman, 2019). The major objective of the project is to develop a cost-effective ultra-low emissions combustion system retrofit for existing installed gas turbines in the output range of 1MW to 300MW (Koeman, 2019). Also in the industry, General Electric, Mitsubishi Hitachi Power Systems and Siemens have been developing turbines that run on varying mixtures of hydrogen and natural gas (from 10% to 70% H_2) (Brown et al., 2007; Goldmeer, 2018a). In northern Netherlands, a coalition of companies and governments constituting the Northern Innovation Board (NIB) have established an investment agenda for the development of a green hydrogen economy. The salt caverns near EnergyStock, Veendam will be used for large scale storage of green hydrogen to be used in electricity generation and other applications (Weeda, 2019). Hydrogen handling, compression and storage in regions with no pre-existing geological structures (salt caverns, depleted gas reservoirs) are considered to be the biggest challenges for the hydrogen economy (Wolf, 2015; Crotogino, 2016). This raises the question of whether hydrogen fuel is still preferred for such locations.

To overcome some of these challenges, irreversible chemical storage of hydrogen in liquid organic hydrogen carriers (LOHC) is a promising solution (Aakko-Saksa et al., 2018). LOHCs such as ammonia (nitrogen compound), formic acid and methanol (carbon compounds) are liquid at room temperature, and exhibit similar handling, storage and utilization as well-known oil-based fuels (diesel and gasoline) (Niermann et al., 2019). On the other hand, the process of synthesizing hydrogen into LOHC consumes energy, which has implications on the fuel costs, the overall efficiency and many other factors. The prospect of using LOHCs for power generation is at varying stages of research and maturity. Formic acid is yet to be considered for power generation both in scientific literature and industrial level. Studies have been carried to improve the understanding of ammonia fuel blends for gas turbine power generation, however this remains to be an immature field with relatively few publications (Valera-Medina et al., 2018). That being said, methanol has been investigated as a fuel for gas turbines both academically (Murray & Furlonge, 2009; Turaga & Johnson, 2017), and in practice (Day, 2016; Haain, 2012). *Zero Emission Fuels* (*ZEF*) is a startup from TU Delft that is developing a solar-to-methanol micro-plant. Hydrogen is synthesized with carbon directly captured from the atmosphere, to produce methanol fuel. Methanol fuel can then be easily transported and stored from the site of production to the location of the peak power plant (Niermann et al., 2019).

1.1 Problem Definition

Decision-makers across the energy sector are often faced with the challenge of selecting sustainable energy systems to invest in. In The Netherlands, hydrogen fuel is being considered for power generation in locations with adequate geological storage. However, it is not clear what alternative fuel is preferred in locations with no natural storage reservoirs.

Alternative fuels are part of complex energy systems, and their adoption requires the availability of infrastructure, development of specific equipment, appropriate legislation and investment in R&D and many other technical and economic hurdles. In order to make a decision, stakeholders often need to balance trade-offs between multiple criteria regarding the technical, economic, social, political and environmental implications of the different alternatives (Wang et al., 2009; Campos-Guzmán et al., 2019). Some of the criteria they analyze are accurately quantifiable, such as process efficiencies and energy losses of hydrogen production compared to LOHCs. Other criteria are quantifiable yet not accurate, for instance, the fuel's environmental impact, cost of production, infrastructure and investment needs, etc. Also some aspects are typically difficult-to-quantify such as the system safety, security of supply and other social criteria.

This research focuses on the selection of a renewable alternative gas turbine fuel for peak power plants in The Netherlands. The interest is in identifying the preferred alternative fuel by key stakeholders for locations where no pre-existing geological structures can be utilized for energy storage. The relevant criteria for decision-makers will be compared for two possible alternatives, hydrogen and methanol. While a hydrogen has been extensively analysed, and is deemed by many as the transition fuel to make the switch from a natural gas-based economy to a sustainable economy in the Northern Netherlands (Weeda, 2019; Jorg, 2019), little research has been carried for other alternative fuels for power generation in The Netherlands. LOHCs, and specifically methanol, represent a convenient way for hydrogen transportation, long-term storage and utilization in current gas turbines, and should also be part of the discussion for gas turbine alternative fuels.

A few underlying assumptions and conditions are set for the analysis of both alternative fuels, and their production systems. The technologies selected for fuel production, handling and utilization are either commercially available, or undergoing current investment, research and experimentation. The peak power plant should be able to operate independent of the presence of any special geological structures for energy storage. The system boundaries are thoroughly described in section 2.2, and include the entire life-cycle phases of fuels from production, transport, storage to utilization.

Peak power plant selection

The peak power plant is assumed to be located in Rotterdam. *Maasstroom Energie* have an existing natural gas power plant of 428 MW capacity. The plant is located near the port of Rotterdam which is convenient for methanol import, and also close to the North Sea which is convenient for renewable electricity transmission from planned offshore wind projects. Furthermore, the grid infrastructure is already in place to handle the electricity generated from the existing gas power plant. Fuel blending is also being considered to allow for a smooth integration of renewable fuels into the energy mix, and to offset the carbon emissions of fossil fuels. For this reason, hydrogen fuel cells were not considered to fulfill peak demand. The peak plant is assumed to have a capacity of 34.3 MW, which is based on proposed hydrogen turbine capacities (Goldmeer, 2018a). Gas-fired peak power plants typically have capacity factors between 5% (Lin & Damato, 2011), 4.9-6.9% (Energy Information Administration, 2018). A table with capacity factors of typical gas powered plants built in the period 2013-2017 is attached in fig.29 in the appendix. Accordingly, the peak power plant is modeled to run for 522 hours per year, or a capacity factor of 5.9%.. This corresponds to an annual energy generation of around 17960 MWh per year.

Peak power plants often employ an open cycle gas turbine (OCGT) with a single compressor and a simple turbine. Thermodynamic efficiencies of OCGT plants are much lower than base-load plants, and are typically around 25-40% (Energy Information Administration, 2018). Since peak power plants run for relatively few hours per year, capital investment costs in the plant are minimized, while fuel costs constitute a more significant share of life-cycle costs.

Peak power plant	Maasstroom Energie
Gas Turbine Rating	34.3 MW
Capacity Factor	5.96 %
Operation hours	522 hr/year
Annual generation	17957 MWh

Table 1: Peak power plant specifications

Figure 1: Location of Maasstroom Power plant in Rotterdam (retrieved from Google Maps)

In this thesis, the approach taken to analyze the power turbine subsystem requirements is to study the modifications required to allow existing natural gas turbines to run on hydrogen or methanol. This approach is taken for two reasons. Firstly, the focus of this research is not to design a gas turbine for alternative fuels, but to analyze the value chain as a whole; from fuel generation, transport, storage and finally utilization in the gas turbine. Secondly, it is of interest to understand the possibility of modifying existing gas turbines to run completely on alternative fuels, or varying mixtures of natural gas and alternative fuels. That being said, for the purposes of the analyses carried, the gas turbine in the peak power plant is designed to operate on 100% renewable hydrogen or methanol.

1.2 Knowledge Gap

A literature review was carried on decision making tools applied by researchers for analysing renewable energy systems. It is well documented that the selection of a renewable energy route to invest in is a task that requires incorporating multiple conflicting criteria (Daim & Taha, 2013). Multi-criteria decision making tools are typically utilized to rank possible alternatives according to the relevant criteria for decision makers. This research contributes to the existing body of knowledge on multi-criteria decision making (MCDM) of renewable energy systems in three ways.

1.2.1 Applying the TRL method as a tool for MCDM

Multi-criteria decision making methods rely on a combination of methods to evaluate the different sub-criteria. For example, environmental life-cycle assessments are commonly carried within the framework of the MCDM analysis to evaluate the environmental impact of the different alternatives. This research introduces the utilization of the technology readiness level (TRL) developed by NASA as a technical indicator to evaluate the technological maturity of the system components. In existing MCDM assessments for sustainable energy systems, technology maturity has been analysed in only very few cases (Campos-Guzmán et al., 2019; Amer & Daim, 2011). In existing MCDM literature, technology maturity is either subjectively identified by the decision maker (Nigim et al., 2004; Wang et al., 2009), or quantified by the number of patents, SCI[1] papers and paper proceedings published over a certain period of time (S. K. Lee et al., 2008).

The TRL is a method that can be consistently applied to evaluate the technological maturity of the system components. The method applies a step-wise staging process which identifies two things; what has been demonstrated by the technology, and under what conditions. The incorporation of the TRL as a tool to measure the technological maturity represents a contribution to the research methods utilized in multi-criteria assessments.

1.2.2 Contributions to Criteria weighting

Criteria weighting is a critical step in MCDM studies, one that highly influences the outcome of the assessment (Martín-Gamboa et al., 2017). The weighting refers to the relative importance of each criterion and sub-criterion with regards to the decision-making process. In existing AHP studies, the criteria weighting is typically performed by the researchers themselves (Papalexandrou et al., 2008; Chatzimouratidis & Pilavachi, 2008; Pilavachi et al., 2009), or survey instruments distributed to energy professionals from industries and universities (Amer & Daim, 2011). In the former case, researchers rely on their own subjective judgement, or on distributing the criteria weights among all criteria evenly (Pilavachi et al., 2009). While in the latter case, surveys from a wide range of professionals in the industry and academia are all averaged to obtain one set of criteria weights.

This research proposes evaluating the performance of the alternatives according to different sets of criteria weightings, each set representing the view of a different key stakeholder. This approach is different from the common convention of applying only one criteria weighting set, whether assumed by the researcher, or averaged from collected surveys. By evaluating the performance of the possible alternatives for each stakeholder group independently, a better understanding can be made on whether there is widespread support for one alternative by all stakeholders, or if there is disagreement on which alternative shapes the future. To apply this method to the topic of this research, for

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[1] Science Citation Index, contains journals that have undergone a rigorous selection process and are judged to meet certain criteria (for example, number frequency of citations)

an alternative fuel to be adopted, interest and commitment of many stakeholders are required across the entire fuel value chain from production to utilization. For example, equipment manufacturers need assurances to invest in R&D and development of specific equipment, and policy-makers should be contributing policies and funding in the same direction.

1.2.3 Alternative fuel for gas turbines

MCDM assessments are not new to sustainable energy development projects, studies have been carried for the selection of renewable energy sources and power-plant locations (Pilavachi et al., 2009; Chatzimouratidis & Pilavachi, 2008; Amer & Daim, 2011). However there are very limited assessments for the selection of alternative fuels for power generation. Existing literature is focused on evaluating different liquid bio-fuels for combustion engines in the transport sector (Papalexandrou et al., 2008; Erdoğan et al., 2019), and only one study analysed the use of bio-fuels in a diesel turbine for power generation (Durairaj et al., n.d.). This research contributes to the discussion of possible alternative fuels for power generation from gas turbine, with an emphasis on comparing hydrogen fuel against liquid organic hydrogen carriers.

1.3 Research Objective

The main objective of this research is to apply existing tools and methods to the problem of selecting an alternative fuel in Rotterdam. The focus is on evaluating hydrogen fuel against a liquid organic hydrogen carriers (LOHC). The outcomes of the assessment will be used to provide recommendations to decision-makers on what alternative fuel shapes the near and far future for peak power generation in Rotterdam. This is to be done in light of the limitations and assumptions taken for the selected location, technologies and fuel alternatives. In the process, contributions are made to the existing MCDM methods, which can be applied to similar selection problems in sustainable energy development.

1.4 Research Question

The following research question describes the academic challenge at hand, and it is elaborated into five sub-questions that provide structure for the entire research:

"What alternative fuel is most preferred by key decision-makers for peak power generation in Rotterdam?"

1. What are relevant criteria for decision-makers that play a role in the decision making process?
2. How does the production, transport, storage and utilization of the selected alternative fuels perform on the relevant criteria?
3. How can the criteria be weighed and combined to allow for a comparison of the alternative fuels?
4. How robust are the results to the outcomes of the analysis?
5. What can be recommended for the short-term and long-term selection of alternative fuels for power generation?

1.5 Scientific and Societal relevance

1.5.1 Societal relevance

The subject of this research is of current national public interest. The northern Netherlands is investing heavily in a hydrogen economy (Weeda, 2019), and the Dutch government is funding research into hydrogen turbines. While this presents one route for the energy transition, it is not the only route. Attention should also be brought to other possible alternative fuels, more specifically LOHCs which can facilitate transportation and long-term storage of hydrogen and utilization of existing oil infrastructure with little modifications for storage and utilization.

In essence, MCDM tools help in evaluating multiple conflicting criteria for decision makers. These tools have been developed, applied and refined extensively in the academic world, often relying on the judgement of researchers in universities. This research attempts to apply the tools using input from real decision-makers in the Dutch energy sector. Experts from CE Delft, Shell, Eneco, Frames and Warburg Pincus represent the views of local policy-makers, and key decision-makers in the investment decisions for alternative fuels and sustainable energy development.

1.5.2 Scientific relevance

The results of this research are somewhat case specific to The Netherlands, since local geological conditions, energy resources are assumed and Dutch stakeholders are involved. That being said, this research contributes to the MCDM research in a variety of ways.

Relevant criteria that influence the comparison of hydrogen and LOHC as gas turbine alternative fuels are identified. For instance, energy efficiency and technology maturity proved to be influential in the decision-making process, while system safety is of less relevance for the selected fuels.

Also, the contributions to the MCDM methods are transferable to other MCDM studies, and can be used in selection problems for alternative future energy systems, for example electric vehicles vs. hydrogen vehicles for public transport. This research incorporates a quantitative method to indicate technological maturity. Technological maturity is often overlooked by researches, and based on the relatively small sample of interviewees in this research, it is a relevant component of the decision making process.

1.5.3 Relevance to MSc. program

In this research, a complex decision-making problem is addressed by applying several tools and methods. The research is based on principles of system engineering where trade-offs between the economic, technical, social and environmental criteria are highlighted across the life-cycle of alternative fuels. The research includes a technical component, where two alternative fuel production systems are designed and compared. A technical understanding is required to design the systems by incorporating the capacity factors of the renewable energy source, energy efficiencies of the components, electrical and pressure requirements and other specifications.

That being said, the research goes beyond analysing the technical aspects of the system. A variety of research methods are applied to gather and analyse data to contribute to a multi-disciplinary understanding of the problem. The environmental impact is quantified using modeling tools. Academic literature is analysed to incorporate relevant criteria and to validate the results of the assessment from similar research. The social aspects of the alternative fuels are studied in terms of job creation, system safety and security of supply. The vital role of stakeholders across the value in adopting an alternative fuel is recognized. Valuable input is obtained by carrying interviews with key stakeholders from the industry.

1.6 Thesis structure

The rest of this research is structured as follows, Chapter 2 describes the research design employed to answer the research question. The chapter starts with a literature review of MCDM tools applied by researchers, and the major decision-making criteria and sub-criteria relevant to decision makers for renewable energy initiatives. This is followed by demarcating the system boundaries, and designing the production system for both alternative fuels. Finally, the research criteria and methods are selected based on the system boundaries, and the literature review.

In chapter 3, the individual assessments are carried for both alternative fuel according to the major criteria and sub-criteria selected in chapter 2. In each assessment, the tools, assumptions and limitations are described, and the assessment ends with a summary of the outcomes. Chapter 3 ends with a summary of the fuel performance across all major criteria and sub-criteria.

In chapter 4, the MCDM method selected is defined. The methodological steps are described in detail, and the contributions made to the criteria weighting are elaborated. This is followed by the selection of stakeholders, the interview structure and outcomes of the proposed criteria weighting method.

In chapter 5, the outcomes of the MCDM research are reported and discussed. A sensitivity analysis is performed to test the robustness of the outcomes. The most relevant criteria for decision makers are used to create two scenarios. Finally, the limitations of the proposed method are discussed

Finally, chapter 6 reports the answers to the sub-questions, main conclusions and findings, reflects on the limitations and proposes opportunities for future research.

2 Research Design

2.1 Literature review

Energy planning often involves a multitude of actors with diverging interests and means to realise the energy alternatives (Tsoutsos et al., 2009). The Dutch ministry of Economic Affairs published a report on the required actions to realize the energy transition. The report stresses that for the energy transition to succeed, the public, businesses and NGOs must be constructively involved at an early stage in the discussion of the energy planning process. Wherever possible, all stakeholder interests should be involved in weighing the benefits of an energy supply initiative against the hindrance or risks it involves (EZK, 2016).

The selection of a preferred renewable energy route is becoming more difficult due to the increasing complexity and trade-offs between the economic, technical, social and environmental factors (Daim & Taha, 2013). Conventional single-criteria approaches are no longer sufficient to deal with such complexity, and multi-criteria methods are applied to handle such problems (Daim & Taha, 2013). Multi-criteria decision making methods (MCDM) are frequently used by the scientific community to deal with such decisions for a variety of reasons. They allow for the integration of the interests of multiple actors by incorporating both their quantitative and qualitative input through the use of criteria and weighting factors (Tsoutsos et al., 2009). The results of the assessment are often simple and easy to communicate to actors, and the entire process is not energy and cost intensive (Tsoutsos et al., 2009).

2.1.1 Review of MCDM Research tools

MCDM methods are computational tools used by researchers to support the subjective evaluation of performance criteria relevant for decision-makers (Mardani et al., 2015). Comparing and adopting alternative energy sources is a multidimensional decision making process involving a number of different, often contradictory, characteristics at different levels that can be economic, environmental, technical, social and even political (Daim & Taha, 2013). These methods can handle both quantitative and qualitative criteria and analyse their conflicts for decision makers (Daim & Taha, 2013). To this effect, researchers rely on different MCDM tools to merge and analyze the different factors that go into making a decision, and to clearly and consistently justify choices in the energy sector (Daim & Taha, 2013).

Campos-Guzmán et al. (2019) carried a literature review to analyze the MCDM tools that have been used by the scientific community for renewable energy systems during the period 2007-2017. The authors studied 154 cases of sustainable energy management systems, and report a multitude of tools used in MCDM. Tools vary in terms of information needed and their degree of mathematical programming sophistication. Some of the methods typically used are the Analytic Hierarchy Process (AHP), Analytic Network Process (ANP), Technique for Order Performance by Similarity to Ideal Solution (TOPSIS), Multi-Criteria Optimization and Compromise Solution (VIKOR), Elimination et Choix Tradusiant la Realite (ELECTRE) (Martín-Gamboa et al., 2017).

The authors concluded that the Analytical Hierarchy Process (AHP) is the most popular method applied among researchers due to its simplicity, and firm theoretical foundation (Campos-Guzmán et al., 2019). Wang et al. (2009) also conducted a detailed review of MCDM tools applied for sustainable energy systems, and recommend AHP as the most powerful and comprehensive technique for such systems. The authors compared the MCDM tools according to their weighting techniques (subjective, objective and combination) and methods (weighted sum, priority setting, outranking, fuzzy set methodology) (Wang et al., 2009). AHP is also the method used the most for calculating the weight of the criteria analyzed, and the final score calculation of scenarios and alternatives (Campos-Guzmán et al., 2019). However, the biggest weakness of AHP method, and indeed MCDM in general, refer to its subjectivity of weights and to the ranking method. This is particularly a problem when translating qualitative information, such as preferences of actors, into weights associated with specific criteria (Tsoutsos et al., 2009). This is overcome by the utilization of Fuzzy number principles, however since the majority of information used in this research is quantitative by nature, the Fuzzy approach is not explored.

AHP has been applied in the energy sector in several occasions to solve multi-criteria decision problems. Researchers have utilized the method for a variety of applications including energy policy formulation, energy planning, power-plant selection, power-plant location selection, energy resource allocation and developing energy management systems (Amer & Daim, 2011). (Pilavachi et al., 2009) used AHP to evaluate and rank hydrogen production from 7 methods, based on CO_2 emissions, operation and maintenance costs, capital cost, feed stock cost and hydrogen production cost. Papalexandrou et al. (2008) used the method to evaluate the utilization of conventional and advanced liquid bio-fuels in the European transport sector according to bio-fuel substitution cost over conventional fuels, potential of substitution, total cycle greenhouse gas emissions and total cycle energy consumed (Papalexandrou et al., 2008). Economic, technical, environmental and social criteria were also analyzed using AHP for wind farm site selection in several literature studies (Al-Yahyai et al., 2012; van Haaren & Fthenakis, 2011). AHP has also been used for project selection in several publications to rank renewable energy alternatives (solar, onshore and offshore wind, hydro-power and bio-fuel) based on a variety of technical, environmental and economic criteria (San Cristóbal, 2011; Stein, 2013; Chatzimouratidis & Pilavachi, 2009).

2.1.2 Review of decision-making criteria

The selection of the criteria is the most critical part during problem formulation, which depends on the availability of qualitative and quantitative data (Tsoutsos et al., 2009). From several literature reviews on MCDM for sustainable energy decision-making, all criteria selected by researchers can be categorized to fall under one of four categories: Economic, environmental, technical and social (Wang et al., 2009; Campos-Guzmán et al., 2019). These 4 major criteria are then split into sub-criteria depending on the nature of the decision at hand, whether it is the selection of a renewable energy source, power plant type or energy storage system. A review will be discussed of typical sub-criteria in order to motivate the selection of the relevant sub-criteria for this research. The following subsection describes the fuel production systems for hydrogen and methanol, the criteria were selected with the both fuel production systems in mind.

With regards to economic criteria, decision makers are often interested in indicators that determine the way in which limited resources are distributed between the construction, production and operation of the system. Capital investment costs and operation and maintenance (fixed and variable O&M) costs are the most applied economic criteria (Wang et al., 2009). Fuel/electricity costs, energy costs, payback period, energy payback time and R&D costs are also investigated depending on the goal of the MCDM analysis (Amer & Daim, 2011; Wang et al., 2009).

Environmental criteria are highly dependent on the project being assessed. For example, acidification potential and land use are very relevant for environmental indicators for discussions on biomass production, while climate change and characterization of resource use are relevant for solar projects (Campos-Guzmán et al., 2019). That being said, climate change (or global warming potential measured in CO_2 equivalent) is performed in 100% of MCDM analyses that include an environmental impact. For offshore wind projects, climate change is the most commonly applied environmental indicator, followed by the acidification potential (ph depletion) (Campos-Guzmán et al., 2019). As for conventional power generation from natural gas turbines, apart from CO_2 emissions, nitrous oxide (NOx) emissions cause significant environmental effects which have led to active research into NOx control (Navajas et al., 2019). Alternative fuels are widely proposed to reduce such emissions (Goldmeer, 2018a; Murray & Furlonge, 2009). Pilavachi et al. (2009) conducted a multi-criteria assessment comparing power generation from natural gas with hydrogen turbines for power generation, and concluded the relevance of including NOx emissions and global warming potential as environmental indicators.

Technical factors are also popular among researchers. Depending on the nature of the study, different sub-criteria are analysed. For power plant selection, Chatzimouratidis & Pilavachi (2009) focus on reserves to production ratio, efficiency coefficients (ratio of useful energy output to energy input), time availability (amount of time the plant produces electricity in a given period, divided by the same period) and capacity factors. Amer & Daim (2011) assessed different renewable energy generation technologies for deployment in Pakistan based on technical maturity, resource availability, reliability, availability of human resource expertise, efficiency and capacity factors. Technology maturity has been analysed in only very few AHP studies for sustainable energy development (Campos-Guzmán et al., 2019; Amer & Daim, 2011). Technology maturity is a measure of the operational status of a technology, and specifies whether it is at experimental laboratory scale or at commercial levels and theoretical limits of efficiency have been reached (Amer & Daim, 2011). S. K. Lee et al. (2008) proposed a technological status criterion which is quantified by the number of patents, SCI papers and paper proceedings published over a certain period of time. The authors quantified the number of paper proceedings for hydrogen storage, production and utilization to indicate the technological status of hydrogen as a fuel (S. K. Lee et al., 2008).

Social criteria address issues that affect people both directly and indirectly, and are expressed on whether they benefit or harm the population (Campos-Guzmán et al., 2019). Currently, there is no consensus on which evaluation method to apply to evaluate social criteria, which often involve gathering both quantitative and qualitative data. The most commonly used social criterion for energy projects is job creation (Campos-Guzmán et al., 2019). Other commonly applied indicators are public acceptance (for power plant selection), social benefit (to progress local community), impact on human health, resources security, national energy security, safety and expected mortality in case of an accident (Amer & Daim, 2011; Campos-Guzmán et al., 2019; Acar et al., 2019). Political criteria are commonly regarded as a subset of social criteria and mostly refer to national energy security (Kahraman et al., 2009).

2.2 System Boundaries and Design choices

In this section, the system boundaries and the motivation behind the technological design choices will be discussed. Equally as important, the assumptions taken for each process unit in the value chain are elaborated. The value chain is split into four phases. The generation of electricity from a renewable energy source and the production process of alternative fuel (**production**), followed by the **transport** of the fuel, fuel **storage** and finally **utilization** in a peak power plant in Rotterdam.

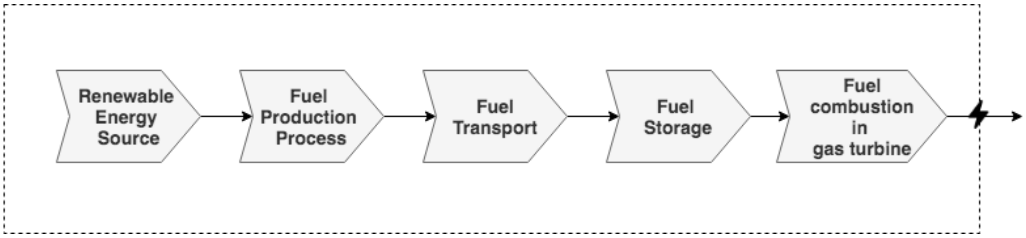

Figure 2: Systems boundaries for multi-criteria assessment

The motivation behind the demarcation of this system boundary is that excluding parts of the value chain would significantly influence the outcome of the analysis. The goal is to gain an understanding of the requirements and repercussions of selecting an alternative fuel throughout the entire value chain. For example, while hydrogen production chain is much shorter and *maybe* more efficient than methanol, the transportation, handling and storage of the methanol is much easier and less energy demanding compared to hydrogen. A rich, multidimensional analysis of all decision-making criteria across the entire fuel value chain is beneficial for all stakeholders involved in the selection, and indeed the adoption of an alternative fuel.

2.2.1 Hydrogen production system

A bottom-up approach is taken to size the entire ”Wind to Hydrogen” system. The energy demand for hydrogen production is required to be completely met with electricity generation from the wind turbine. Offshore wind capacity factors for The Netherlands are used to estimate electricity generation potential. The hydrogen production system is designed to produce, compress and store hydrogen on site at the peak power plant location. By doing so, the challenges faced with hydrogen transport are eliminated. Hydrogen fuel production is sufficient to run the peak power plant for around 10 hours per week, or around 517 hours per year. The storage unit is capable of storing enough hydrogen to run the power-plant for 5 full hours at a time. One shortcoming of such a system is the assumption of the match between the hydrogen production from offshore wind, with the peak demand hours in a given week. While this is not feasible due to the intermittent nature of the energy system, the offshore wind capacity is sized such that the electricity generation over the its lifetime is equal to the hydrogen production system energy consumption.

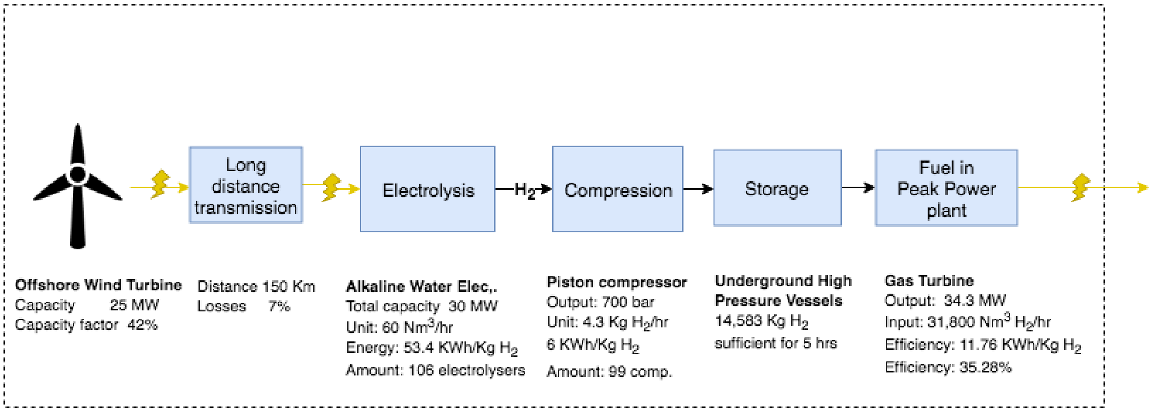

Figure 3: Hydrogen fuel system boundaries

1. *Production*

   The expected annual generation from the wind farm is based on a 42% capacity factor for offshore wind projects in The Netherlands (Kling et al., 2007). To fulfill the energy demands of the system, a 25 MW offshore wind farm will be constructed in the North Sea, and connected to the grid. The produced electricity is transmitted to the power plant location (Maasstroom Energie power plant in Rotterdam), where hydrogen is produced locally on site via electrolysis.

   Acar & Dincer (2014) performed a comparative environmental assessment of hydrogen production from renewable and non-renewable energy sources. The two major routes for hydrogen production from renewable energy are electrolysis, and biomass gasification. Biomass gasification involves the use of wood processing, agriculture residues, municipal and animal waste as biomass feed-stock for hydrogen production. However currently biomass gasification is not able to produce enough hydrogen at a competitive price for large scale applications. A further concern for this method is the significant land and natural resource requirement as result of growing quantity of biomass as an energy crop Acar & Dincer (2014).

   The most common method for hydrogen production from renewable energy sources is via electrolysis Ozbilen et al. (2013). Electrolysis is regarded as a potentially cost effective method of production, albeit at a higher cost and energy requirement compared to the fossil fuel alternative of steam reforming. Solar photo-voltaic based electrolysis is considered one of the most costly methods for hydrogen production, costing about 25 times production from fossil fuels Ozbilen et al. (2013). Wind powered electrolysis is the most promising renewable hydrogen production method. The cost is currently 6-10 times that of fossil fuels, with the expectation that the gap to be halved in the near future Ozbilen et al. (2013).

Three common electrolyzers exist, depending on the type of electrolyte material utilized: Alkaline electrolyzers, Proton Exchange Membrane electrolyzers (PEM) and Solid Oxide electrolyzers (Ozbilen et al., 2013). Alkaline electrolysis is a fully mature technology, and has been widely used in the industry for non-energy purposes (Taibi et al., 2018). The lifetime of alkaline electrolysers is twice as long as PEM, and have much lower capital and expenditure costs. PEM electrolysers are able to operate more flexibly and re-actively compared to current alkaline electrolysers (Taibi et al., 2018), with startup times of 1 sec - 5 minutes, compared to 1-10 minutes for Alkaline electrolysers. However, PEM electrolysers are still regarded as a young technology with questionable scalability (Taibi et al., 2018).

The 60 Nm^3 H_2/hr alkaline water electrolyser used in (Burkhardt et al., 2016) is selected for this system. The electrolyser is designed to handle rapid short-term fluctuations in energy input (Burkhardt et al., 2016) and consumes 53.4 KWh/Kg H_2 (4.75 KWh/kg H_2). The energy requirement is similar to the assumption in existing literature, where it ranges from 3.8-4.4 KWh/Kg H_2 (Hydrogen Electrolyser, 2018) to 5.45 KWh/Kg H_2 (Goldmeer, 2018a).

The power input for the electrolysers is calculated by estimating the generating hours of the wind turbine per day (10.6 hours/day for a 42% capacity factor), and the amount of hydrogen production needed to run the peak power plant for 10 hours per week (gas turbine hydrogen fuel requirement addressed in the gas turbine section). The product gives 106 60-Nm^3 electrolysers, consuming 4.75KWh/Nm^3H_2 (Burkhardt et al., 2016) and producing 6309 m^3 H_2/hr. This adds up to an alkaline electrolyser hydrogen production plant of 30 MW capacity. The assumption is made that the electrolysis runs entirely on electricity from the wind farm. Also excess electricity generated by the wind farm (not utilized in the system processes) is out of the scope of this research, both in cost and benefit terms.

Electrolyser	Alkaline water electrolyser
Capacity range per unit	60 Nm^3 H_2/hr
DC power consumption	53.4 KWh/Kg H_2 4.75 KWh/Nm^3 H_2
Efficiency (HHV)	73.80%
Operating temperature	80 °C
Electrolyser lifetime	50,000 hrs
Output pressure	15 bar
Working range	5-100%
Number of units	106 electrolysers
Hydrogen plant capacity	30 MW

Table 2: Electrolyser specifications (Burkhardt et al., 2016)

2. *Transmission*

For the purposes of this analysis, the offshore wind turbines are connected to the grid, and the electricity is transmitted to the location of the peak power plant where it is used for hydrogen production on site. Transmission losses are estimated to be 7% grid based on existing literature from (Ozbilen et al., 2013; Ghandehariun & Kumar, 2016a). This number is dependent on transmission distance, and a rough estimation is assumed based on literature in this case. Another alternative that was considered is the HYGRO system which integrates the wind turbine, and transporting the hydrogen via pipeline that act as a transport/storage medium. This technology was not considered due to its early development stages, and challenges for hydrogen transport via pipelines (Fekete et al., 2015).

3. *Storage*

Large scale hydrogen storage is regarded as one of the biggest challenges for the utilization of pure hydrogen fuel. Several hydrogen storage technologies exist, either in physical, chemical or electro-chemical form (Wolf, 2015; Crotogino, 2016). Physical storage in pure molecular form is relevant for the utilization in peak power plants and is currently applied at a commercial scale in both liquid or gaseous states(Andersson & Grönkvist, 2019). Solid storage of hydrogen in hydrates is dismissed, since it is still in development phases(Andersson & Grönkvist, 2019).

Hydrogen liquefaction is a substantially energy-intensive process, due to the extremely low boiling point of hydrogen (-253 °C at 1 bar) Energy demands for liquefaction are 12.5-15.0 KWh/KG hydrogen(Sheffield et al., 2014). Furthermore, upon liquefaction, it is essential to minimize hydrogen evaporation and to vent out the evaporated gas to avoid pressure buildup inside the storage vessel. This loss of hydrogen over time is referred to as boil-off, which is minimized by using double-walled insulation and a high vacuum applied between the walls(Andersson & Grönkvist, 2019). To minimize this evaporation effect during storage, liquefied hydrogen requires energy for constant cooling in cryogenic tanks (at -252°C for ambient pressure) in order to keep the hydrogen under proper thermodynamic conditions and maintain its liquid state. So not only is energy lost during liquefaction, but also hydrogen losses due to venting off the evaporated hydrogen, as well as cooling the vessel. All together, the energy required throughout the liquefaction value chain accounts to 36 wt.% of the starting hydrogen energy content (Di Profio et al., 2009). An alternative to liquefaction is the storage of compressed hydrogen in gaseous state. Naturally, compressed gas offers lower energy per unit mass compared to liquefied hydrogen, yet is less energy demanding. Compression to 700 bar, which is the storage pressure required for vehicle application, is 6.0 KWh/kg hydrogen(Sheffield et al., 2014). As for stationary storage applications for industrial purposes, where requirement for energy density is not as stringent, lower pressures of 200-350 bars are sufficient, and thus even lower energy demand for compression. At pressure of 300 bar, volumetric density of hydrogen is 20 kg/m^3 (Makridis, 2016).

Compressed hydrogen gas storage systems consist of a compressor to reach the storage pressure, and a storage compartment. The storage can be located underground or overground. Underground storage is typically geologically dependant, where hydrogen is stored in subsurface salt cavities, aquifers and in depleted oil and gas fields. These geological larges-scale storage reservoirs offer low construction costs, low hydrogen leakage rates (Andersson & Grönkvist, 2019), however are not geologically available in the Rotterdam area. Overground hydrogen storage vessels are typically modeled after natural gas vessels (gas holders, spherical tanks and pipe storage) (Carpetis, 1988). However such containers operate close to atmospheric pressure, which is not suitable for the pressure conditions of electrolysers and the hydrogen grid (Stolten & Emonts, 2016).

Andersson & Grönkvist (2019) propose hydrogen storage in underground highly pressurized metal containers, which can save space and offer insulation and protection from physical weathering impact. On the downside, maintenance and inspection of the underground tanks becomes more challenging, and special care is needed to prevent corrosion(Andersson & Grönkvist, 2019). This concept is referred to as lined rock caverns storage (LRC), and has been commercially operated for over 10 years in the 40,000 m^3 storage in Skallen, Sweden (Tengborg et al., 2014). In this storage system. The below ground facility consists of several storage caverns which are connected to the surface facilities by a gas pipeline running through a vertical shaft. The typical cavern dimensions are 35-45 meters in diameter and 60-100 meter in height, excavated as vertical cylinders with rounded tops and bottoms at 100-150 meter depths. Storage volumes needed are achieved by modular addition of caverns. The surface facilities are similar to facilities needed for conventional underground storage (in salt caverns, depleted reservoirs), including compressor stations, heating/cooling stations, piping, valves, metering and control systems (Tengborg et al., 2014). The storage tanks can be designed to hold pressurized gases (natural gas, air or hydrogen) in excavated caverns with medium to high quality rock types. The cavern wall transfers the pressurized gas load to the surrounding rock structure. This wall is built of a layer of steel lining which seals the gas from escaping, followed by a concrete layer with a steel reinforcement mesh to transfer the load to the rock (Tengborg et al., 2014). A typical system is shown in figure 4 as constructed in Sweden.

LRC system is selected for hydrogen storage for several reasons. The concept does not require the presence of special geological characteristics such as salt caverns. Also the structure can contain highly pressurized gases, and allows high-frequency cyclic loading which is relevant for

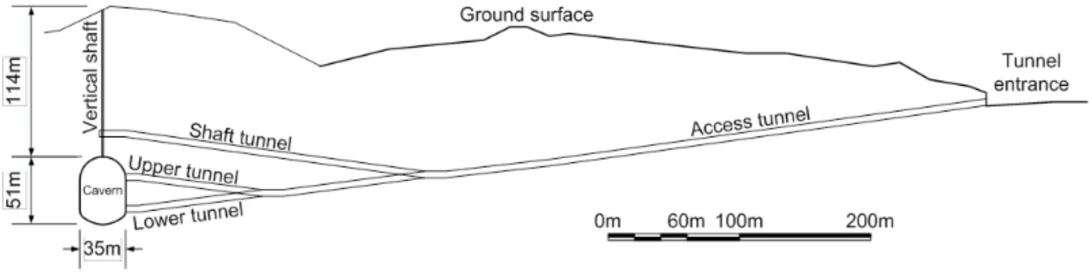

Figure 4: Storage cavern and tunnel arrangements for LRC demonstration plant in Sweden (Tengborg et al., 2014)

peak power plant fuel storage (Tengborg et al., 2014). Moreover, underground storage reduces land use and significantly reduces accident risk, which is typically applied in hydrogen refueling stations (Sheffield et al., 2014).

In order to store hydrogen at pressures of 400 bar and over, hydrogen is mechanically compressed using a piston diaphragm compressor. This is an electro-hydraulically drive n multi-stage process which uses an electric motor, hydraulic oil tank, high pressure gas intensifier and an intensifier shifting mechanism (Makridis, 2016). The compressor runs simultaneously to the electrolyser, and the hydraulic aggregate uses a mineral oil to that is changed after around 2500 hours operation which is then changed (Burkhardt et al., 2016).

Compressor	Diaphragm Compressor (Taljan, 2008), Sheffield, 2014)
Capacity per compressor	48 Nm3 H_2/hr
Power consumption	6 KWh/Kg H_2
# of compressors	99 compressors

Table 3: Compressor specifications

Compressed hydrogen can be stored in 4 types of storage tanks (type 1, 2, 3, 4) (Barthelemy et al., 2017). Type 1 pressure tanks are all metal (limited to 300 bar pressure), while type 2 contain a thick metallic liner wrapped in a fiber resin composite and offer unlimited storage pressure (Barthelemy et al., 2017). Types 3 and 4 are the fully composite based vessels made of a plastic or metallic liner wrapped with carbon fibers, embedded in a polymer matrix. They are very light, yet very expensive and designed for automobile applications. In industrial applications, hydrogen is typically stored at 200-300 bar in type 1 containers. Type 1 vessels have very poor mass storage efficiency (about 1 wt.% of H_2stored), and hydrogen embrittlement issues at higher pressures (Stolten & Emonts, 2016).

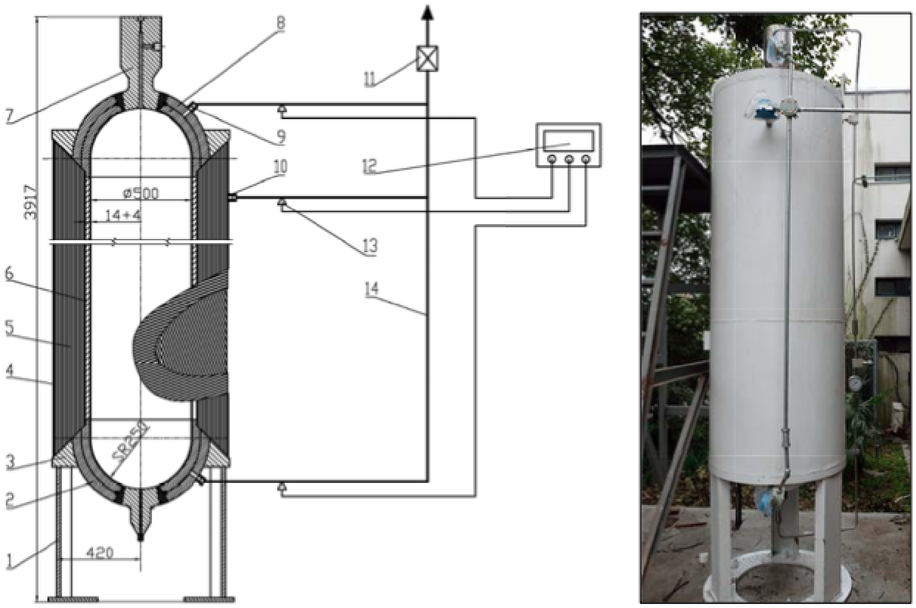

Figure 5: Multi-functional type 2 high pressure hydrogen storage tank (1: support, 2: outer hemispherical head, 3: reinforcing ring, 4: protective shell, 5: steel ribbon layer, 6: inner shell, 7: top nozzle support, 8: inner hemispherical head, 9: head nozzle, 10: cylinder nozzle, 11: hydrogen flame arrester, 12: display and alarm instrument, 13: sensor, 14: vent pipe) (Zheng et al., 2016)

The hydrogen storage is designed to store 14,580 kg H_2 of compressed hydrogen, which is sufficient to run the 34.3 MW hydrogen peak plant for 5 hours. However, the hydrogen produced on a daily basis is sufficient to run the turbine for just 2 hours. The assumption is that the peak power plant may not be called for several days, so hydrogen is cumulatively produced and stored to allow to up to 5 hours of operation. The storage tank is modeled after type 2 storage tanks which are commonly used in high pressure refueling stations (Vickers, 2017). Zheng et al. (2016) developed a multi-functional layered stationary hydrogen storage vessel, which is composed of a flat steel ribbon wound cylinder (made of a thin inner shell, a layered shell, and a protective shell), two double-layered hemi-spherical heads and 2 reinforcing rings (see 5). There are no manufacturing limitations for the cylinder length or shell thickness, which allows for very large hydrogen storage vessels at high pressure. Hydrogen embrittlement is addressed by using materials with good hydrogen compatibility for the layer in contact with hydrogen (Zheng et al., 2012). The steel tank manufacturing process and materials are discussed in (Zheng et al., 2016), and material breakdown can be found in the appendix. Hydrogen losses during electrolysis, compression and storage are often hard to determine(Burkhardt et al., 2016). For example, losses due to the degradation of the electrolyser stack. This can be translated into electricity demand for the electrolyser, and is assumed to be included in the electricity consumption of the electrolyser reported in table 2.

Storage	Multi-functional high pressure vessels (Zheng, 2016)
Storage pressure	700 bar
Tank diameter	1.5 m
Tank height	30 m
Tank volume	212 Nm3
Empty tank weight (3.5 wt.%)	188,680 Kg
Total number of tanks	8 tanks

Table 4: Hydrogen Storage tank specifications (Zheng et al., 2016)

4. *Utilization*

Utilization of hydrogen as a fuel for gas turbines has been researched both in academic literature, as well as in practice. Siemens, and General Electric have developed gas turbines that run on varying mixtures of natural gas and hydrogen, from 10% H_2- 90% Natural gas to 100% hydrogen. In scientific literature, the possibility of burning hydrogen in existing natural gas turbines for large-scale electricity generation has already been studied (Chiesa et al., 2005). Chiesa et al. (2005) studied the behavior of the turbine by analysing the operational aspect of switching natural gas turbines to run on hydrogen, addressing the effects of variation in volume flow rates and thermo-physical properties on matching the turbine with the compressor and on blade cooling, and also the necessary NOx control (Chiesa et al., 2005). This is elaborated in greater detail in the technology readiness section in chapter 3. The gas turbine selected for the peak power plant is the 34.3 MW TM250 developed by *GE* (Goldmeer, 2018a), specifications are in table 5. The turbine efficiency is based on hydrogen LHV from table 6 and the heat input of the turbine. Efficiency of the turbine is calculated to be 11.76 KWh/Kg H_2, by using the heat input from the turbine specifications, and the LHV of hydrogen.

Gas turbine	TM250 (GE)
Output	34.3 MW
Heat input	350 GJ/hr
H2 flow rate	3,1800 m^3/hr
Turbine efficiency	35 %
Turbine efficiency (LHV)	11.76 KWh/Kg H_2

Table 5: Hydrogen Gas turbine specifications

	Unit	**Methanol**	**Hydrogen**	**Natural Gas**
Chemical Formula		CH_3COH	H_2	
Molecular weight	g/mol	32	2	
Density (STC)	kg/m3	794	0.089	0.777
Density (at 350 bar)	kg/m3	-	23	-
Density (700 bar)	kg/m3	-	38	-
LHV (per volume)	Mj/Nm3	15.8	10.8	36.4
LHV (per mass)	MJ/Kg	20.1	120	53.6
Laminar flame speed	cm/sec	5.2	170	
Flammability range	%	6-36.5	4-75	5.3-15
Boiling temperature	°C at 1 bar	65	-253	
Flash point	°C	12	-231	-188
Ignition temperature	°C			

Table 6: Fuel properties

2.2.2 Methanol production system

The production chain of methanol is designed according to the *ZEF, B.V.* model. Solar PV is currently the cheapest source of renewable energy production, with prices continuously dropping since the development of the technology and expanding global demand (Gielen, 2012). Methanol is produced by connecting one *ZEF* micro-plant to the back of three solar panels. Each micro-plant is able to produce 588 grams of methanol per day, assuming a 7 equivalent sun hour day. The methanol production is based on a scaling by numbers, as opposed to economies of scale approach. Meaning that the production units are modular, and based on simple components, and production is scaled to meet the methanol demand. Each micro-plant stores its own methanol production, which can be emptied and shipped to the utilization site.

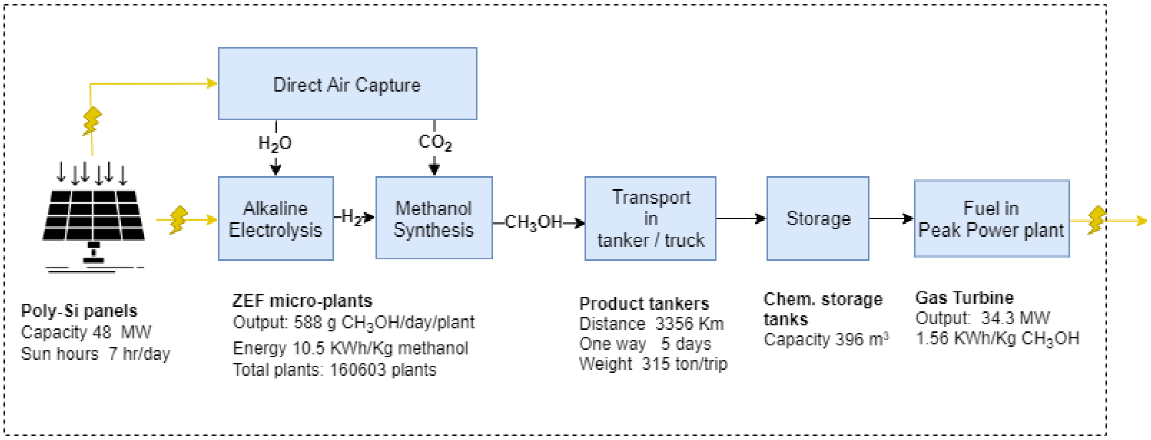

Figure 6: Methanol fuel system boundaries

1. *Production*

   The micro-plant is designed to operate autonomously, and consists of 4 major sub-components. A Direct Air Capture (DAC) system captures carbon dioxide and water from air. An air compressor unit compresses the air mixture to a pressure of 15 bar, and passes the mixture onto a Degasser. The degasser separates the carbon dioxide atom from the water, and the water is used in Alkaline Electrolyser to produce hydrogen. In the methanol synthesis unit, hydrogen is combined with CO_2 to produce the methanol fuel (CH_3OH). The final step is to separate the methanol from any water in the Distillation unit and collect the methanol is then collected in a storage tank.

Figure 7: ZEF micro-plant. (David Van Nunen, ZEF)

2. *Transport*

   Methanol transportation is a mature concept, since the lack of proximity between producers and consumers dictate that as much as 80% of the wold's annual production to be transported between continents. Methanol is pumped into sealed cargo holds of tanker ships for Trans-oceanic transport in double hulled vessels (Medina & Roberts, 2013). Methanol handling is similar to other hydrocarbon liquids, such as crude oil, gasoline and diesel where leak detection, appropriate firefighting equipment are required (Medina & Roberts, 2013).

   Transport distance from Agadir port in Morocco to the port of Rotterdam is estimated based on several online resources for freight shipping distance calculation. An average shipping distance of 3356 Km is selected based on one resource[2]. The trip is completed in 5 days, therefore a 10 day round-trip (ship going back empty) is assumed for further calculations of environmental emissions and cost estimates. The methanol production from the entire plant is around 315 ton for 10 days and is to be transported in product tankers. These are typically used to transport refined chemical products such as gasoline and other oil-based products.

3. *Storage* Storage of methanol is subject to substantially the same provisions as those used for gasoline storage. Methanol is routinely stored in tank farms consisting of above-ground, floating roof tanks and smaller. Tanks are often grounded to avoid hazards associated with static discharge. Ignition controls often done by nitrogen padding, natural gas padding, or simply by designation of a hazard zone with ignition control. (Medina & Roberts, 2013)

   The storage tank is designed to store the methanol produced by the entire plant from 10 days of generation. This corresponds to around 315 tons. At standard conditions, the methanol would require a total storage volume of 400 m^3.

4. *Utilization*

   Methanol has the highest hydrogen to carbon ratio of any liquid fuel, and has been both scientifically and commercially considered as an alternative fuel for electric power generation from gas turbines. Methanol is especially being considered as a possible fuel for isolated areas on land and in near-land areas at sea (Day, 2016). Commercial applications have taken place in a

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[2] *Sea route map; distance - ports.com* (n.d.)

50 MWe Gas Turbine in Eilat which has been modified to consume 30 metric tons of methanol per hour (Day, 2016). The new plant yielded significant reductions in NOx and SOx emissions. Also in Trinidad and Tobago, MHTL (Methanol Holdings Trinidad Limited) retrofitted a 9.7 MW Gas Turbine from diesel to methanol at a commercial scale. For this research, the specifications of the methanol turbine are designed based on the work of Murray & Furlonge (2009). The gas turbine efficiency for methanol fuel is calculated based on the LHV of methanol from the fuel characteristics in table 6 and a turbine heat rate of 12.77 MJ/KWh (Murray & Furlonge, 2009). This give a gas turbine efficiency of 1.56 KWh/Kg methanol, or 28%.

Gas turbine	(Murray & Furlonge, 2009)
Output	34.3 MW
Turbine Heat Rate	12.77 MJ/kWh
Turbine Efficiency	28 %
Turbine Efficiency (LHV)	1.56 KWh/Kg methanol

Table 7: Methanol turbine specifications

2.3 Research methods and RFD

In this section, the criteria that are relevant to the decision making process will be selected, followed by defining the research methods that will be applied. With regards to the relevant criteria, the literature review revealed that all sub-criteria relevant to decision makers can be categorized under four major types of criteria: economic, technical, environmental and social criteria (Campos-Guzmán et al., 2019).

The economic assessment carried in this research is based on quantifying the capital investment and operating expenditure of the entire value chain. This incorporates the equipment, labour as well as the energy costs which can be quantified and compared across systems.

As for the technical criteria, two sub-criteria are very relevant to the selected alternative fuels. Firstly, it is still unclear how methanol and hydrogen compare in terms of total system efficiency. While hydrogen constitutes a shorter production chain than methanol, energy is still consumed for compression in order to make its storage feasible (Makridis, 2016). Secondly, the system design for the production of both alternative fuels revealed that system components are at varying stages of development. Decision makers should be aware of the challenges both fuels face different across the fuel value chain. Technical maturity has been sparsely evaluated in MCDM research, yet it is a significant sub-criterion in this discussion. Other technical criteria such as time, resource availability and capacity factors are not influential for this system, as production conditions are optimised for both alternative fuels.

Environmental criteria are selected based on a few characteristics of the systems evaluated. Global warming potential (CO_2 equivalent) is a common indicator for all renewable energy-based life-cycle assessments. Although the methanol production system is located outside the Dutch borders, greenhouse gas emissions are of global interest to decision makers. The same cannot be said for land use, water use and acidifcication potential which are more location based. Since the alternative fuels are being proposed to replace natural gas for power generation, NOx emissions of the alternative fuels are also included.

Finally, three social criteria selected for the analysis of the alternative fuels, which are job creation, energy security of supply and system safety. Health related criteria were not selected here to avoid overlap with the environmental criteria. Although public acceptance is commonly applied in MCDM research, it is more synonymous with power plant selections (Amer & Daim, 2011). All the selected criteria are displayed in figure 8.

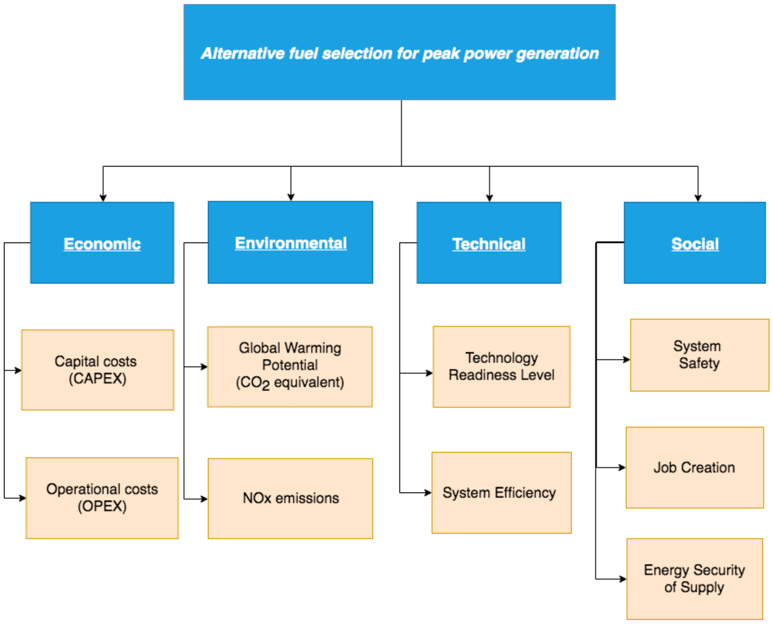

Figure 8: Criteria selection for assessment of alternative fuels

The Analytic Hierarchy Process (AHP) is selected for this research. AHP is the preferred MCDM tool due to its proven theoretical foundation for analysing sustainable energy systems, and its ability to incorporate both qualitative and quantitative criteria (Wang et al., 2009). That being said, the method has been criticised for the subjectivity of the weighting method (Warren, 2004). Warren (2004) explain that the concept of relative importance between heterogeneous concepts is difficult to achieve. This problem is overcome by explicitly describing the sub-criteria that constitute each major criterion to the decision maker. The AHP method is based on three fundamental concepts (Amer & Daim, 2011):

1. Structure the decision making problem as a hierarchy of goals, criteria. sub-criteria and alternatives at the bottom.
2. Perform Pair-wise comparisons between each element at the same level of the hierarchy tree, with respect to the preceding level in the hierarchy. Calculate the ratio-scaled criteria priority for each criterion accordingly.
3. Synthesize the judgements over the different levels of the hierarchy with regards to each alternative's performance and criteria priority.

In this research, the AHP method involves the implementation of several research tools. A literature review is carried to specify the major and minor criteria for decision makers relative to the selected alternative fuels. Alternative fuel performance assessment for the selected criteria is performed through using modeling the system using SimaPro software for the environmental criteria, and through desk research for the economic, social and technical criteria. Interviews are carried with key stakeholders from to perform the pair-wise comparisons between the elements (second step of the AHP). Finally, the outcomes of the criteria weightings and the fuel performance assessments are synthesized mathematically using the AHP method. The description, assumptions and limitations of each tool are described in the chapters where they are applied.

3 Alternative fuel performance on the selected criteria

In this chapter, the research methods and results are detailed. The first analysis covers the environmental impact of both energy routes. This provides a thorough understanding of the processes involved in the form of an inventory analysis, which is an early step in the LCA. This will allow for a more accurate and systematic analysis of economic, technical and social implications across the value chain. This is followed by an economic assessment of the value chain detailing the CAPEX and OPEX of the energy alternatives. Third analysis attempts to quantify the social dimension, and lastly an analysis of the technology readiness and compatibility of the methanol and hydrogen for the dutch energy system.

3.1 Environmental Assessment

Life Cycle Assessment (LCA) is a method that provides a quantitative analysis of the environmental aspects of a product over its entire life-cycle. It is performed through a systematic set of procedures of compiling the inputs and outputs of materials, energy use and environmental impact attributable to all the stages of a system's life-cycle; from raw material extraction through material processing, manufacturing, transportation, maintenance and disposal (K.-M. Lee & Inaba, 2004). ISO 14040 series details the overarching standard for carrying LCA studies through four phases of: goals and scope, inventory analysis, impact assessment and interpretation.

Alternative fuels have a significantly lower environmental impact compared to natural gas where hydrogen combustion simply releases water, and methanol combustion releases CO_2 which is captured from the atmosphere during methanol production, making it effectively a carbon neutral fuel. However in such renewable-based systems, there is an environmental impact due to the manufacturing and transportation of the system components, and also the operation of the system (Burkhardt et al., 2016). Therefore, for each alternative energy route, the entire value chain of fuel production, transportation, storage and utilization are considered in the LCA. The environmental impact of both alternative fuels is compared to a base case of continuing to fire natural gas in peak power gas turbines. The comparison with natural gas does not directly affect the selection of an alternative fuel, and is carried to provide better context to the discussion.

SimaPro software (version 8.5.2.0) is used to model all the system processes. The software is developed by PRé consultants and is in accordance with ISO/TS 14067 and the ISO 14040 series (Lozanovski et al., 2011; Castellani et al., 2018). Ecoinvent 3 library is used to document the majority of processes, and was complemented with ETH-ESU product processes for natural gas system components. The ReCipe 2016 Midpoint (H) method is applied for the impact assessment.

3.1.1 Goals and Scope

The objective of this analysis is to quantify the environmental impact of the life cycle activities across the value chain of alternative fuels production and utilization in peak power plants. The goal is to support decision makers with a better understanding of the environmental impact of both energy routes, as part of a multi-criteria assessment.

System boundaries

A "well to wheel" analysis is chosen to account for the phases of production, transport, storage and utilization of the alternative fuels assessed. It is fairly obvious that burning methanol produces CO_2, while burning hydrogen only produces water. However as discussed in the utilization section, the carbon produced by the methanol utilization is completely carbon neutral, as it is captured from the ambient air. Moreover, burning hydrogen also produces NOx due to the, which contribute to global warming. For this reason, the utilization phase is included within the system boundaries. System boundaries are essential to define the unit processes included in the analysis. The evaluated system boundaries are defined in figures 3 and 6 in chapter 2.2.

The material requirement (cement, steel, aluminum, etc.) for the system assembly (wind turbines, solar panels, storage tanks, etc), and their transportation to the site of use will be referred to as the production phase. The operation phase considers the maintenance requirements such as oil change, spare part replacement and similar activities. The disposal phase is addressed for major components, eg. wind turbine, but is not extensively studied due to lack of scientific data. The combustion of the alternative fuel

Functional unit

In order to be able to compare different alternative fuels, a functional unit is used to act as a reference unit to quantify the performance of the system (Valente et al., 2017). The functional unit is typically expressed in terms of mass, and the selection of a functional unit significantly affects the results of the LCA (Valente et al., 2017). The functional unit used for the LCA is is MWh generated from the peak power plant.

3.1.2 Inventory Analysis

Life-cycle inventory is the process of quantifying the raw materials requirement, atmospheric emissions, waterborne and solid wastes for the entire life-cycle of the product (Curran, 2006). Ecoinvent database in SimaPro was used to account for the material requirements for both system assemblies. The inventory analysis for methanol production process is based on the actual system components for one ZEF micro-plant. The weights of the material needed for the micro-plant were logged into SimaPro. As for the hydrogen production route, material requirements for the system components were obtained from multiple sources. Wind turbine specifications were obtained from the Ecoinvent database. Databases in SimaPro document the environmental impact of typical system components, such as wind turbines and solar panels, which can be scaled according to the system requirements. Other system components, such as the electrolysers, compressors and storage tank specifications were obtained from LCA literature carried for different hydrogen applications.

Hydrogen production system

The material requirement for construction and operation of the offshore wind turbine was obtained from Ecoinvent database. The 2 MW offshore turbine model was selected, since it was the largest turbine available, which is modeled with a capacity factor of 30%. This deviates from the capacity factor of the actual system, which is 42% and the state of the art offshore wind turbines sizes which can reach 6 MW (Lensink & Pisca, 2018). The materials included in the model cover the fixed parts (tower and base), their transportation, energy and area needs. The moving parts include the rotor, nacelle, electric parts and the transformer. The processes covered relevant to the moving parts are their processing, energy demands for assembling, transport, and the connection to the grid. The operation and maintenance of the turbines is also included, for example the necessary change of gear oil. The lifetime of the turbine is modeled for 20 years. The main components of a gird connection of a wind turbine are the cables, the transformer and the sub-station with the circuit breaker and the electricity meter inside it. The environmental impact carried included all main materials for the construction of the network connection and their treatment, the excavation of the cable trench, land transformation and use.

The material requirements for manufacturing the electrolysers and compressors were entered manually. There were no readily available Ecoinvent data-sets for these system components, however LCA studies have been carried and provided a comprehensive breakdown of the equipment components. The electrolyser components breakdown were obtained from (Burkhardt et al., 2016). The authors carried a life-cycle assessment of hydrogen production from wind, for utilization as vehicle transport fuel. Alkaline water electrolysers with a capacity of 5.4 Kg H_2/hr were used in their analysis, the same electrolysers are assumed for this system. The compressors inventory is also modeled after the material composition proposed by the authors. The authors created the material inventory by estimating the material weights needed to construct the system components (steel, piping, etc.) based on the dimensions from manufacturer documentation (Burkhardt et al., 2016). Burkhardt et al. (2016) validated the material inventory through cumulative masses measurements taken by cranes during decommissioning. The inventory analysis of the electrolysers and compressors does not include the transportation of the components from the manufacturer to the site of utilization, and the energy requirement for manufacturing them.

The storage tank is based on ”type 2” tanks, which are manufactured of low alloy steel and a fiber resin composite. Furthermore, these tanks are place underground and enclosed in a cement layer. Lifetime is assumed to be 20 years. Type 1 storage tanks offer 1 wt.% gravimetric density, due to their cheaper material consumption and consequently lower storage pressures. The European targets for weight efficiency of type 3 and 4 on-board vehicular storage vessels is 4.8 wt.% (Barthelemy et al., 2017). Based on these values, a reasonable assumption of 3 wt.% is assumed for the type 2 vessels used. The volume of cement needed is based on the dimensions of the largest available storage vessels (3m diameter and 30m height) (Zheng et al., 2016).

Methanol production system

The life cycle stages of the methanol production system are split into one assembly and three processes. The assembly covers to the physical components of the system, which are the the solar panels, ZEF micro-plants, and the methanol storage tanks next at the peak power plant. The processes during the life cycle are (1) the methanol production, (2) the transportation of the produced methanol and finally (3) the combustion of the methanol in the gas turbine.

The material requirement for the construction of the system assembly was developed as follows. Firstly, the solar PV construction process is obtained from a combination of Ecoinvent data-sets. The processes included are the panel material construction and the mounting of the PV system. A 156x156 cm^2 PV ribbon-Si data-set is assumed, and is scaled to 4.6 m^2 to correspond to the panel used in the real life ZEF system (3 x 300 W). The included activities are the production of the cell matrix, cutting of foil and washing of glass, production of laminate and the aluminium frame of the panel. The PV mounting system is also included as part of the assembly, assumes open ground mounting using piled foundations. Water requirement for panel washing is entered manually and is estimated based on the work of (Jones et al., 2016). The authors carried a study to estimate the optimum frequency of washing solar panels in desert conditions. On the one hand, soiling effects reduce the efficiency of the solar panels, and on the other hand it is costly to wash the entire solar panels on a daily basis at such large scale. They identify an optimum frequency of washing once every 20 days using washing trucks, and estimate a water consumption of 0.5 liters/m^2 of solar panel.

The second part of the assembly is composed of the ZEF micro-plant unit. The weights of the different components making up one methanol micro-plant have already been complied by the company in a SimaPro model. The data was imported and adjusted to the number of micro-plants required for the system. The components included are the direct air capture unit, compressor, alkaline electrolyser, methanol synthesis unit, distillation unit and the storage unit. The material used vary from glass, aluminium, mono-ethanolamine, steel and rubber.

Finally, The large-scale storage tank used to store the transported methanol near the peak power plant is based on scaling an existing liquid chemicals storage tank from the Ecoinvent database in SimaPro. The processes included are the material construction and transportation of the tanks.

Three processes are included in the life cycle. These are the methanol production, shipping and combustion in a gas turbine. The process of methanol production is modeled separately in the life-cycle assessment. This process involves the direct air capture of carbon dioxide from air, therefore it accounts for a net negative CO_2 emission since carbon is absorbed to produce methanol in the micro-plant. Complete combustion of the methanol in the gas turbine is assumed, and carbon emissions are assumed according to the following mass balance equation 1.

$$2CH_3OH + 3O_2 \rightarrow 2CO_2 + 4H_2O \tag{1}$$

More research is needed for the estimation of carbon monoxide and NOx emissions of methanol powered gas turbines. The general consensus in the industry is that methanol is a cleaner-burning than diesel or fuel oil and can help power plants meet the increasingly stringent emission regulations. In comparison to fuel oil and diesel, methanol burns at a lower temperature and its use for power generation can reduce NOx emissions by at least 80% (Turaga & Johnson, 2017). Also, methanol does not contain sulfur or heavy hydrocarbons thereby precluding SOx and particulate matter emissions. Finally, complete combustion of methanol creates fewer CO_2 emissions in comparison to fuel oil and diesel (Turaga & Johnson, 2017).

Methanol shipping is modeled in SimaPro using a transoceanic freight ship. The environmental impact is measured in terms of tonne kilometers of transported methanol over the 20 year lifetime of the project. The inventory includes the construction, and operation of the vessel (based on the total kilo-metric performance of 2 million km), and also the construction, operation & maintenance and land use of the port where 2 ports are required for each transport activity. The data is based on the port of Rotterdam.

3.1.3 Impact Assessment

The impact assessment step addresses the potential human and ecological effects of energy, water and material usage and the environmental releases identified in the inventory analysis (Curran, 2006). By doing so, establishing a linkage between a product or process and the its potential environmental impact. LCA procedure gives a systematic methodology to classify and characterize the environmental impact of the inventory analysis.

The steps to carry an LCA impact assessment are to first select and define the impact categories (global warming, land use, eco-toxicity, etc.). The classification step assigns the results to impact categories (for instance, classifying CO_2 to global warming). In characterisation, all substances are multiplied by a factor which reflects their relative contribution to the environmental impact, quantifying how much impact a product or service has in each impact category. This means for example that global warming of methane is 22 KG CO_2 equivalent. The aforementioned steps are obligatory in an impact assessment, while the following steps (normalization and weighting) are optional. Normalization is used to express the impacts in ways that can be compared, while weighting is the aggregation of the normalisation scores to a single environmental index with help of weighting factors (e.g. climate change is 10 times 'worse' compared to acidification) (Curran, 2006).

Another essential step is deciding between midpoint and endpoint impact assessment methods. Midpoint impact assessment methods reflect the relative potency of the stressors at a common midpoint within the cause-effect chain (Curran, 2006). This is the first point in the assessment where impacts are unified, and provides information on environmental problems, for instance climate change and acidification (Campos-Guzmán et al., 2019). Endpoint impact assessment evaluates the environmental impact at the end of the cause and effect chain. It is used to model the environmental impact on issues of concern. The method translates the weighting of the impact categories into three high level categories: 1) effects on human health, 2) damage to the ecosystem and biodiversity and 3) scarcity of resources (RIVM, 2011).

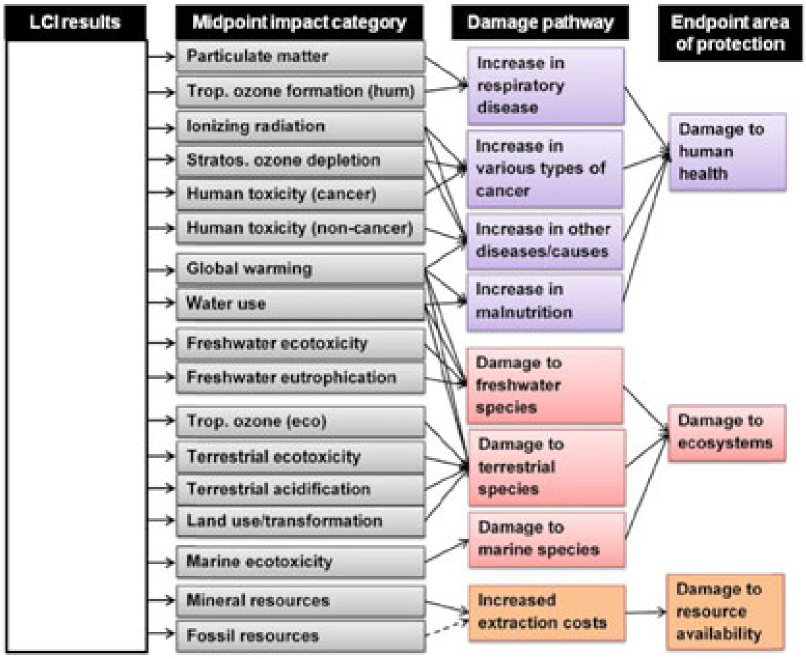

Figure 9: Overview of the impact categories that are covered in the ReCiPe2016 method and their relation to the areas of protection (RIVM, 2011)

In this research, a midpoint analysis is performed using The ReCipe 2016 Midpoint (H) method. A midpoint analysis is preferred for a variety of reasons. Firstly, it allows for a higher level of detail and for identifying trade-offs between categories, while endpoint merely shows the impact level on ecosystem quality and human health, without indicating the source. Moreover, Midpoint impact assessment have lower statistical uncertainty compared to endpoint methods, and are considered much more robust (Pennington et al., 2004). The reason being that midpoint modeling minimizes assumptions and value choices and reflects a higher level of societal consensus.

Climate change factor, which is more commonly referred to as the global warming potential (GWP), refers to the life-cycle greenhouse gas (GHG) emissions of the system. GWP is expressed in equivalent tonnes of CO_2 using an integrated time horizon of 100 years; the major emissions included as GHG emissions are CO_2 (GWP =1), CH4 (GWP=25[3]), N2O (GWP=298) and chlorofluorocarbons (GWP=4750) (Raga Mexico et al., 2007).

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[3] This means that global warming potential of methane is 25 times that of carbon dioxide.

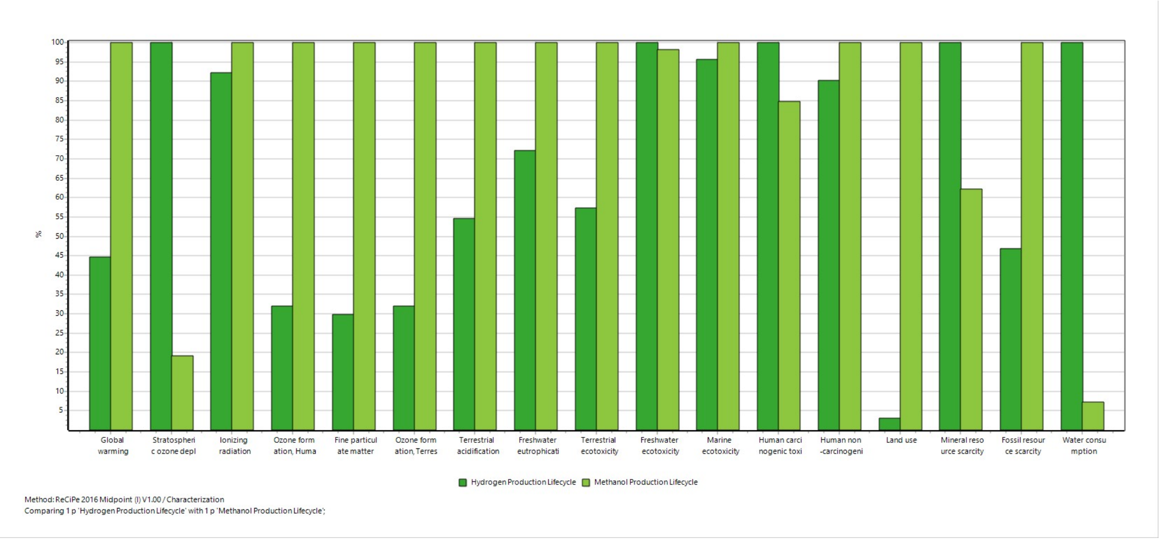

Figure 10: Impact assessment across all categories for both alternative fuels

Hydrogen production system

The global warming potential of the entire Hydrogen production chain is displayed in fig 30 in the appendix. The largest contribution is due to the construction and maintenance of the offshore wind turbines (46%). This LCA model is validated by comparing to other LCA literature analyzing greenhouse gas emissions of Wind to Hydrogen systems. Ghandehariun & Kumar (2016b) conclude that the for wind-to-hydrogen systems, the manufacturing and installation of the system assemblies have the most significant environmental impact. The construction of wind power generation being the largest contributor with 65% and electrolysis and compression contributing 29%, however one difference is that this system does not include the hydrogen storage in the system boundaries (Ghandehariun & Kumar, 2016b). Total system emissions are validated with LCA studies from similar hydrogen production value chains. The life-cycle global warming potential for the system is 43,105 ton CO_2 eq., or 120 Kg CO_2/MWh based on the selected peak power plant electricity output. NOx emissions from the entire value chain is around 0.29 Kg NOx/MWh.

Component	GWP (ton CO_2 equiv.)
Offshore Wind Turbines	19800
Grid Transmission	167
Electrolysers	12200
Compressors	37.6
Storage Tanks	10900
Total	43105
GWP	120 Kg CO_2/MWh

Table 8: Life-cycle global warming potential of hydrogen production

Methanol production system

The global warming potential of the solar to methanol route is displayed in the network analysis in figure 31 in the appendix. This is an unconventional method of energy storage, therefore the validation of the model is more challenging. That being said, the network analysis shows that the majority of the life cycle global warming potential (69%) is due to the construction and maintenance of the solar panels, which can be compared to existing literature. The life cycle GWP of the 48 MW solar plant modeled is 6.67 x10^7 Kg CO_2 equiv. (31). With the assumptions mentioned in section

2.1 (solar irradiation, panel lifetime, etc.) this equates to 38 kg CO_2/MWh[4]. This value lies within the GWP range of 20-60 kg CO_2/MWh in (Yue et al., 2014), and 37.5 - 53 kg CO_2/MWh (Beylot et al., 2014).

Component	GWP (ton CO_2 equiv.)
Solar PV	66700
ZEF micro-plants	20940
Methanol Shipping	8330
Storage tanks	0.599
Total	95971
GWP	268 Kg CO_2/MWh

Table 9: Global Warming potential of methanol production system

Natural gas system

The environmental impact for "the business as usual" scenario of utilizing natural gas to power the peak power plant is analyzed to provide more context for the discussion. There are two relevant processes that are studied: the production processes of natural gas (exploration, drilling, distribution of the gas) and the emissions from combustion in the gas turbine. A single cycle turbine (SC) is assumed throughout this research, which are typical for peak power plants. SC turbines have low energy efficiency (25-40%) and are typically used to meet peak demand (Energy Information Administration, 2018). This selection is consistent with the turbine efficiency of the methanol and hydrogen gas turbines in the earlier sections.

Aksyutin et al. (2018) assess the real carbon footprint of natural gas, by including the stages of production, transportation, storage, and distribution. They report varying amounts of environmental impact depending on the natural gas source. For example, carbon footprint drops from 18 kg CO_2-eq./GJ for gas from the Ukrainian Corridor to 9 kg CO_2-eq./GJ for Russian gas imported via the *Nord Stream*. In gas turbine KWh terms, the carbon footprint can be expressed for the production of natural gas as 30 g CO_2 eq./KWh, which corresponds to 4.5-7 % of the total carbon footprint of natural gas in electricity production (Aksyutin et al., 2018). This is consistent with scientific literature, where Hafizan et al. (2013) report that natural gas combustion contributes to 93% of the global warming potential of using natural gas in power generation, while the remaining 7% is attributed to the process of natural gas production. Exhaust gas constituting the bigger portion due to the emission of both carbon dioxide and nitrogen dioxide in the gas stack. Methane leakage during distribution is another major contributor to the life cycle emissions (known as fugitive emissions) (Hafizan et al., 2013), and can constitute anywhere between 1 and 9% of the total transported gas (Pétron et al., 2012). The longer the distance covered by the gas from the source, the heavier the greenhouse has emissions incurred, not just based on the extra pipeline requirement, but also on methane fugitive leakage (methane causes 25 times the GWP of CO_2).

As for the sizeable emissions due to gas combustion, Turconi et al. (2013) carried a literature review on carbon footprint of electricity generation from gas turbines and report 480-730 Kg CO_2 eq./MWh of direct emissions from single cycle gas turbines. The same authors report NO-x emissions from SC turbines of 1.8-3.8 Kg NOx/MWh, and SOx emissions of around 0.01-0.32 Kg/MWh (Turconi et al., 2013). Other sources estimate higher greenhouse gas emissions from gas turbines of around 773 kg CO_2 eq./MWh (Zabihian & Fung, 2009). Based on these 2 sources, an average global warming potential of 689 Kg CO_2/MWh is assumed for the gas turbine emissions.

Therefore, total emissions for the gas fired turbine are in the range of 697 Kg CO_2/MWh, assuming gas is imported from Russia through *Nord Stream*. Similar literature reports total carbon footprint of up to 662 Kg CO_2-eq./MWh for natural gas-fired power generation (Aksyutin et al., 2018), which is consistent with the estimation taken here.

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[4] Energy here refers to lifetime electricity generation from the solar plant

3.1.4 Outcomes of the environmental impact assessment

A life-cycle assessment is performed using SimaPro, and the results are displayed in figures 11 and 12. A well to wheel system boundary is defined where the GWP and NOx emissions are modeled for the renewable energy source and the fuel production, transport, storage and combustion in the gas turbine. The emissions are compared with a business as usual scenario where natural gas is fired for peak power generation.

The results show that hydrogen is the cleaner alternative fuel for power generation. For both alternative fuels, the biggest environmental impact is due to the construction of the renewable energy source. To that effect, the installed offshore wind capacity for hydrogen production (25 MW) is much lower than the size of the solar farm required for methanol production (48 MW). This is partly due to the higher capacity factors for offshore wind compared to solar, and the lower energy demands for hydrogen production compared to methanol. On top of this, offshore wind contributes less emission per KWh compared to solar PV for the same installed capacity (Varun et al., 2009). Nugent & Sovacool (2014) assessed 153 life-cycle studies of solar and wind energy systems, and report a mean of 34 g CO_2 eq./KWh for wind projects, and 50 g CO_2 eq./KWh for solar projects. While this is strictly dependant on design choices, for example if the components are manufactured in a country with fossil-based electricity generation (e.g.: solar panels in this system are manufactured in China which remains highly dependant on coal), the results are consistent with the outcomes of the SimaPro model.

In terms of GWP, methanol and hydrogen are both extremely preferred to natural gas. While methanol combustion emits CO_2 during combustion, the carbon emitted was captured from the atmosphere during methanol synthesis, therefore methanol combustion is a carbon neutral process as seen in figure 11. The same can not be assumed for NOx emissions, however experiments show that methanol fuel contributes to 80% less NOx emissions than natural gas (Turaga & Johnson, 2017), while Pilavachi et al. (2009) report no NOx emissions from hydrogen turbine combustion. More research is needed for the estimation of NOx emissions from alternative fuel combustion, which is currently lacking in existing literature. That being said, the life-cycle NOx emissions from other remaining processes are significantly also much lower for hydrogen fuel.

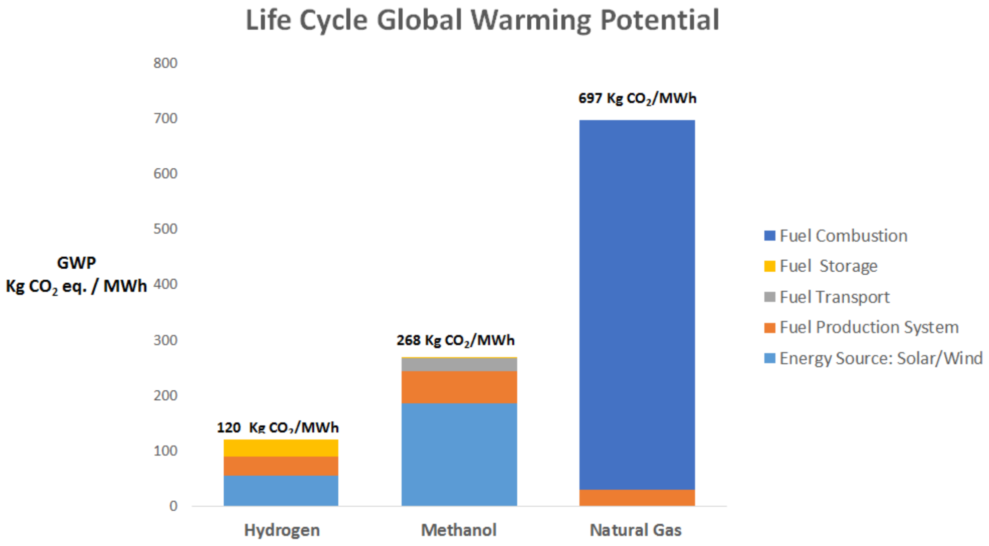

Figure 11: Global warming potential per MWh from life cycle production of both alternative fuels

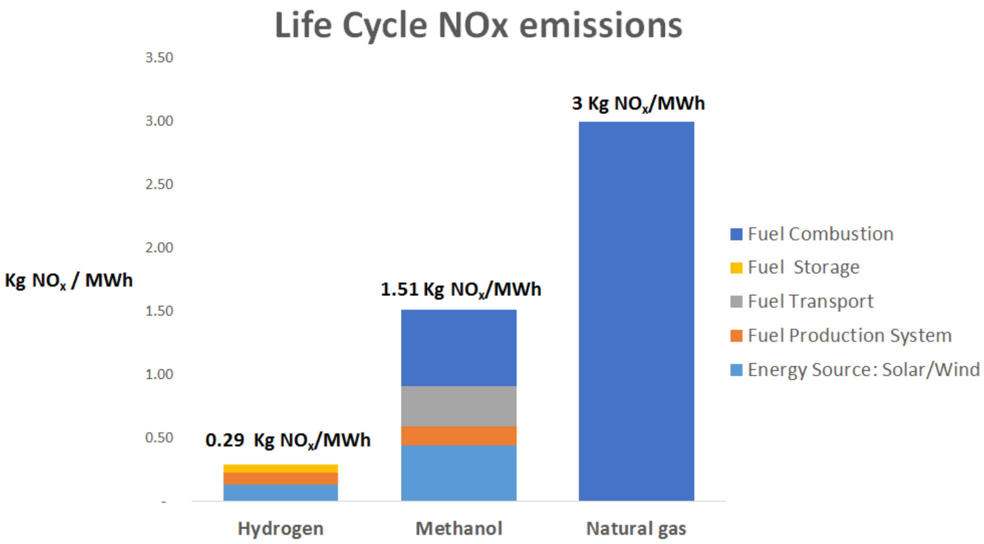

Figure 12: Nitrogen oxide emissions per MWh from life cycle production of both alternative fuels

A few limitations to this assessment should be made clear. Disposal after end of life has only been included for the system components that are obtained from existing databases, such as the offshore wind turbine components and the solar PV system. Similarly the environmental impact due to energy consumption for manufacturing of the manually entered system components (electrolysers, compressors and storage tanks for hydrogen production, and ZEF micro-plants for methanol production) is not accounted for. Also, combustion behaviour of alternative fuels is still the subject of current research. The emissions assumed here are the most conservative estimates, where 100% methanol combustion is assumed (no carbon monoxide) and no NOx emissions are assumed from the hydrogen turbine.

3.2 Economic Assessment

The economic assessment is carried to assess the feasibility of the entire system. The *euro* (€) currency is used in the analysis, and where relevant, is exchanged from the US dollar at a rate of: €1 = $1.12 (exchange rate for May, 2019). The economic assessment is based on capital expenditure (CAPEX) and operating expenditure (OPEX).

Capital expenditure is related to expenses whose benefit extends beyond one year. This includes costs associated with building and installing the plant. CAPEX comprises material and labour costs for solar panels, wind turbines, grid connection, etc. On the other hand, Operating Expenditure (OPEX) include administrative costs, operation and maintenance costs, insurance, etc. OPEX typically have high uncertainty due to the lack of published data, and are generally expressed as percentage of CAPEX costs.

Both systems are designed to have a lifetime of 20 years. CAPEX costs are assumed to be paid in the first year of operation and are based on costs of commercially available technologies from scientific literature, manufacturers and business cases. OPEX costs are assumed to be paid annually, and are discounted to present value using a 10% discount rate. The peak plant is assumed to run for 2 hours every working day of the year (261 days), for 20 years. Therefore, the annual generation of the 34.3 MW peak power plant is 17960 MWh. Financing costs including interest payments are not included for both systems, as they should not affect the comparison. However financing costs should be included if one system is being analyzed independently to obtain a more accurate absolute cost.

In order to compare both energy systems, the Levelized Cost of Energy (LCOE) is calculated per MWh produced from the peak power plant. The same system boundary chosen for the environmental assessment is selected here. The economic assessment includes the electricity generation (wind and solar), the fuel production, transport and storage. The following formula is used for calculating the LCOE:

$$LCOE = \frac{\text{Total Life Cycle Costs}}{\text{Total Electricity Generation over Lifetime}} = \frac{\sum_{t=1}^{n} \frac{I_{\mathrm{t}}+M_{\mathrm{t}}+F_{\mathrm{t}}}{\frac{1}{(1+r)^t}}}{\frac{\sum_{t=1}^{n} \mathrm{E_t}}{(1+r)^t}} \tag{2}$$

$\mathrm{I_t}$: Investment expenditures in the year t (CAPEX)

$\mathrm{M_t}$: Operations and Maintenance expenditures in the year t (OPEX)

$\mathrm{F_t}$: fuel expenditures in the year t

$\mathrm{E_t}$: electrical energy generated in the year t

r: discount rate

n: expected lifetime of system or power station

3.2.1 Hydrogen production system costs

The economic assessment for the hydrogen production system is completely based on existing literature. Large-scale hydrogen projects have not been commercially implemented, especially for the electrolysis phase. Component prices from suppliers are often confidential (Taljan et al., 2008), however several scientific articles are compared to find reasonable cost estimates for the CAPEX and OPEX of the subsystem components.

Wind turbine & Grid connection

The capital investment for setting up the wind-farm is based on the report of the PBL Netherlands Environmental Assessment Agency carried in 2018 (Lensink & Pisca, 2018). The report details the production costs of 5 recent offshore projects in The Netherlands: Hollandse Kust (Zuid, Noord and West), Boven de Wadden Eilanden and IJmuiden Ver. The cost disparities between the projects depend on site characteristics such as the distance to the nearest harbour, water depth and soil conditions (Lensink & Pisca, 2018).

The major cost components relevant to offshore wind projects are the turbine costs, foundation costs and the electrical infrastructure. The foundation costs depend mainly on the water depth and seabed characteristics, and to a less extent on the turbine capacity and wave conditions (Gonzalez-Rodriguez, 2017). Electrical infrastructure (grid connection) costs comprise the inner array cables, export cables, an offshore substation and HV connection to the grid (Gonzalez-Rodriguez, 2017). Grid connection costs also vary between projects, depending on the distance to the grid, and the greater deployment strategy of the grid at sea, which may include setting-up of artificial islands, the combination of wind farm connections, inter-connector capacity as part of the needed development of the North Sea Grid (Lensink & Pisca, 2018). The specific location for the proposed offshore wind turbine is not selected, therefore an average cost is assumed for the purpose of this research.

The investment costs for the 5 projects analyzed by Lensink & Pisca (2018) range from 1600-1900 €/KW, and operation and maintenance (O&M) costs range from 41-64 €/KW/year. The O&M costs include insurance, regular maintenance, repair, spare parts and administration and increase as the equipment ages (Gonzalez-Rodriguez, 2017). The O&M costs published in the report do not include decommissioning costs. Based on the CAPEX and OPEX ranges for recent projects in The Netherlands, the average base amount cost for offshore wind projects in the North Sea is 0.048 €/KWh excluding grid connection costs (Lensink & Pisca, 2018). The economic lifetime of these offshore wind project is 25 years. Although this is 5 years longer than the technical lifetime of the proposed systems, the same economic lifetime for the offshore wind generation is assumed for this project since the wind farm is connected to the grid. The PBL report also estimates the grid connection costs for the five projects to range from 0.017-0.032 €/KWh. An average cost of 0.0207 €/KWh is assumed. The O&M costs are paid yearly and are discounted to their net present value using a 10% discount factor. The same reasoning is applied for all other OPEX calculations throughout this research.

The total electricity demand of the hydrogen production system were calculated in 2.2.1. The processes covered include the loss in transmission, electrolysis and compression energy demands. The annual energy requirement of the system processes amount to 93,278 MWh, and is assumed to be completely provided by offshore wind energy.

Electrolysers

The capital cost assumed for alkaline water electrolysers is 1100 €//KW power input (Gambhir et al., 2017). The international Renewable Agency (IRENA) predicted costs of 750 €//KW for Alkaline electrolysers for 2017, and 1200 €//KW for PEM electrolysers (Taibi et al., 2018). Schmidt et al. conducted an expert elicitation to determine the potential future capital cost, lifetime and efficiency of water electrolysis technologies that can be used for utility-scale energy storage. They concluded that capital costs for alkaline water electrolysis systems by 2020 at current R&D funding and without production scale-up lie between 700 and 1400 €/kWe (Gambhir et al., 2017). Therefore, the median cost of 1100 €/kWe is selected for this analysis. Lifetime of alkaline water electrolysers ranges in the literature from 60,000-90,000 hours (Gambhir et al., 2017), 80,000 hours (Taibi et al., 2018). The electrolysers in the system are assumed to run for just 6 hours a day, during wind production hours, and therefore no replacements for the electrolyser stacks is assumed throughout the 20-year plant lifetime. OPEX costs for electrolysers are estimated to be 2% of the initial capital expenditure/year (Taibi et al., 2018).

Compressors

Compressors require the use of expensive materials in order to avoid hydrogen embrittlement and the associated risk of part failure during use (Vickers, 2017). The large number of moving parts in diaphragm and reciprocating compressors increase maintenance issues and costs (Vickers, 2017). The cost of compressors vary from 10000-27142 USD/Kg/hr for diaphragm compressors of capacity 48 Nm^3 H_2/hr (4.27 Kg H_2/hr) (Taljan et al., 2008). This is comparable to the $515,000 33 Kg/hr compressor used in similar literature (15600 $/Kg) (Parks et al., 2014). An average cost of 18,000 US$/Kg H_2 is assumed for the designed system.

Reducing the costs for compressors is considered a challenge. Although the compression technology is mature, the material properties and quality requirement for pure hydrogen production present challenges to existing compression technologies. Main challenges are the material compatibility with hydrogen, compressor reliability and minimizing contamination of hydrogen by the compressor (Parks et al., 2014). O&M costs for the compressors are estimated to be 4% of the capital investment of the system, per year (Reuß et al., 2017). Performance of compressors is expected to deteriorate at the 15 year mark (Reuß et al., 2017), however it is not to be replaced due to the relatively higher O&M costs that were assumed.

Storage Tanks

The hydrogen storage subsystem consists of eight type-2 storage tanks (15m diameter, 30m height), capable of storing 14,583 kg of hydrogen at 700 bar. This is sufficient storage to run the peak plant for 5 hours per day. Current cost estimates for low (160 bar), medium (430 bar), and high (860 bar) pressure are 600$/kg, $1100/kg and $1450/kg H_2 stored. Ongoing research has potential to reduce high pressure storage tank dramatically (Vickers, 2017). Other sources assume capital cost of $900 per kilogram of H_2 storage at 2,500 psi (170 bar) (Ramsden et al., 2008). Therefore, $1100/Kg H_2 (982 €/Kg H_2) is a reasonable assumption. Storage tanks are reported to have lifetimes of 30 years, which is sufficient for the system requirements (Parks et al., 2014). Cyclic loading of tanks, which tend to heat up as they are filled by compressed hydrogen, generally reduces the tank life-time (Sheffield et al., 2014), however high pressure gas storage in LRC are adapted for cyclic operations (Tengborg et al., 2014).

Table 10 summarizes the total costs associated with hydrogen production.

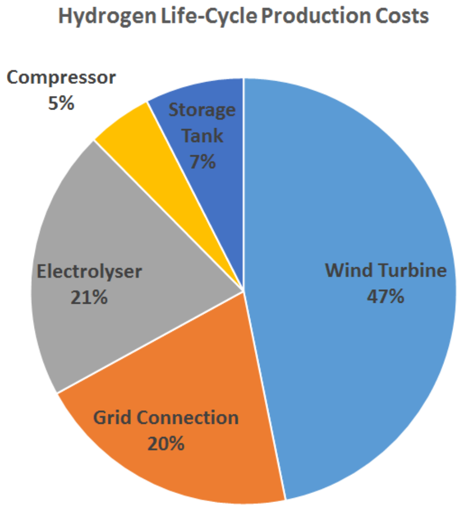

Figure 13: Hydrogen life-cycle production costs

Component	**Amount**	**CAPEX**	**OPEX (yr)**		**Total costs (€)**
Wind Turbine	25.35 MW	1760 €/KW	49 €/KW	0.048 €/KWh	89,342,276
Grid Connection				0.0207 €/KWh	38,528,856
Electrolyser	30 MW	1100 €/KW	2% of CAPEX		39,163,402
Compressor	425 Kg H_2/hr	16071 €/kg H_2	4% of CAPEX		9,381,978
Storage Tank	14,583 Kg H_2	982 €/kg H_2	-		14,322,917
Total Costs					€ 190,739,429
LCOE					**1,138 €/MWh**

Table 10: Hydrogen production system costs

3.2.2 Methanol production system costs

The costs associated with the ZEF methanol production system are quite different from the wind to hydrogen route. To begin with, the system is based on a ”numbering up” approach as opposed to large scale system components. This means that each micro-plant consists of its own components, and can work independently of the whole system. As explained in the design choices section in chapter 2, each micro-plant is connected to 3 solar panels, producing 84 grams of methanol per hour (588 gm per day for 7 equivalent hours). Another major difference is that the solar panels are not connected to the grid, which saves on grid connection costs, and allows for flexibility in locating the plant. On the other hand, transportation of the produced methanol from the production site (Morocco) to the utilization site (Rotterdam) is required. Another cost consideration is the import taxes included since the produced fuel crosses country borders, unlike in the case of hydrogen production chain. However, import costs have not been included in the costs calculations.

A variety of data sources is used to build the methanol production economic assessment. Costs associated with methanol production system is based on financial models developed by the company. CAPEX and OPEX costs for each micro-plant components are obtained from the *ZEF* business case. Further costs for solar PV costs, shipping and storage are obtained from relevant scientific literature.

Solar Panels

The entire solar field capacity is around 48.4 MW. Ramirez et al (2017) provide a comprehensive cost estimation for solar field capital and operational expenditures (Castillo Ramírez et al., 2018). Capital investment costs for solar PV systems are comprised of the PV module cost and the Balance of system (BOS) (Gielen, 2012). The PV module is the interconnected array of solar panels that build up the 48 MW generating capacity needed. Its costs are dominated by raw material costs (namely silicon price), cell manufacturing and the module assembly costs (Gielen, 2012). Balance of system (BOS) costs relate to the structural costs of the system (structural installation, racks and site preparation), and the electrical system components (inverter, transformer, wiring, etc.) (Gielen, 2012). The solar system is not connected to the grid, since the methanol production micro-plants are attached to the PV panels, therefore an electrical system is not required. Generally, the solar module represents a third to one half of the total solar PV cost, depending on the size and panel choice (Gielen, 2012). The costs for the structural support are included in the CAPEX calculations for the micro-plant. To conclude, the relevant CAPEX for the solar PV system are the PV modules, installation costs, site preparation and land leasing costs. The land costs fall under the PV category, as they are a function of the solar panel area required.

Confidentiality issues are difficult to overcome for the utility scale solar PV market in Africa (Taylor & So, 2016)). For this reason, data is compared to cost structures in other markets to predict the cost structure of utility-scale solar PV projects in the region. In 2012 PV system costs for large-scale utility applications (greater than 1 MW) have reached 1.59\$/W for mono-crystalline PV modules and 1.63\$/W for multi-crystalline factory gate prices, or 1420 €/KW (Gielen, 2012). A more recent analysis of cost development of different renewable energy technologies estimates solar module costs to be 660-850 \$/KW for large scale PV system(Van Den Akker, 2017). Van Den Akker (2017) assumes a 20 year economic life-time for the solar project, which is consistent with the assumptions for this system. An average cost of 755 \$/KW is assumed (674 €/KW) for the solar modules. Installation and site preparation costs are reported for large-scale solar projects to be around 650 \$/KW (580 €/KW) (Van Den Akker, 2017). The assumption for land costs is based on land costs of similar projects in North Africa. In Egypt, desert land along the Red sea was auctioned for costs between 1 $\$/m^2$ and 9 $\$/m^2$ (Smyrnakis et al., 2016). For the purposes of this investigation, a cost of 5 $\$/m^2$ is assumed. Accurate cost projections for desert land in Morocco was not readily available in the existing literature.

Component	Cost
PV Module cost	674 €/KW
Installation costs & Site preparation & Road building	580 €/KW
Land costs	4 €/m2

Table 11: Capital investment costs for the PV system

Operational costs are traditionally split into fixed and variable costs, the latter is commonly neglected for solar PV projects (Castillo Ramírez et al., 2018). Fixed OPEX costs are composed of occasional costs and total fixed annuities. Total fixed annuities are the most significant operational costs, and account for the equipment maintenance and complementary costs (insurance, environmental management), while the occasional costs cover component replacement and decommissioning. Decommissioning costs are not included in the wind turbine cost analysis for hydrogen production, so they are also excluded here to maintain a fair comparison. Total fixed annuities costs included in the OPEX calculation are: equipment maintenance (routine preventive maintenance), personnel salaries, road maintenance (annual inspection and cleaning of road), operational environment management (measures to reduce environmental impact on local environment), operational insurance (hedging mechanism against civil labour risks and environmental catastrophes) and land leasing. Land lease costs are typically site and market specific, they can be extremely low where land values are minimal (ex. deserts and uninhabited areas) or much more expensive in densely populated cities (Adnan, 2018). The area requirement for Solar PV projects typically is around 5 acres/MW capacity, which gives a total area requirement of 241 hectares (Stevens et al., 2017). This estimation is consistent with th 5.8 m^2 reported area of the solar panels in the ZEF business case. Equipment maintenance costs in (Castillo Ramírez et al., 2018) are relevant for inverters, which are not used in this system. However this is replaced with an estimation of the panel module cleaning costs. Dust accumulation in desert conditions can reduce PV module performance by 0.3-1% daily (Ferretti, 2018). A semi-automatic panel cleaning system is typically used for panel cleaning in dessert conditions (Ferretti, 2018). The system consists of a brush attached to a truck which drives between panel rows, and is operated by trained labour(Ferretti, 2018). The cost estimate for truck cleaning systems was analysed for 100 MW solar PV farm in desert conditions in Saudi Arabia, and the authors estimated cleaning costs of 3 \$/KW nameplate capacity (0.89\$/panel) (Jones et al., 2016). This operating costs is assumed to be the same for the case of Morocco. This is a reasonable estimation which is close to other literature which estimates 0.35\$/panel for simple washing and 0.5 \$/ panel for intense washing (Enbar et al., 2015)

Based on life-cycle costs of solar modules, site preparation, road costs and total operation and maintenance costs, the costs of electricity from the the solar system are estimated at 0.0259 €/KWh.

Table 12: Total Fixed annuity costs for the PV system (OPEX)

Component	Cost
Panel cleaning	2.67 €/KW/yr
Salaries	0.70 €/KW/yr
Road maintenance	0.21 €/KW/yr
Insurance	9.55 €/KW/yr
Operative Environmental management	3.20 €/KW/yr

Figure 14: Solar panel truck cleaning system (Ferretti, 2018)

Tables 11 and 12 summarize the CAPEX and OPEX costs relevant to the installation and operation of the solar panels.

ZEF Micro-plant

The costs for 1 micro-plant were obtained from the *ZEF* business case. The cost breakdown for the components used in each micro-plant is displayed in table 13. The electrolyzer is injection molded, which significantly reduces the costs for hydrogen production. Another factor is that system components are small in size and high production volume allows for further reduction in costs. The lifetime of the assembly is assumed to be 20 years by the manufacturers. Other costs relevant to setting up the micro-plant are the racks, piping and storage units. The racks are the vertical support structure displayed in 7. Their function is to carry the solar panels and the micro-plant. The piping transports the produced methanol from the methanol synthesis compartment to the storage unit. In total, 53,534 micro-plants are needed to supply the sufficient methanol fuel to operate the gas turbine. The system is designed to operate with an automatic dynamic control which handles fluctuating weather conditions, such as temperature, irradiance intensity and humidity.

As the methanol production is scaled to more than 50,000 micro-plants, project management costs and developer fees should also be accounted for. For a 40,000 micro-plant operation, project management fees are estimated to be around 31.4 €/micro-plant, covering security supply, installation and management costs. Developer fees are estimated at 19 €/micro-plant and include data processing, technical services and legal services. These values are assumed to hold true for the required plant capacity, and are categorized as CAPEX costs.

The OPEX costs are reported to be 7.17 €/micro-plant. OPEX constitutes technical operation and

Component	CAPEX (€)
Direct Air Capture	47.52
Alkaline Electrolyser	41.5
Methanol Synthesis	24.7
Methanol Distillation	11.2
Control and Integration	10
Assembly	15
Total costs [1 Micro-plant]	€ 149.92

Table 13: Component costs for 1 ZEF micro-plant (ZEF business case)

maintenance for the micro-plant, site security, business rates, metering and communication and insurance. A detailed cost breakdown is attached in the appendix.

Shipping

Methanol is to be shipped in product tankers, which are designed to carry hydrocarbons (gasoline, kerosene, etc) and chemicals (ammonia, methanol) at relatively smaller capacities compared to crude oil tankers. Product tanker costs are affected by fluctuations in the oil market, which affect the refining activities and the demand for vessels (UNCTAD, n.d.). In 2016, freight rate for delivery from West Africa to North Western Europe averaged 71.75 \$/ton for a 75,000 DWT[5] tanker (UNCTAD, n.d.). The total cost over the 20 year lifetime is obtained by using the tonnage of methanol produced over the same period. This is a highly uncertain and bold claim as the freight rates are highly variable, and can even fluctuate on a daily basis. The freight rate used in this calculation is the average of freight rate for 12 months, for the West Africa-North West Europe route. The freight transport cost is also assumed to be the same for the 20 year lifetime of the project.

Storage tank

The cost for methanol storage is based on above-ground storage tanks similar those used for gasoline storage (Medina & Roberts, 2013). The storage tank has a capacity to carry 396.5 m^3 methanol. The costs of chemical fluid storage tanks are around 519 €/m^3.

Methanol Gas Turbines

Methanol as a fuel is compatible with existing diesel and fuel oil infrastructure (Turaga & Johnson, 2017). Retrofitting gas turbines to run on methanol involves low capital costs and few infrastructure modifications for small and medium-sized gas turbines (Turaga & Johnson, 2017). This is especially advantageous for regions that are isolated from natural gas supply, which would otherwise require setting up LNG infrastructure. That being said, the gas turbine costs are not included in the LCOE calculation, due to the unavailability of accurate CAPEX and OPEX estimates in literature. Table 14 summarizes the costs associated with the system components.

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[5] Dead-weight tonnage (DWT) is a measure of how much weight a tanker can carry

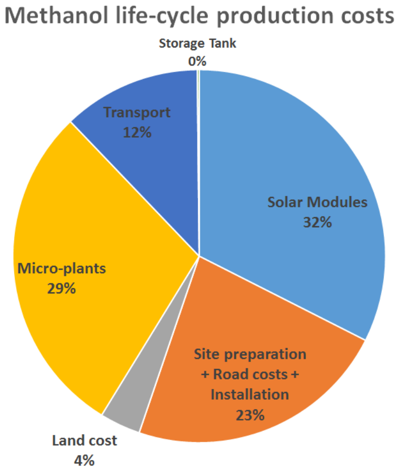

Figure 15: Methanol life-cycle production costs

Component	Amount	CAPEX	OPEX		Total costs
Solar Modules	48.48 MW	674 €/KW	787 €/KW/yr	0.0162 €/KWh	39,851,529
Site preparation & Road costs		580 €/KW		0.0114 €/KWh	27,962,120
Land cost	241 acres	4 €/m2			4,352,261
Micro-plants	160603	222 €/plant	6.2676 €/plant/yr		35,699,017
Transport	3356		64 €/ton		14,720,966
Storage Tank	105	1964 €/tank			205,722
Total					€ 122,791,615
LCOE					**732 €/MWh**

Table 14: Methanol life-cycle cost breakdown

3.2.3 Natural gas fuel costs

The costs associated with the ”business as usual” scenario of simply using natural gas to power the peak plant are quite straightforward to estimate. Since the Maasstroom powerplant is connected to the dutch gas pipeline network, no gas storage tanks are needed. For this reason, the main cost drivers for the electricity generation using natural gas are the gas price and the purchase of CO_2 emission allowances equal to the amount of CO_2 the plant emits (Greunsven, 2017).

The gas prices are constantly fluctuating based on the global market supply and demand, which means that energy companies often enter into long-term contracts with gas providers to reduce their investment risks. Figure 16 illustrates the development in gas prices in Europe in the period 2015-2017, as reported by TenneT[6]. The TenneT report describes the recent developments of the different elements in the western European electricity markets (Greunsven, 2017). Natural gas prices were around to 17.2 €/MWh$_{th}$[7] in early 2017. It is worth mentioning that gas prices typically rise in the winter, due to higher demand in cold winter months. In the subsequent period, prices stabilized at around 15 €/MWhth, which is still higher than the average value for 2016. In late 2017, prices

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[6] TenneT is the leading transmission system operator (TSO) in The Netherlands and Germany.

[7] Fuel prices are expressed in €/MWh$_{th}$, in this case MWh$_{th}$ is the amount of heat released during the combustion of the fuel (heating value).

spiked again to over 21 €/MWh$_{th}$, to meet higher winter demand (Greunsven, 2017). These costs represent the daily market prices, however as mentioned earlier, electricity generators usually opt for long-term contracts. Long term gas prices are reported at around 25-27 €/MWh by TTF[8] in the for North-Western European market (Franza, 2014). Therefore, an average price of 26 €/MWh is assumed for the long-term gas contract. Based on a 30% efficient single cycle gas turbine, the total lifetime consumption of natural gas is 107,427,600 m^3, which is used to calculate the fuel costs. The gas prices indicated are based on the LHV of natural gas (13.1 KWh/Kg). The natural gas price and characteristics in table 6 are used to translate it to 0.264 €/m^3 Natural gas, or 170 €/MWh generated from the peak plant turbine.

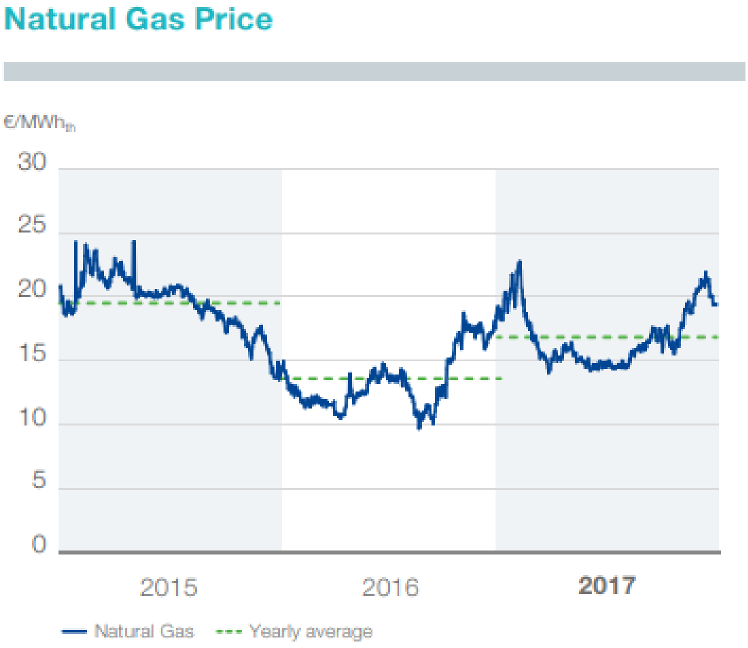

Figure 16: Natural Gas price (Greunsven, 2017)

Carbon price has been rising since early 2017, and reached 29 €/ton CO_2 in 2019. One of the reasons behind this rise is the European Commission's submission of a legislative proposal which proposes a faster reduction in the amount of emission allowance starting after 2019 (Greunsven, 2017). The Dutch government is also making similar strides, with its ambition to set a CO_2 floor price for electricity producers of 12.30 €/ton CO_2 starting 2020, and raising to 31.9 €/ton CO_2 in 2030[9]. These developments explain the sharp rise in carbon allowance price, as emitters stock up on allowance in anticipation. Since the project lifetime is assumed to be 20 years, an average carbon emission cost of 25 €/ton CO_2 is assumed here. In section 3.1.3, gas emissions from gas combustion in the single cycle turbine were reported as 667 Kg CO_2/MWh. Therefore, carbon tax will be, a minimum of, 14.7 €/MWh generated from the gas turbine. In this calculation, only the equivalent carbon emissions released from natural gas combustion are included. Carbon emissions due to the production and transport of natural gas are not included.

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[8] Title Transfer Facility, which is the Dutch gas trading platform that handles and delivers gas through the gas pipeline network.

[9] According to the article: *"Bill submitted on minimum carbon price in electricity production"* published on www.government.nl

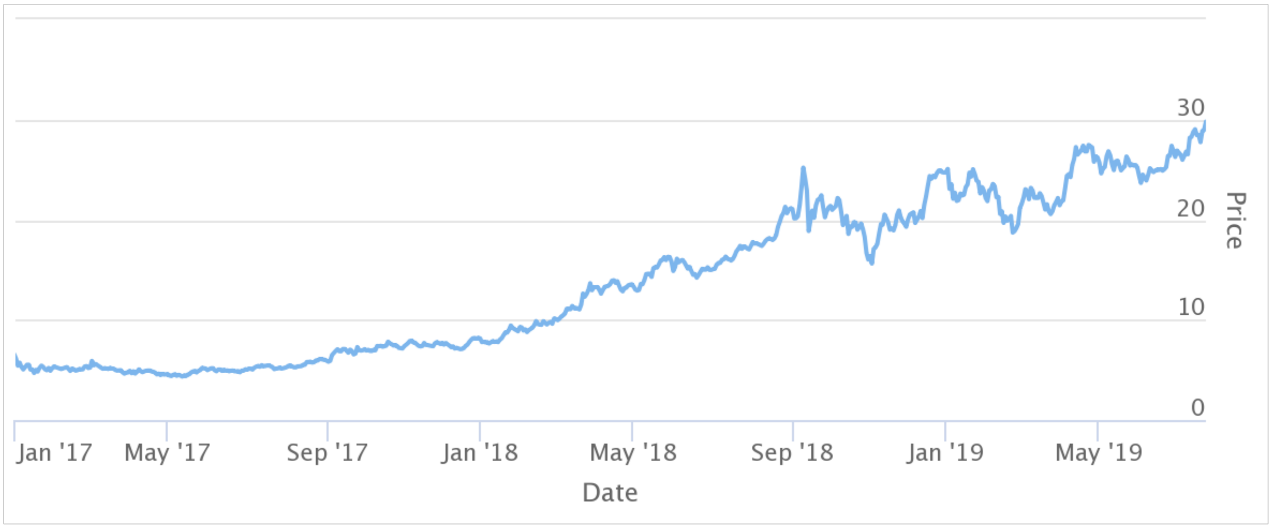

Figure 17: CO_2 emission allowance price in €/ton CO_2 (sandbag.org)

3.2.4 Peak power plant costs

CAPEX costs for an open cycle gas turbine (OCGT)[10] peak power plant are usually reported as function of the installed capacity. The investment costs are estimated at around $800-1000/kW (Seebregts, 2010) or 1100 $/KW (Namovicz & Diefenderfer, 2016). CAPEX costs taken for this analysis is approximately 893 €/KW. O&M costs for the same peak power plants are 21-36 $/KW/yr (Seebregts, 2010; Namovicz & Diefenderfer, 2016). OPEX assumed here are 25 €/KW/yr for the gas turbine capacity, and are discounted to net present value at a 10% discount rated. The capital investment costs for the power plant installed capacity are typically minimized by power generation companies, since the plant runs for only a few hours per year. The extra investment and maintenance cost of combined-cycle-gas-turbines (CCGT) is more expensive than the extra fuel costs due to the lower efficiency of OCGT. For this reason, gas costs constitute a significant share of total life-cycle cost of peak power plants.

3.2.5 Outcomes of the Economic Assessment

The results of the economic assessment are displayed in figure 18. The levelized cost of energy from hydrogen and methanol fuels are compared. In order to put the discussion in context, both alternative fuel costs are compared with the present case of continuing to fire natural gas in gas turbines. Also, the total life-cycle costs of constructing, operating and maintaining a typical peak peak power plant are included for reference.

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[10] OCGT plants consist of a single compressor and gas turbine connected to an electricity generator via a shaft

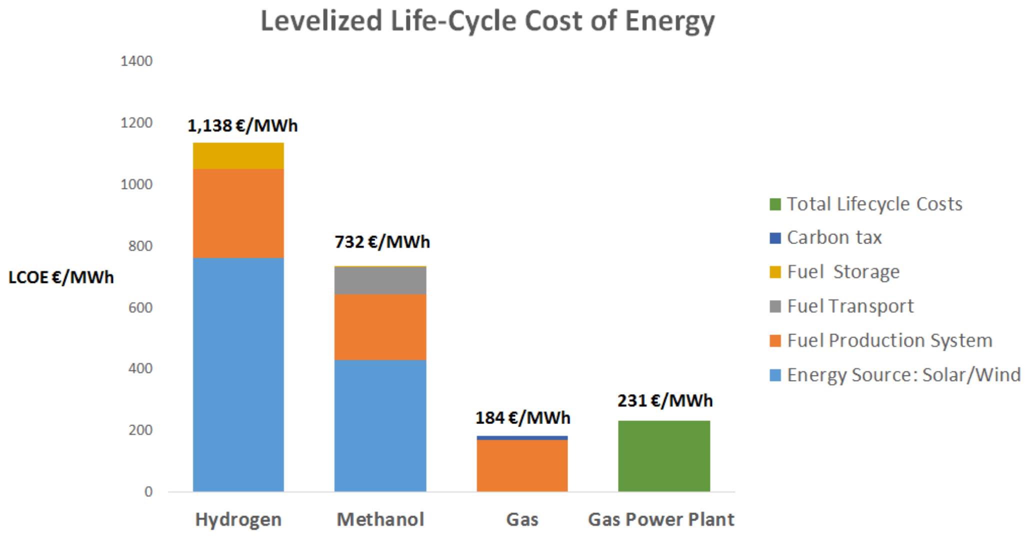


Figure 18: Levelized cost of energy for different gas turbine fuels

CAPEX and OPEX costs are combined for each part of the fuel value chain. Cost averages are estimated are based on recent academic literature for current technology. The costs are expressed in terms of 1 MWh generated from the peak power plant, and reflect the cost of each components of the value chain. Energy source refers to the renewable electricity production for both alternative fuels (offshore wind farm and grid connection for hydrogen production, a off-grid solar modules and site preparation for methanol). The fuel production costs refer to the *ZEF* micro-plants units for methanol production, and the electrolysers and compressors for hydrogen production. Storage costs are relevant for both fuels, while transport costs are only relevant for methanol.

Natural gas costs are composed of the long-term contract fuel costs (which is categorized as a fuel-production cost), and the Dutch carbon tax that will be imposed on electricity generation companies. No storage costs are assumed for the natural gas case, since the Maasstroom plant is assumed to be connected to the Dutch gas grid.

The analysis shows that methanol fuel produced from renewable energy is significantly cheaper as an alternative fuel compared to hydrogen produced locally. The major contributor to the difference is the renewable energy production costs. Although significantly more installed capacity is needed for methanol production (48 MW) compared to hydrogen (25 MW offshore wind farm), electricity production from solar panels remains to be the cheapest source of renewable energy at current prices. Grid connection costs are a major contributor to renewable hydrogen costs which are not required in the methanol production from solar energy. Alternative fuels still remain significantly more expensive compared to natural gas for power generation. Even with future carbon taxes, methanol is around four times more expensive, while hydrogen is over 6 times more expensive.

The total life-cycle costs (CAPEX and OPEX) for the peak power plant are estimated based on conventional natural gas power plants. Gas turbines running on methanol are expected to be slightly more expensive, due to minor modifications needed to allow gas turbines to run on methanol (Medina & Roberts, 2013). Hydrogen gas turbines may be more expensive than gas turbines modified for methanol due to the bigger technical challenges involved. One limitation of this assessment is that the cost difference between both turbine fuels are not included, due to lack of scientific literature detailing the differences in cost. This is included as a recommendation for future research.

3.3 Social Assessment

Social criteria deal with issues that affect people both directly and indirectly, and are expressed on whether they benefit or harm the population (Campos-Guzmán et al., 2019). The most commonly analysed social criterion for energy projects is job creation (Campos-Guzmán et al., 2019). Other criteria typically investigated are public acceptance, social benefit, impact on human health, resources security, national energy security, safety and expected mortality in case of an accident (Amer & Daim, 2011; Campos-Guzmán et al., 2019; Acar et al., 2019). In academic literature, there is no consensus on the evaluation methods that should be used to measure the indicators of this social criteria (Campos-Guzmán et al., 2019). The reason being that researchers define the goals and criteria of their research differently. For instance, in some cases political and even environmental indicators are a subset of social criteria, and in other cases form independent major criteria of their own. This research assumes environmental criteria are a separate major criterion, and assumed political indicators to be a subset of social criteria. Therefore, three sub-criteria are defined for the social dimension. Energy security of supply (political), system safety and job creation. These criteria are relevant to the alternative fuels defined in this analysis, especially that the hydrogen fuel is produced locally, while methanol is produced and imported from abroad.

3.3.1 Energy Security of Supply

In The Netherlands, security of supply is often discussed when creating policies related to natural gas and fuel production (Lazarevska & Mladenovska, 2016; Ball & Weeda, 2015). Energy security of supply is regarded as more of a political criterion and addresses how a country can enhance its own energy security by utilizing indigenous renewable energy resources, and by doing so they can reduce foreign dependency for their energy sources (Kahraman et al., 2009). By this definition, local hydrogen production from offshore wind projects in the North Sea is strongly more preferable to importing methanol from a foreign, non-EU country.

3.3.2 System safety

The safety assessment is carried to identify the hazards and evaluate the risks involved for both alternative fuels. Following a number of catastrophic international accidents in the chemical, oil and gas and energy sectors, system safety has evolved from simply minimizing individual risk to the concept of process safety (Medina & Roberts, 2013). The focus of process safety is to prevent large-scale system risks in advance. Key differences are identified between methanol and hydrogen both in risk and hazard terms, which influence their process safety across production, transport, storage and utilization as an alternative fuel. Hazards represent inherent threats of a substance due to its chemical structure. Typical threats for fuels can be their flammability, toxicity or reactivity with other elements (Medina & Roberts, 2013). The term risk is commonly misinterpreted to refer to hazards. The definition assumed for risk in this research is the probability of occurrence of an event that leads to a negative effect (for example 10% probability of one explosion in 20 years) (Medina & Roberts, 2013). The focus in this analysis is on comparing hazards rather than risks.

Hydrogen System Safety

Hydrogen as a fuel is not toxic in of itself, however it presents some technical risks due to its high flammability. As seen in table 6, hydrogen has a significantly higher laminar flame propagation speed compared to other fuels (Mazloomi & Gomes, 2012). That being said, a hydrogen fire lasts around 0.1-0.2 times the duration of a hydrocarbon-fuel fire of the same volume (Mazloomi & Gomes, 2012). This is due to its much higher vapor-from-liquid generation speed. Also, unlike other fuels, smoke inhalation of hydrogen is harmless, posing minimal choking rates (Mazloomi & Gomes, 2012). Hydrogen is also not inherently explosive, so in the absence of an ignition source it is less likely to self-ignite (Abdel-Aal et al., 2005). In comparison, auto-ignition temperature of Hydrogen is 585 °C, Natural gas is 540 °C and Methanol is 358 °C (Mazloomi & Gomes, 2012).

On the downside, Hydrogen has a wider flammability range (4-75%) and low ignition energy (0.017 mJ) (see table 6). In general, the flammability of a fuel depends on two factors: the tendency of the fuel to release vapour, and its flammability limits (Medina & Roberts, 2013). Flammability limits are defined as the concentration range where the vapor can burn in air. Under the lower limit, oxygen is not enough for sustained combustion, and above the upper limit the mixture is too rich and combustion is suppressed (Medina & Roberts, 2013). Hydrogen is therefore more flammable than methane, which has a flammability range of (5-36.5%). This is one of the biggest threats for utilizing hydrogen as a fuel, as it may cause unwanted combustion. Also, the robustness of hydrogen flames requires five times the extinguishing agents as methane (Moliere & Hugonnetl, 2004). Hydrogen flames also have low luminosity so they are hard to detect visually and therefore require special flame detection systems (Goldmeer, 2018a). Moreover, having the lowest density of all elements, hydrogen can diffuse very easily through air, seals and into materials (Moliere & Hugonnetl, 2004). In the case of outdoors storage, hydrogen hydrogen leaks tend to expand more quickly and pose limited risk. However since the hydrogen storage is proposed to be underground, this creates much higher risk. Hydrogen can also diffuse through seals that are regarded a airtight for other gases (Goldmeer, 2018b). All in all, hydrogen leaks entail increased safety risks which require changes to current plant safety zones and procedures.

Methanol System Safety

Methanol, similar to gasoline and diesel, is regarded as a toxic fuel. Methanol ingestion of as low as 10 ml can cause partial blindness and can be fatal over 100 ml. Also methanol does not have to be ingested to pose a risk, as it can be absorbed through skin or lungs by vapour (Medina & Roberts, 2013). However, unlike hydrogen, methanol has quite a pungent smell for concentrations over 2000 ppm therefore poses little inhalation risk. At lower concentrations, the risk for fires and explosions becomes more significant.

Methanol has a flammability range of 6-35% by volume, which is more favourable than hydrogen. Methanol combustion behaviour is different from conventional fuels. Similar to hydrogen, methanol flames are invisible to the naked eye (Medina & Roberts, 2013). Methanol burns efficiently, releasing little residual products (soot) which normally give yellow color to flames and are released due to incomplete combustion. This is also the reason behind the lower total heat of combustion of methanol (20.1 Mj/Kg) compared to diesel (40 MJ/Kg) and gasoline (38 Mj/Kg), as these residual particles contribute to more heat transfer by radiation. Large methanol fires are extinguished using alcohol resistant foam, while smaller fires can be extinguished using water (Medina & Roberts, 2013).

In case of accidental spillage of methanol while shipping, environmental effects are less pronounced compared to gasoline and diesel spills. This is due to the high solubility of methanol in water, which renders methanol spillage non-toxic to marine-life after a 1 mile radius (Medina & Roberts, 2013).

to sum up, modifications to current safety systems would include special flame detection equipment, firefighting systems would be modified to use alcohol resistant foams. Finally, protective gear is required for personnel directly handling methanol (Turaga & Johnson, 2017).

3.3.3 Job creation

Renewable energy systems employ many people throughout their life-cycle for construction, operation and eventually decommissioning (Şengül et al., 2015). Job creation is a social criteria that is commonly assessed by researchers in multi-criteria decision making assessments of energy projects (H.-C. Lee & Chang, 2018). An alternative that generates more job opportunities is regarded as a more preferred alternative. Campos-Guzmán et al. (2019) performed a comprehensive review of criteria used in MCDM for sustainable energy systems, and concluded that job creation is the most frequent indicator for the social dimension.

The job creation criterion is evaluated for the renewable energy source only, in other words, the solar PV and offshore wind farms. The job creation from operating the power plant is assumed to be the same for both hydrogen fuels. Furthermore, limited data is available for the employment numbers for hydrogen storage. While this may influence the results, the effect should not be too significant with regards to the total system employment creation. Since the offshore wind project is located locally and the solar farm is located abroad, the job creation is very strongly preferred for hydrogen fuel. Offshore wind projects typically create around 15 jobs/MW/yr (Kahouli & Martin, 2018; Chatzimouratidis & Pilavachi, 2008), which corresponds to a total of 375 jobs created per year for hydrogen fuel production. This is not to mention job creation from the hydrogen production (30 MW production plant), compression and storage.

3.3.4 Outcomes of the Social Assessment

With regards to the energy system safety, it is difficult to directly compare methanol and hydrogen to each other. The safety risks of both fuels are very different from conventional fuels, as well as from each other. Adamson & Pearson (2000) conclude that there is no clear safer fuel between methanol and hydrogen. While hydrogen has an ”explosive” reputation, the fuel is much safer than the general public opinion. During fires, only the fuel vapour tends to ignite. While hydrogen is mainly stored and utilized in vapour form, its low density means it will disperse in areas with high ventilation. Methanol vapour tends to ”pool” around leaks due to it being heavier than air, but hydrogen also exhibits similar behaviour in areas with low ventilation. With regards to toxicity hazards, methanol is classified as a toxic fuel, while hydrogen is non-toxic. On the other hand, Hydrogen has a wider flammability range than methanol, which makes methanol a safer fuel in that sense. Also, hydrogen is odourless, while methanol is characterized with a pungent smell, thus leaks are easier to identify. Both hydrogen and methanol give off low heat during combustion, which makes it less likely that surrounding objects catch fire in case of an accident. Also, both fuels have an invisible flame which poses challenges for flame detection. Therefore, there is no clear safer fuel. In areas with good ventilation, gaseous hydrogen is considered safer than methanol, while the opposite is the case in enclosed areas (Adamson & Pearson, 2000).

The energy security and job creation of the local hydrogen production is *strongly preferred* to the reliance on imported methanol. The system boundaries entail methanol production in a non-EU country (Morocco), which poses more risk to the security of supply.

3.4 Technical Assessment

3.4.1 Energy Efficiency

The definition taken here for the energy efficiency is the ratio of the energy output from the peak power plant to the energy input into the whole system from the renewable energy source (solar/wind) (Amer & Daim, 2011). This indicates how much of the renewable energy generated is translated into useful electrical energy output from the peak power-plant. The useful electricity output from the peak plant is the same for both system, and corresponds to the generation from the 34.3 MW for 522 hours per year (5.96% capacity factor).

The wind-to-hydrogen route includes a 25 MW offshore wind farm, operating with a 42% capacity factor. The electricity generated is used to power the electrolysers and compressors and also incorporates long distance transmission losses. The overall energy efficiency of the chain is **19%**.

The solar-to-methanol route requires a 48 MW solar farm, in a region with 7 equivalent sun hours per day. The electricity produced powers the electrolysers, compressors, direct air capture unit and methanol synthesis unit. The energy consumption of the transport of methanol is not included in the efficiency estimate. The efficiency of the entire process is around **15 %**.

One caveat is that this calculation is sensitive to the efficiency of the gas turbine assumed in the utilization phase. In this analysis, the efficiency of the hydrogen turbine selected was 35%, while the efficiency of the methanol turbine was 28%. This selection was based on turbine specifications in existing literature, and has a significant impact on the results.

3.4.2 Technology Readiness Level

The technology readiness level (TRL) assessment is based on the framework developed by NASA, which is a tool used by engineers to evaluate the state of the art of a given technology (Shea, 2007). Identifying the TRL is a straightforward process that applies a systems engineering approach to determine two things: what has been demonstrated by the technology, and under what conditions (Shea, 2007).

The method was developed to evaluate a single technology and its integration with other technologies within broad, complex products. While the method has been typically related to space system environments, it has attracted other industries and agencies to also implement it (Beims et al., 2019). The method has been applied to evaluate the TRL of biomass fuel production(Stafford et al., 2019; Beims et al., 2019), the chemical industry (Buchner et al., 2019), industrial organization (Heslop et al., 2001) and nuclear fuel development (Heslop et al., 2001). The reason behind this multitude of applications is its step-wise staging process which allows the development of a disciplined, effective and metric-driven technology readiness scaling (Beims et al., 2019).

That being said, the technologies being analyzed often operate in a network of complexity and require integration within a broader system, therefore the TRL method comes with some constraints. The main challenge being the use of definitions during TRL assessments, which are certainly subjective, and may be challenging to apply consistently (Beims et al., 2019). However, TRL is a useful guide to provide comparisons between the technological advances of different systems, by visualizing the progress in specific subs-system components (Olechowski et al., 2015). It is also not recommended that the TRL be taken as an absolute number describing the status of maturity, but rather considered within the bigger context of technology development(Olechowski et al., 2015).

The assessment framework can be visualized in figure 32 in the appendix. A series of questions are asked to identify where the technology lies on a TRL scale of 1 to 9. The definition assumed for each technology level is summarized in table 15. The technology assessment is an iterative process that makes use of the product breakdown structure, which provides a break down the system its subsystems and components that can be assessed. The next step is to develop milestones and metrics to track the progress of the technology by (1) using the TRL to identify the current technological maturity and (2) determination of the technological difficulty to jump to the next TRL (Shea, 2007).

Hydrogen system

The technology readiness level of the entire value chain for hydrogen production, storage and utilization is analysed here. The analysis is based on academic literature and commercially available technologies from the industry, and the results are displayed in figure 19.

To begin with, alkaline water electrolysers have been used in the chemical industry at a large scale in non-energy purposes for nearly a century (Taibi et al., 2018). However, the technology has been developed to operate at constant load to meet the industrial demands, as opposed to the flexible load output from renewable energy generation. Photoelectric membrane (PEM) technology is much more responsive to rapid fluctuations in energy supply, however is still at very early stages with half the lifetime and around twice the costs of alkaline water electrolysis (Taibi et al., 2018). Nonetheless, some progress has been noted in improving the operational flexibility of alkaline water electrolysers, where they have reached 1-10 minute ramp-up/shutdown time compared to 1 second-5 minute ramp-up/shutdown times for PEM (Taibi et al., 2018). TRL of alkaline water electrolysers has been estimated at 5-7 for the same reason by (Grond & Holstein, 2014). Therefore, a technology readiness level of 7 is assumed here.

Hydrogen compression is an integral prerequisite for efficient hydrogen storage. Mechanical compression of hydrogen is performed either using reciprocating technologies (diaphragm compressors assumed in this research) or using centrifugal compressors (Rustagi & Soto, 2017). Reciprocating diaphragm compressors are the current most used technology, however the technology suffers from low reliability and potential for contamination from the lubricants (Rustagi & Soto, 2017). Low reliability is currently a problem, especially under intermittent operation, with the common causes for failure being mechanical stresses on the valves and diaphragms, hydrogen seepage into the polymeric seals as well as the thermal stresses induced on the system (Rustagi & Soto, 2017). Furthermore, lubricating oil sometimes contaminates the hydrogen as it is being compressed, and design improvements are being researched to ensure zero-leakage, or even eliminate the need for lubrication oil. Centrifugal compressors are typically used for natural gas compression, however implementation in hydrogen compression is still at prototype stages. The main challenge being the lower molecular weight of hydrogen, which requires three times the tip speeds of natural gas centrifugal compressors (Rustagi & Soto, 2017). Therefore, the current status of hydrogen compressors can be placed at TRL 7, as the technology is operational at existing fueling stations, yet improvements are needed for large scale reliable implementation.

Large scale hydrogen storage is yet to be commercially demonstrated in storage tanks due to reasons of material properties and costs (Andersson & Grönkvist, 2019). Nonetheless, large scale underground hydrogen storage has been already implemented in Teeside, UK, and in Texas, USA where salt caverns proved to be suitable and also cost effective for storing hydrogen (Wolf, 2015). Another alternative being proposed is to, similar to natural gas, store hydrogen in distribution pipelines (Andersson & Grönkvist, 2019). However, hydrogen pipeline is much more expensive compared to conventional natural gas pipelines, mainly due to a phenomenon known as hydrogen embrittlement (Andersson & Grönkvist, 2019). Hydrogen embrittlement negatively affects the mechanical properties of steel materials over time leading to degradation of mechanical properties and premature cracks due to the diffusion of hydrogen into the metallic structure (Barthelemy et al., 2017). Barthelemy et al. (2017) gave an overview of hydrogen storage technologies and their current status.

Physical storage of hydrogen, independent of geologic structure such as underground reservoirs and salt caverns, has been commercially demonstrated at small scale for on-board vehicle storage. European level weight specifications and standards for mass storage efficiency have already been identified for such applications (4.8 wt.% of hydrogen stored) (Barthelemy et al., 2017), yet no regulatory framework has been achieved for large scale compressed hydrogen storage, especially addressing their safety concerns. Zheng et al. (2012) conclude that codes and standards, by the

Table 15: Technology readiness level scale adapted from (De Rose et al., 2017)

Scale	**Environment**	**Description**
9	**Industrial**	**Actual system proven in operational environment**
		- Technology proven fully operational and ready for commercialization. - Full production chain is in place and all materials are available. - System optimized for full rate production
8	**Industrial**	**System is complete and qualified**
		- Technology is proven in real world conditions, training and maintenance documentation are completed. Full certification acquired - Manufacturing process is stable enough for entering a low-rate production. System integration is mature
7	**Industrial**	**System prototype demonstration in operational environment**
		- *Full scale* pre-commercial system is demonstrated in operational environment. - Compliance with relevant environment conditions, authorization issues, local/national standards is guaranteed. - The integration of upstream and downstream technologies has been verified and validated.
6	**Pilot**	**Technology pilot demonstrated in relevant environment**
		- Demonstration in relevant environment of the technology fine-tuned to a variety of operating conditions. Inter-operability with other connected technologies is demonstrated. - Manufacturing approach is defined and environmental, regulatory and socio-economic issues are addressed.
5	**Laboratory**	**Technology validated in relevant environment**
		- Components are integrated with supporting elements and auxiliaries in the large-scale prototype. - Robustness is proven in the *simulated* relevant working environment. The process is reliable and the performances match the expectations. - Other relevant parameters concerning scale-up, environmental, regulatory and socio-economic issues are defined and qualitatively assessed.
4	**Laboratory**	**Technology validated in lab**
		- *Reduced scale* prototype developed and integrated with complementing subsystems at laboratory level. - Key Performance Indicators are measurable. - The prototype shows repeatable/stable performance
3	**Laboratory**	**Experimental proof of concept**
		- First laboratory scale prototype or numerical model realized. - Testing at laboratory level of the technological element, but not the whole integrated system. Verification of proof of concept through cross validation with literature data.
2	**Theoretical**	**Technology concept formulated**
		- Enhanced knowledge of technologies, material and interfaces. Initial numerical knowledge and preliminary evaluation of feasibility.
1	**Theoretical**	**Basic principles observed**
		- Identification of the new concept, expected barriers, integration of concept and materials based on literature

International Standardization Agency (ISO), can facilitate manufacturers' investment in the technology and facilitate public acceptance by providing a systematic and accurate means of assessing and communicating the risk associated with the use of hydrogen. Currently, stationary hydrogen storage vessels are mainly used for hydrogen refueling stations in seamless hydrogen storage vessels. These vessels have very constrained storage volumes due to the diameter limitation of seamless thick-walled tubes (Zheng et al., 2012). This could be overcome by using higher strength steel, however then the embrittlement issues becomes very significant. Zheng et al. (2016) have addressed these issues in their pilot design of the multi-functional layered stationary hydrogen storage vessel selected in the system boundaries in section 2.2.1. The 0.5 m^3 vessel was designed to withstand a pressure of 98 MPa, and the safety of the system was verified, and the stress level for the inner shell was reported to be uniform with the hydrogen embrittlement mitigated. This places the status of the high pressure stationary hydrogen storage tanks at TRL level 5, with further validation required in the actual operational environment, addressing scaling up and integration with the compressor system and other system components.

The technological challenges for hydrogen fuel utilization in gas turbines have been discussed at length in existing literature. Hydrogen is by a factor of 8 lighter than methane (major component of natural gas) and has a higher lower heat value (LHV) per unit mass (Stolten & Emonts, 2016). Even though the LHV per unit mass of hydrogen is more than twice the LHV of methane, the LHV per unit volume of hydrogen is around three times lower compared to methane. This means that for the same thermal power output in the gas turbine combustion chamber, the required volumetric flow rate is more than two times higher than natural gas (Stolten & Emonts, 2016). Hydrogen also has much wider flammability limits than methane/natural gas. The wider limits relate to chemical kinetics, and a larger diffusion coefficient. This is the reason behind the higher laminar flame speeds of hydrogen compared to methane (an order of magnitude higher) (Stolten & Emonts, 2016). In combustion reactions, flame speed is the speed the unburnt gas propagates into the flame. This is relevant to determine if the flame will propagate upstream from the combustion zone to the premixing zone at the nozzle (Goldmeer, 2018a). For this reason, the combustor fuel inlet should be designed for hydrogen use. Another challenge is the ignition delay time, which determines the duration of time available for air/fuel premixing before prior to the onset of ignition and combustion (Stolten & Emonts, 2016). Ignition delay is a function of the evaluated temperature, and for pure 100% hydrogen, it is significantly shorter for hydrogen compared to methane. While a high level of pre-mixing is required to ensure complete fuel combustion, the pre-mixing section should be designed to avoid unwanted ignition in order not to overheat the walls (Stolten & Emonts, 2016). This is a difficult task to balance due to the high inlet pressure and temperature of hydrogen, as well as its highly reactive nature. The final hurdle is the nitrogen oxide emissions (NOx) during hydrogen combustion in atmospheric air (instead of pure oxygen). Burning hydrogen can cause a higher combustion temperature, which encourages the formation of nitrogen oxides, this can be overcome by increasing the excess of air thus lowering the burning temperate (Johansson, 2005). To sum up, the main technical challenges for utilization of hydrogen as a gas turbine fuel are related to its significantly higher flame speed and shorter ignition time compared to natural gas. This leads to its high risk of flashback and auto-ignition.

Gas turbines running completely on hydrogen are still in the research and development phase (M. C. Lee et al., 2010; Jin & Ishida, 2000). Progress has been made in hybrid turbines that run on mixtures of natural gas and hydrogen. Goldmeer (2018a) have demonstrated an accumulated one million operating hours from 25 GE gas turbines running on 50-70% hydrogen (by volume). Two examples are the Daesan refinery in South Korea operating a *GE 6B.03* gas turbine on hybrid fuel of around 70% hydrogen for over 20 years, and the high hydrogen turbine at Enel's Fusina, Italy running a *GE-10* gas turbine produce 11.4 MW. Goldmeer (2018a) report that the advantage of using gas turbines for power generation is that they can be re-configured to run on alternative fuels, including fuels with increased concentrations of hydrogen. The technology readiness of the shift in turbines simply depends on the concentration of hydrogen in the fuel. In the case of fuel blending with low levels of hydrogen, and higher levels of natural gas, the required modifications are simple such as limited controls updates along with new combustor fuel nozzles (Goldmeer, 2018a). As for high concentration hydrogen mixtures, much more changes are required for more sub-components beyond the gas turbine controls. A switch to a new combustion system may be required with new fuel accessory piping and valves. Moreover, new fuel skids, enclosure and ventilation system changes will be needed. Finally, more research is needed to upgrade flame detectors and gas sensors as opposed to deal with the low hydrocarbon content. Based on the state of the art of hydrogen fueled gas turbines, the TRL of 100% hydrogen turbines is difficult to identify. Only one 12 MW turbine exists, in Fusina, Italy that runs on almost 97% Hydrogen, however the majority of developments focus on fuel blending with natural gas. The technology is faced with a lot of challenges, and there is no scientific literature to supports its readiness for commercial deployment. Stolten & Emonts (2016) provide a nice overview of state of the art development in utilization of high concentration hydrogen fuel in integrated gasification combined cycles (IGCC). The alternative fuel combustion's effects analyzed by Siemens, GE, Alstom amd Ansaldo Energia mainly focus on syn-gas with high concentrations of hydrogen. The results show that high efficiency levels hydrogen conversion to power in gas turbines can be achieved, with an efficiency of up to 42% in single cycle and 61% in combined cycle mode (gas + steam turbines). To conclude, hydrogen use in gas turbines is feasible, yet many modifications are still needed for the gas turbines components to run on 100% hydrogen. Major technical are related to the high flashback and auto-ignition risk due to the higher flame speed and shorter ignition delay time of hydrogen compared to natural gas, which entail the requirement of redesigning the turbine combustor. Therefore, based on the technological challenges that are reported, and the state of the art of the current turbine developments, hydrogen gas turbines can be placed at TRL 6.

Methanol system

In 2015, more than 70 million tonnes of methanol was produced globally. Currently, methanol is primarily produced from natural gas in areas with high hydrocarbon feed stock presence, such as the Persian Gulf, South America, Africa, the Caribbean and Russia. Methanol is consumed around the world, with the largest consumption in areas with high industrial development such as China, Taiwan, Japan, South Korea and also in North America and Western Europe (Medina & Roberts, 2013). The system being developed by *ZEF B.V.* is at laboratory experimentation phase, with current focus on developing the subsystem components, and then the complete system integration. The subsystem components (electrolyser, direct air capture, compressors, methanol synthesis, etc.) are at varying stages of development with the concept being already developed. Methanol production from renewable energy has already been commercially implemented at the George Olah Methanol Plant in Svartsengi, Iceland (Olah, 2013). Carbon dioxide is separated from the off-gas emissions stream of a geothermal plant in Svartsengi, and is reacted with hydrogen produced from water electrolysis (hydrogenation process) (Olah, 2013). The TRL of the *ZEF* micro-plant is at level 2. However other renewable methanol production systems are in operation in Japan (100 tonnes/year) and Iceland (3500 tonnes/year) (Olah, 2013).

The geographic distance between methanol producers and consumers entails that 80% of the produced methanol is transported in trans-oceanic ships, stored in marine terminals and distributed via truck, rail or barge to chemical production facilities (Medina & Roberts, 2013). Methanol is stored in overground storage tanks in tank farms. Fire protection mechanisms installed for gasoline storage are suitable for handling methanol. Extra modifications are simple, and include leak detection and ensuring the presence of alcohol-compatible fire suppression foam (Medina & Roberts, 2013). Methanol storage and transport is at TRL level 9, since the technologies are mature and have been commercially applied for years.

Utilizing methanol fuel in stationary turbines is the subject of current research and has been commercially investigated in pilot projects. Stationary turbines typically run on natural gas which emits nitrogen and sulfur oxides. Since methanol contains no sulfur and nitrogen contaminants, and burns at a lower temperature, this has potential to significantly improve stack gas air quality (Medina & Roberts, 2013). GE, Siemens, Wartsila, Mitsubishi Hitachi Power Systems (MHPS) and Original Equipment Manufacturers (OEMs) have reported that it is technically feasible to retrofit gas turbines to run on methanol (Turaga & Johnson, 2017). Currently, 2 power plants run entirely on 100% methanol: a 9.7 MW *MHTL* gas turbine in Trinidad and Tobago, and the 50 MW gas turbine power plant in Eilat (Turaga & Johnson, 2017). Some technical and economic considerations are noted for switching fuels from natural gas to methanol. The considerations are similar to modifying combustion chambers to run on gasoline (Turaga & Johnson, 2017).

Methanol has a lower heating value when compared to natural gas (table 6), so a greater volume should be injected into the combustion to produce the same heat output as natural gas. The turbine storage and fuel transfer mechanism should be modified to accommodate the larger fuel volume. Also, methanol has inherently low lubricity due to low sulfur levels, which creates problems for the valves and fuel controls in the fuel delivery system (Murray & Furlonge, 2009). The lubricity of the fuel can be enhanced by the use of fuel additives, or dealt with using modified fuel pumps (Murray & Furlonge, 2009). Another challenge is the low flash-point of methanol, which means that at low temperatures the fuel has rather low vapour pressure. This creates turbine startup issues in cold weather, which are typically overcome by using conventional fuels (Turaga & Johnson, 2017). Based on commercial utilization of methanol fuel in reciprocated gas turbines of small and large scale (10-50 MW), and the simplicity of the technical challenges for further implementation, methanol gas turbines are placed at TRL 7.

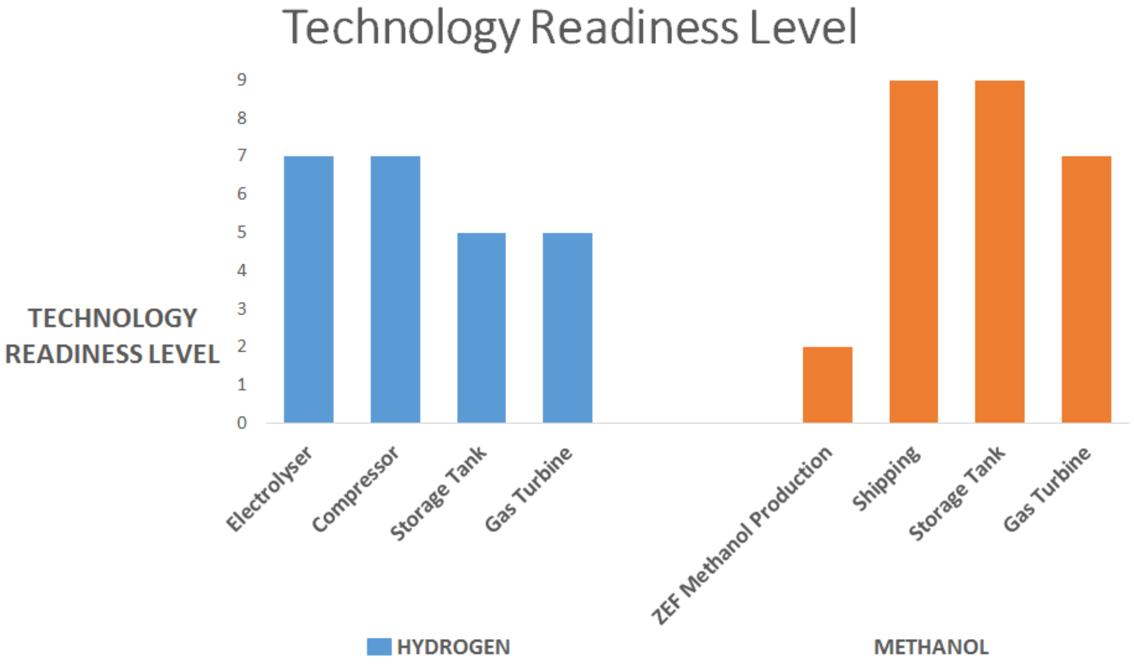


Figure 19: Technology readiness level of alternative fuels' value chain

3.4.3 Outcomes of the Technical Assessment

It is worth mentioning that several technologies exist for each sub-component of the system. The results of the comparison of the technology readiness of both systems are based on the selections made in the system boundaries in section 2.2, and are displayed in figure 19. For example, while underground storage of hydrogen is technologically mature and demonstrated in salt caverns (advanced TRL level), the same is not true for the large-scale stationary metallic storage tanks which are selected in the system boundaries. For the case of 100% renewable energy fuel, methanol is overall *slightly preferred* to Hydrogen based on the higher technology readiness of its storage, transport and utility in gas turbine.

The energy efficiency of the hydrogen chain is *slightly preferred* to the methanol production route. Indeed, hydrogen is a feed-stock for methanol production, which makes the fuel production of methanol constitute a longer chain with more efficiency losses. However, hydrogen produced still requires significant energy consumption for compression to ensure adequate storage. That being said, the overall energy efficiency was at 19% for the hydrogen chain and 15% for the methanol chain.

3.5 Fuel performance summary

In this chapter, the performance of hydrogen and methanol as alternative fuels for gas turbines is compared across a range of selected criteria. Several design requirements are made in chapter 2 that are translated into technological selections for both fuel value chains. Economic, environmental, technical and social assessments are carried for each alternative based on nine sub-criteria pertinent to decision makers. While numerous decision-making criteria are identified from existing literature, the selection is based on indicators that are relevant for the system boundaries and design choices defined here. The outcome of this chapter is used as input for the fuel performance in the third step of the AHP method, which is synthesizing the judgements over the different with regards to each alternative's performance and criteria priority. Table 16 explains the scale used in the AHP method to indicate the performance of each alternative fuel. Each one of the nine sub-criteria is evaluated separately. The fuel performance is translated into linguistic terms indicating how much one fuel is preferred over the other, based on the qualitative and quantitative assessments carried. This step however is not sufficient to indicate which alternative fuel is the overall better performer. In order to come to a conclusion on the preferred alternative fuel, the different sub-criteria are weighted according to the decision makers priorities in the chapter 4, and the results of the fuel scores are reported in chapter 5.

Definition	Value
Equal preference	1
Moderately more preferred	3
Strongly more preferred	5
Very strongly more preferred	7
Extremely more preferred	9

Table 16: pairwise comparison scale

Criteria				**Outcome**								
	HYDROGEN	**9**	**7**	**5**	**3**	**1**	**3**		**5**	**7**	**9**	**METHANOL**
Economic												
CAPEX								✔				
OPEX								✔				
Technical												
TRL							✔					
Efficiency					✔							
Environmental												
CO_2				✔								
NOx			✔									
Social												
System safety						✔						
Security of Supply		✔										
Job Creation		✔										

Table 17: Summary of alternative fuel performance for all sub-criteria

4 Analytic Hierarchy Process

The Analytic Hierarchy Process (AHP) was developed by Saaty (2008) and serves as a very powerful and flexible decision making tool for complex multi-criteria problems (Papalexandrou et al., 2008). The complexity of the decision-making process is reduced by decomposing the problem into a set of relevant criteria, and sub-criteria in a hierarchical structure. The hierarchical structure allows for better comprehension of the problem and more accurate assessments (Papalexandrou et al., 2008). The shift to an alternative fuel will require substantial changes and investments by the industry across the value chain. The selection of an alternative fuel will be influenced by the decisions made by many stakeholders, specifically the energy companies, equipment manufacturers, electricity generation companies and also by energy policy makers. The AHP method allows decision makers to subjectively evaluate the criteria through pairwise comparisons, and minimizes errors due to arbitrary subjective evaluations by checking the comparisons using a consistency ratio. The fundamental theory behind AHP is the reliance on theory of relative measurement to produce a rating of the possible alternatives (Brunelli, 2015). Brunelli (2015) state that AHP is ideally placed in the intersection between decision analysis and operations research.

As was mentioned in the research methods section in chapter 2, The AHP method is based on three fundamental concepts ((Amer & Daim, 2011)):

1. Structuring the decision making problem as a hierarchy of goals, criteria. sub-criteria and alternatives at the bottom.
2. Performing Pair-wise comparisons between each element at the same level of the hierarchy tree, with respect to the preceding level in the hierarchy. Calculating the ratio-scaled criteria priority for each criterion accordingly.
3. Synthesizing the judgements over the different levels of the hierarchy with regards to each alternative's performance and criteria priority.

In the following subsections, the AHP method is detailed and the hierarchical structure is introduced. Then the criteria weighting are assigned for each stakeholder based on the input from the energy industry. Finally, the performance of both alternative fuels are compared based on their performance on each criterion, and the weight of each criterion in the decision making process.

4.1 Hierarchy structure

The first step of conducting an AHP is structuring the complex problem at hand in a hierarchical structure: with an overarching goal at the top, the decision criteria followed by their sub-criteria, and the possible alternatives at the lowest level. The AHP hierarchy tree is displayed in figure 20 and is based on the criteria identified in the literature review in section 2.1.2. One key element of the comparison is how the alternative fuels compare to the conventional fuel they replace, in this case natural gas. While this is relevant for both the environmental and economic impacts of the fuel, gas is irrelevant as an *alternative* for the specified *goal*. Therefore, natural gas is not included as an alternative in the AHP hierarchy.

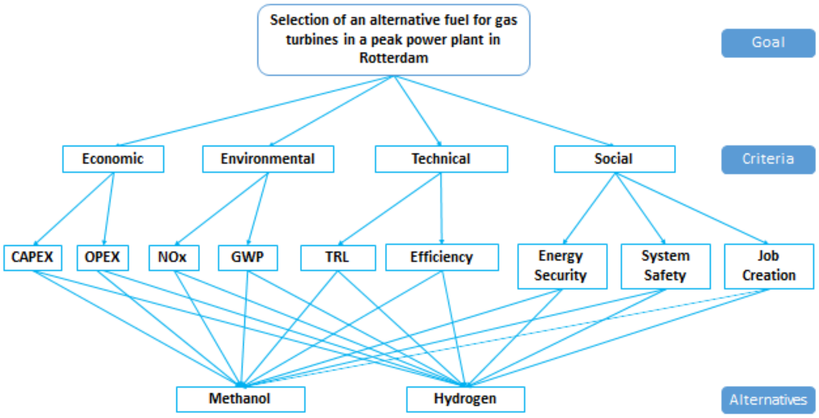


Figure 20: Hierarchy tree for selection of alternative gas turbine fuel.

The basic theory of AHP may be simplified as follows, an assumption is made that ”n” different and independent criteria C_1, C_2.. C_n are relevant to the decision maker. Each criterion has its respective weight W_1, W_2.. W_n, respectively. The decision-maker does not know the weight of each criteria, but can make a pairwise comparison between each two criteria on the same level. This is represented in an nXn matrix in order to appropriately weigh each criterion relative to the whole process. A final score for each alternative is synthesized by incorporating the weight of each criterion and its respective performance of the the alternative fuel.

4.2 Criteria Weighting

Criteria weighting allocates the relative importance of major and sub criteria when synthesizing the overall scores for both alternative fuels. The weighting is carried hierarchically for each level with the respect to the preceding level (Saaty, 2008). This is inherently a subjective process since it depends on how the decision-makers prioritise the range of criteria included. The outcomes can vary significantly between stakeholders with different backgrounds, interests and objectives (Chatzimouratidis & Pilavachi, 2008).

4.2.1 AHP criteria weighting method

In order to translate the pairwise comparison into criteria weights, the priority vector is calculated for each criterion, and the consistency of the comparisons is evaluated using the consistency ratio to ensure the overall consistency of the hierarchy Saaty (2008). This corresponds to the second step of the analytical hierarchy process.

The decision-maker makes pairwise comparisons between each two criteria describing their relative importance relative to the immediately preceding level in the hierarchy, according to a 1-9 scale (or their reciprocals) (Saaty, 2008). Saaty (2008) explains that it is easier for a stakeholders to use linguistic expressions such as: ”Environmental criteria are *slightly more important*” than social criteria, compared to stating that ”Environmental criteria are 2 times more important than social criteria”. The 1-9 measurement scale in table 18 is used for these pairwise comparisons (Saaty, 2008). The scale translates opinions in linguistic terms (slightly preferred, slightly more important) to real numbers (Brunelli, 2015).

Definition	Value
Equal Importance	1
Moderately more important	3
Strongly more important	5
Very strongly more important	7
Extremely more important	9

Table 18: pairwise Comparison scale

The pairwise comparisons are then displayed in a comparison matrix format. The 4 major criteria are arranged in a 4X4 matrix, as shown in table 20. For example, if criterion A is moderately more important than criterion B, then value 3 is reported in the row containing criterion "A" and the column containing criterion "B" in the comparison matrix. By definition, this means that at row B column A, the value is automatically set as 1/3. Or in other words, criterion B is moderately less important than A. The higher the value, the higher the importance, with intermediate values of importance of 2, 4, 6 and 8 also possible.

The process of calculating the priority vector involves some complex mathematical modeling, and was carried in an excel spreadsheet. The comparison matrix table (from the surveys collected) is normalized by dividing each value in a column by its column sum. The priority vector is a set of eigenvalues of the matrix, which is calculated by taking the average from the comparison matrix by taking the row average of the normalized matrix (Stein, 2013).

The pairwise criteria are presented by the following matrix, where $C_{ji} = 1/ C_{ij}$ and i,j = 1, 2..n.

$$C = \begin{bmatrix} 1 & C_{12} & .. & C_{1n} \\ C_{21} & 1 & .. & C_{23} \\ .. & .. & .. & .. \\ C_{n1} & C_{32} & .. & 1 \end{bmatrix} \tag{3}$$

The sum of the values in each column in the pairwise matrix is calculated using:

$$C_{ij} = \sum_{i=1}^{n} C_{ij}$$

The next step is to divide each element in the comparison matrix by its column total to generate normalized pairwise matrix

$$X_{ij} = \frac{C_{ij}}{\sum_{i=1}^{n} C_{ij}} = \begin{bmatrix} 1 & X_{12} & .. & X_{1n} \\ X_{21} & 1 & .. & X_{23} \\ .. & .. & .. & .. \\ X_{n1} & X_{32} & .. & 1 \end{bmatrix}$$

The final step is to calculate the weight of each criterion by dividing the normalized pairwise matrix by the number of criteria analyzed "n" using the following expression

$$W_{ij} = \frac{\sum_{j=1}^{n} X_{ij}}{n} \qquad \begin{bmatrix} W_{C1} \\ W_{C2} \\ .. \\ W_{Cn} \end{bmatrix} \tag{4}$$

There are several methods for calculating the priority vector (criteria weight), such as the geometric mean method (Crawford & Williams, 1985) and the axiomatic method (Cook & Kress, 1988), but the original eigenvector method developed by Saaty remains to be the most commonly used among researchers (Brunelli, 2015).

One of the significant advantages of using AHP in multi-criteria decision-making is that it employs a consistency test to eliminate any inconsistent judgements by the decision makers (Amer & Daim, 2011). This is vital in ensuring that decision makers are consistent with their preferences. The outcomes of the pairwise comparisons performed by the decision maker are used to calculate a consistency ratio (CR). It is recommended by Saaty (2008) that a CR greater than 10% indicates serious inconsistencies and the decision maker should be asked to re-consider their pairwise comparison and identify the source of inconsistency. A CR of 10% or below is therefore required.

The formula for calculating the consistency ratio is:

$$\text{Consistency Ratio (CR)} = \frac{\text{Consistency Index (CI)}}{\text{Random Index (RI)}} \tag{5}$$

$$\text{CI} = \frac{\lambda_{max} - n}{n - 1} \tag{6}$$

$$\lambda = \sum_{i=1}^{n} Cv_{ij} \tag{7}$$

Where Cv is the consistency vector obtained by multiplying the priority matrix in eq. 3 with the criteria weighting in eq. 4. λrepresents the maximal eigenvalue of matrix vector C, and is calculated by averaging the value of the consistency vector using eq. 7. The Random Index (RI) is an experimental value and is a function of the number of criteria being compared. RI is directly obtained from table 19 (Saaty, 2008).

n	1	2	3	4	5
RI	0.00	0.00	0.58	0.90	1.12

Table 19: Random index values for number of criteria ”n”

4.2.2 Contribution to AHP method

In existing AHP studies, the criteria weighting is typically performed by the researchers themselves (Papalexandrou et al., 2008; Chatzimouratidis & Pilavachi, 2008; Pilavachi et al., 2009), or survey instruments distributed to energy professionals from industries and universities (Amer & Daim, 2011). Amer & Daim (2011) proposes to average the outcomes of all the criteria weights given in order to come up with one set of criteria weights for the alternative score calculations. Criteria weightings are then tested in a sensitivity analysis which are also carried by the researchers (Chatzimouratidis & Pilavachi, 2008; Stein, 2013). For example, Stein (2013) carried several scenarios were one criterion was given a 60% weight each time, and the remaining weight is distributed among the other criteria and AHP scores were re-assessed for each scenario. While Chatzimouratidis & Pilavachi (2008) also assumed several scenarios where in each scenario all criteria are given an equal weight, and in other scenarios each criterion is given a 75% weight once.

This research proposes a modification to how criteria weighting and sensitivity assessments are carried. The criteria weightings from four different key stakeholders that will be crucial in the adoption of a renewable alternative fuel. This stems from the understanding that for an alternative fuel to be adopted, interest and commitment are needed across the entire life-cycle from production to utilization is needed. This would involve investments in R&D, development of specific equipment and governmental support in some cases. Therefore, the criteria priorities are obtained from four stakeholder groups” energy companies, equipment manufacturers, policy-makers and investors.

4.3 Interviews

4.3.1 Interview design

The criteria weighting was carried by means of a survey distributed to industry professionals from each category of stakeholders. An interview was carried with each stakeholder separately. In each interview, the system boundaries were first elaborated for both production routes, showing the parts of the value chain included in the scope. The interviewees were then shown the hierarchy tree in 20 displaying the four major criteria and their sub-criteria. The sub-criteria were defined to maintain a consistent understanding across all stakeholders. The interviewees were asked to fill the survey keeping their perspective in mind. The *major criteria* were first compared in a pairwise basis with reference to the *goal*. Then the sub-criteria were also compared in a pairwise basis with reference to their parent criterion. For example the relative importance between the *technology readiness level* and *energy efficiency* with reference to the technical criterion. In order to avoid any bias, the performance of both alternative fuels on the different criteria was not revealed to the interviewees prior to filling the survey. In the end of the interview, they decision makers were asked to add any other sub-criteria or major criteria they typically assess in the decision making process.

4.3.2 Stakeholders interviewed

Four different stakeholder groups were identified as crucial in the selection and adoption of possible alternative fuels for electricity generation. The four stakeholder groups are the energy policy-makers, equipment manufacturers, energy companies and investors. The definition of each stakeholder, and the position of the decision-maker interviewed is described in more detail:

- ***Energy policy-makers:*** Responsible for providing subsidies and investment incentives for renewable fuels, and supporting the required business climate, investment in infrastructure etc.

  Survey was filled by Reinier van der Veen, an energy consultant for renewable fuels at *CE Delft*. *CE Delft* is an energy consultancy that specializes in providing policy expertise to help governments, companies and NGOs. The interviewee was asked to represent the views of a policy maker as a client.

- ***Equipment manufacturers:*** These are companies developing equipment related to the production/utilization of alternative fuels. For example, companies manufacturing PEM electrolysers, methanol reactors, gas turbines that run on hydrogen/methanol. Eg.: Siemens, General Electric, Hydrogenics.

  This stakeholder was represented by Jordi Zonnevel a renewable energy product specialist from *Frames Energy Systems B.V.*, a manufacturing company investing in biogas, carbon capture and hydrogen technologies.

- ***Energy Companies*** This group refers to companies producing both fuels and electricity. Some energy companies mainly currently produce oil and gas (Shell, Exxon Mobil, etc) and are looking into investing in sustainable energy sources to position themselves as future fuel provider whether in electricity, hydrogen, bio-fuels, etc. Other energy companies are more active in electricity and natural gas generation and distribution Eneco, Vattenfall, etc. Those two groups are identified and interviewed to represent the energy company perspective.

  Interviews were performed with *Shell* and *Eneco* for the energy company stakeholder group. Fuel producer criteria weighting was carried by Ahmed El-Itriby, a senior commercial advisor for renewable energy projects at *Shell*. Electricity producer criteria weighting was carried by Roald Arkesteijn, project manager at the Strategy and New Business Development team at *Eneco*.

- ***Energy Investor:*** As was expressed in the technology readiness chapter, alternative fuels still require investment in research and development to tackle several technical concerns. Energy experts from *Warburg Pincus* were interviewed to represent an energy investor's priorities. *Warburg Pincus* is a global private equity firm that holds $ 65 billion in assets in different sectors. They are active investors in early and growth stage technologies for both renewable and conventional energy sources. Interview was held with David Habachy from the renewable energy investment division.

4.3.3 Outcomes of criteria weighting

For each stakeholder group, a matrix is constructed describing the relative importance of each major criterion with respect to the selection of an alternative fuel. Similarly, a matrix is constructed for each sub-criterion with respect to its parent criterion. Table 20 represents the pairwise comparison matrix for all criteria from the equipment manufacturer's perspective. A similar matrix is obtained for each stakeholder group weighing all major criteria. The rest of the matrices representing the perspectives of the other stakeholders can be found in appendix F. In the case of the energy company stakeholder group, more than one interview was carried to represent fuel producers and electricity producers. In this case, the average value for their pairwise comparisons is taken.

	Economic	Technical	Environmental	Social
Economic	1	3	4	7
Technical	1/3	1	4	6
Environmental	1/4	1/4	1	2
Social	1/7	1/6	1/2	1

Table 20: Equipment manufacturer pairwise matrix for all criteria with respect to the goal

The stakeholders were also asked to indicate the relative importance of the sub-criteria. For example comparing the importance of security of supply, system safety and job creation relative to the social criteria. The procedure to calculate the sub-criteria weights with reference to their parent criteria is exactly the same as explained in this section. It is worth mentioning that the stakeholders had very similar views in weighing the economic, environmental and social sub-criteria. The major difference observed were in the relevance of the different technical sub-criteria. Table 21 shows how all stakeholders ranked the social sub-criteria.

	System Safety	Security of Supply	Job Creation
System Safety	1	1	9
Security of Supply	1/5	1	3
Job Creation	1/9	1/3	1

Table 21: Pairwise comparison of social criteria

While objective data are difficult to contest, subjective data can vary significantly between stakeholders according to their interests and objectives (Chatzimouratidis & Pilavachi, 2008). Objective data refer to the alternative fuel performance carried in chapter 3. The outcomes of the analyses were used to indicate which alternative fuel is preferred over the other for each sub-criterion, and summarized in table 17. On the other hand, criteria weighting is completely subjective and depends on how the decision-makers prioritise the range of criteria included. The results of the AHP analysis revealed how the selected sample of decision-makers weigh the four given criteria when deciding on an alternative fuel to support/invest in. The results are displayed in figure 21.

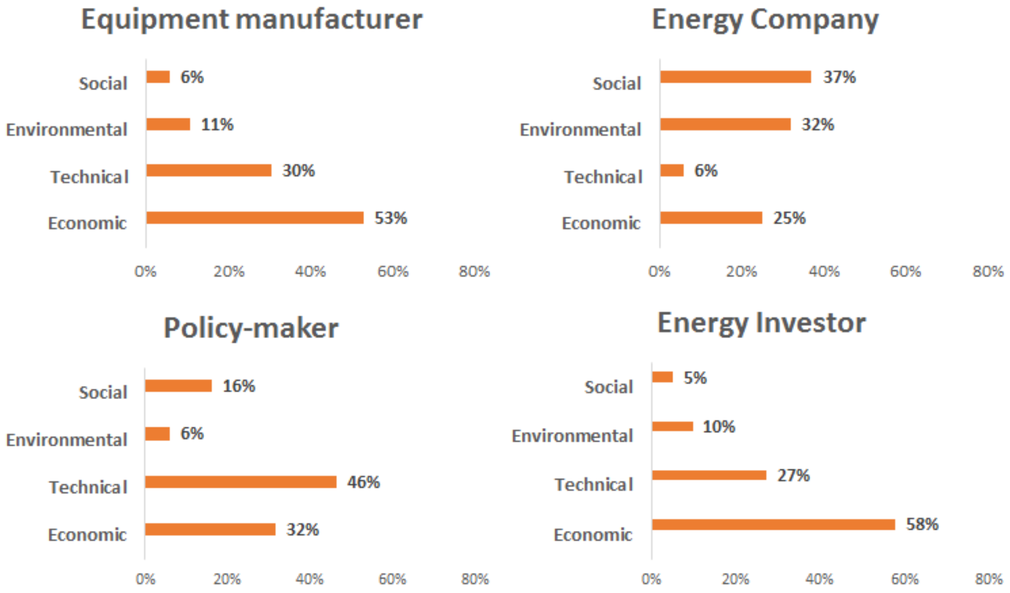


Figure 21: Major criteria weighting according to the different stakeholders

Figure 22 shows the sub-criteria weighting for each stakeholder group. In order to synthesize the results and calculate a total score for each fuel, global criteria priorities are a calculated from the sub-criteria weights. This translates the weight of the sub-criteria with reference to the entire decision making process, for example GWP constitutes 10% of the weight of all criteria with regards to selection of an alternative fuel. The global priority is calculated by multiplying the sub-criteria local priority weight (GWP with reference to environmental criteria) by the criteria weight (environmental criteria with reference to the goal). The results are different for each stakeholder, since both the major criteria and sub-criteria weights vary from one stakeholder to another. Table 30 in the appendix lists the global priorities for each stakeholder group.

The results show that the interviewees have a shared understanding of the social and environmental factors. For example, the weighting for social sub-criteria was very consistent between the different stakeholders, with the highest relevance given for system safety (75%), then security of supply (18&) and lastly job creation (7%). This is understandable since interviewees were mainly from The Netherlands or the United States, where unemployment levels are relatively low, and stringent requirements for system safety are present. This is in high contrast with results reported by Amer & Daim (2011) study of renewable energy technology selection in Pakistan. The author carried a similar multi-criteria assessment, where job creation was the most important social criterion. With regards to environmental criteria, the interviewees also consistently reported a higher relevance of global warming potential (CO_2 equivalent emissions) compared to the environmental impact of Nitrogen oxide emissions. Slight differences were observed in the weighting of the economic criteria, where half the interviewees rated CAPEX and OPEX at equal importance while the other half rated CAPEX slightly more importantly than OPEX.

Technical criteria weighting varied from one stakeholder to another. Equipment manufacturers regard system energy efficiency to be of higher importance compared to the technology readiness level. Energy companies give both criteria equal importance while policy-makers and energy investors are much more reliant on TRL in their decision making process.

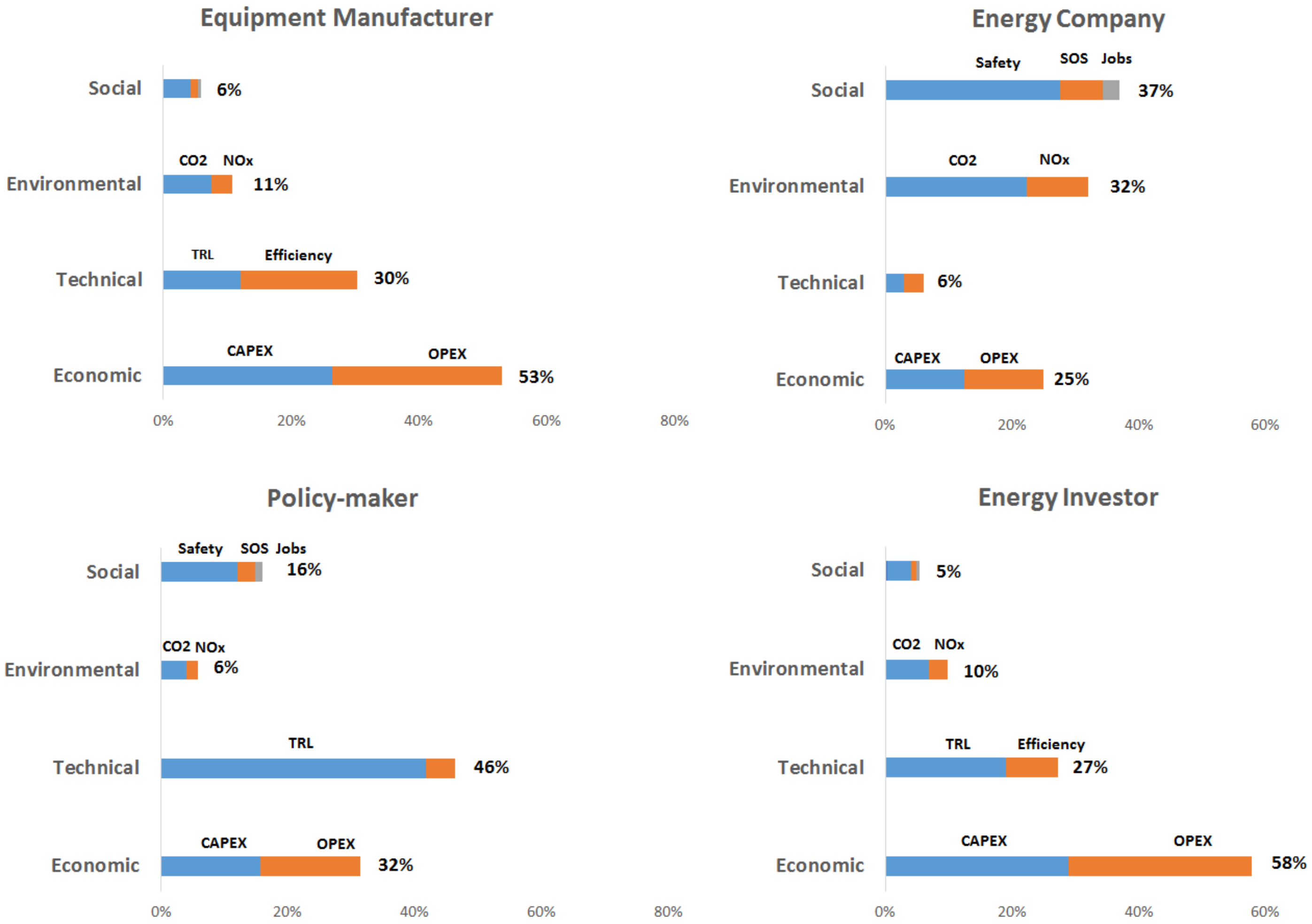
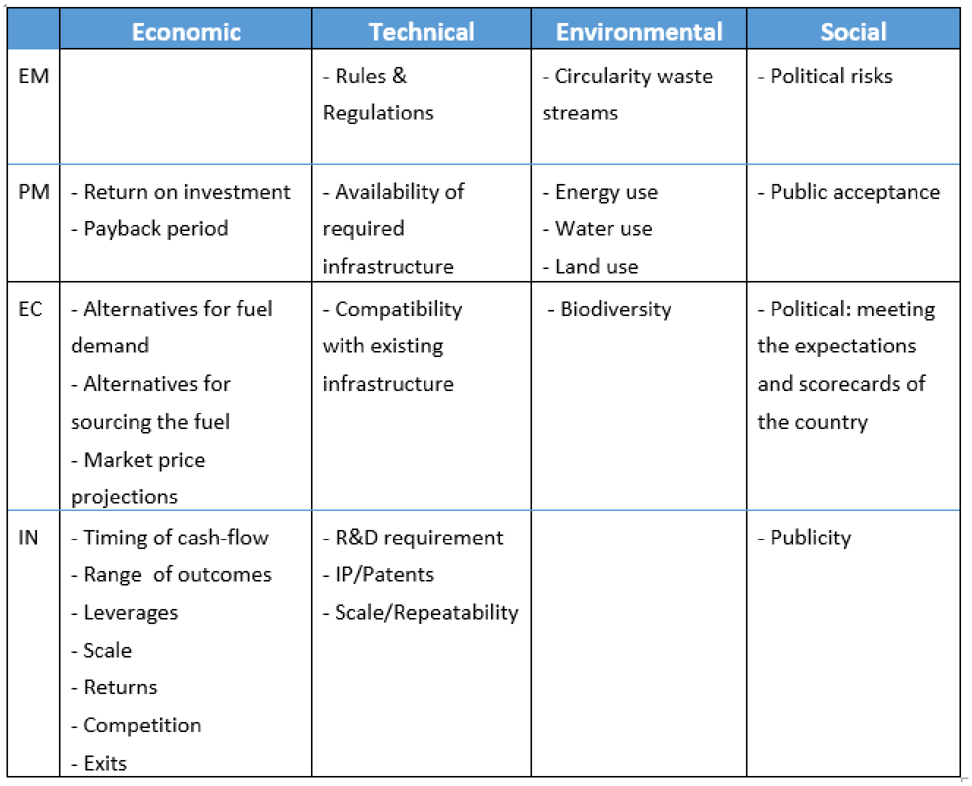


Figure 22: Sub-criteria weighting according to the different stakeholders

Finally, the interviewees were asked to complement the 4 major criteria (economic, technical, environmental and social) with other relevant sub-criteria they commonly use. Stakeholders were also asked to mention other major criteria they analyze when deciding to invest in an alternative renewable fuel. Figure 23 summarizes the extra sub-criteria, and table 22 displays other major criteria considered by decision makers.



	Economic	Technical	Environmental	Social
EM		- Rules & Regulations	- Circularity waste streams	- Political risks
PM	- Return on investment - Payback period	- Availability of required infrastructure	- Energy use - Water use - Land use	- Public acceptance
EC	- Alternatives for fuel demand - Alternatives for sourcing the fuel - Market price projections	- Compatibility with existing infrastructure	- Biodiversity	- Political: meeting the expectations and scorecards of the country
IN	- Timing of cash-flow - Range of outcomes - Leverages - Scale - Returns - Competition - Exits	- R&D requirement - IP/Patents - Scale/Repeatability		- Publicity

Figure 23: Other relevant sub-criteria according to different stakeholders (EM: Equipment Manufacturer, PM: Policy-maker, EC: Energy Company, IN: Investor)

Table 22: Other major criteria according to decision makers

Stakeholder	Major criteria
Equipment manufacturer	
	- Contribution to the purpose of the organization. - The core competencies and skills required to realize systems for subject technology
Policy-maker	
	- Institutional criteria: is new regulation needed, can existing regulation be a barrier, are new markets or organisational structures needed, need for technical standards. - Implementation criteria: how quickly can supply chain be set up
Energy company	
	- Political: To meet the expectations and scorecards of the country. Regulatory developments, such as subsidies and policies. - Reputational: A solution that would safeguard the reputation of the company and portray it as an environmentally responsible partner. - Commercial: What are the alternatives to customers. Preferably multiple customers to spread risk
Energy investor	
	- Quality of the management team and their track record.

5 Results and Discussion

5.1 Alternative fuel scores

The final step of the AHP method is to synthesize the results and calculate the final score for both alternative fuels. The score for each alternative fuel is calculated by summing the product of the criteria weights from table 30 multiplied by the fuel's performance on each criterion from table 17. AHP scores are synthesized using eq. 8, where C stands for the fuel performance on a given criterion, and wt. represents the weight of that criterion according to each stakeholder. The scores are calculated 4 times, once for each stakeholder group. Table 23 shows the scores for both alternative fuels.

$$Score = (\mathrm{C}_1)(\mathrm{wt.}_1) + (\mathrm{C}_2)(\mathrm{wt.}_2) + ... + (\mathrm{C}_n)(\mathrm{wt.}_n) \tag{8}$$

	Criteria weight				**Hydrogen Score**	**Methanol Score**
	Economic	*Technical*	*Environmental*	*Social*		
Equipment manufacturer	53%	30%	11%	6%	0.452	0.548
Policymaker	32%	46%	6%	16%	0.436	0.563
Fuel-producer	17%	8%	33%	42%	0.548	0.452
Investor	58%	27%	10%	5%	0.425	0.575

Table 23: Alternative fuel scores for all stakeholder

For three out of the four stakeholder groups, methanol is the better performing alternative fuel based on the stakeholder weightings. The main motivation being the economic and technical criteria. Although hydrogen is a cleaner fuel compared to methanol, the difference in levelized cost of energy is in favour of methanol. Hydrogen production involves the use of expensive system components for electrolysis, compression and storage, whereas methanol transport and storage is much less challenging. Generally speaking, economic criteria were of more importance compared to environmental criteria. Regarding the technical criteria, hydrogen production chain is slightly more efficient, while the technology readiness level of the methanol chain is slightly more advanced. On a technical level, depending on the stakeholder, the two technical sub-criteria (efficiency and TRL) held different priorities, which in turn influenced the resulting scores. As for the social criteria, the fact that local hydrogen production system involves more job creation, and better security of supply, had almost no impact on the results since they carry a much smaller weight in the decision making process. The reason being that social criteria all together play a minor role in the decision making process (for all stakeholders but the fuel producers), and also because system safety represents the most relevant social sub-criterion according to all stakeholders. There is no clear better fuel between the two alternatives in terms of safety, as the two fuels are similar in some aspects and outperform each other on other safety aspects. To sum up, the biggest influence on the scores are the economic and technical criteria, and for the given system boundaries, criteria selection and weightings, methanol outperforms hydrogen as an alternative fuel for gas turbines.

5.2 Sensitivity Analysis

The results of an AHP are highly influenced by the subjective criteria weighting of stakeholders. One way to overcome this is to carry out a sensitivity analysis for the criteria weighting and evaluate the effect on fuel scores. Papalexandrou et al. (2008) created different criteria weighting scenarios to evaluate the effect on several liquid bio-fuels. The authors assumed four different scenarios, where in each of the four scenarios, one of the four criteria is given 60% of the total weight. The fuel scores are again synthesized for each case to test the robustness of the results. In this research, four different stakeholders perspectives are already incorporated in the results reported in section 4, so the aforementioned approach is not taken. The approach proposed here is to evaluate the effect of various possible scenarios on the objective part of the analysis. The objective part refers to the performance of the fuel for each sub-criterion, i.e. the other "other" half of the score calculation. For example, in 10 years time, the costs of the components of both fuel production systems are expected to drop at different rates depending on the learning rates for the given technologies. This would affect the overall score of the fuel under constant criteria weightings.

The criteria weighting from the base case revealed that economic and technical criteria are consistently more important for the decision makers. The scenarios created address those two criteria, also with some reference to environmental implications. Two scenarios are analysed in this section. The first scenario projects cost reductions for different sub-components of both alternative fuels in 2025-2030, and the consequential effect on levelized cost of energy. The second scenario explores fuel blending as an alternative, where 50% of the fuel used in the peak power plant is provided by fossil fuels, which may be a realistic option for policy makers to smoothly integrate renewable fuels to the energy mix, with less significant cost implications to consumers, higher technology readiness levels (hybrid turbines) yet worse environmental effects. The alternative fuel scores are calculated for all scenarios using the same criteria weights for each stakeholder.

5.2.1 Projected cost reductions

The economic assessment performed in section 3.2, is based on capital and operational costs of commercially available technologies. Due to continued research and steep learning rates, existing literature projects price drops in some of the system components.

In the hydrogen production system, the most significant system costs were the offshore wind electricity costs, electrolysers and hydrogen storage. Offshore wind electricity generation costs are projected to drop due to several technological improvements. One reason is the improvement in turbine sizes from 2 MW to up to 12 MW turbines. This entails significant savings in both capital and operational expenditure, due to the need for less turbines, less foundation and construction costs and also improved reliability and maintainability (Valpy & English, 2017). Valpy & English (2017) estimate a rise in the CAPEX and OPEX per MW of installed capacity in 2025, however higher hub-heights, larger turbine capacities and better rotor efficiencies will allow for increased energy productions and higher capacity factors[11] of up to 52.3%. Although CAPEX and OPEX costs are expected to rise, overall LCOE will drop due to the improvement in capacity factors.

The projected CAPEX for 8-MW turbines 2567 €/KW, OPEX of 68 €/KW (planned and unplanned) deep-water projects in 2025 (Valpy & English, 2017). Also a higher grid connection cost of 0.030 €/KWh is assumed from (Lensink & Pisca, 2018) since the larger turbines are designed for deeper offshore conditions of 35 m water depths at 125 km distance from the shore (Valpy & English, 2017).

One consideration is that the higher electricity generation influences the capacity requirement for the electrolyser stack, which is proportionately reduced to 25 MW (from 30 MW), while the capacity of the wind farm itself drops from 25 MW to 20 MW due to the higher capacity factor. Simply put, since the wind farm is generating electricity more time during the day, a smaller rated capacity for the wind turbines is needed to provide the same amount of energy. Also less electrolyser capacity would be needed to produce the same amount of hydrogen, since the electricity generation hours per day are increased. Overall, the price per KWh generated from the wind farm is assumed to drop to 0.054 €/KWh in 2025 (from 0.0687 €/KWh in 2019).

The International Renewable Energy Agency has carried an analysis of projected future costs for PEM and Alkaline water electrolysers. By the year 2025, Taibi et al. (2018) project CAPEX costs of 700 €/KW, OPEX of 2% of installed capacity for PEM electrolysers and 210 €/KW for stack replacements. While alkaline electrolysers were selected in the original system boundaries, PEM electrolysers would

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[11] Capacity factors in offshore projects are not just location dependant, but are also highly influenced by design choices and trade-offs between selecting appropriate blade costs, electrical components and grid connection costs

better handle intermittent wind generation and demand similar energy consumption per KG H_2 produced (52 KWh/Kg H_2). Lifetime of PEM electrolysers are expected to be in the 50,000 hour range, which renders no major replacement over the project lifetime.

Finally, the third largest cost contributor is the cost of storage. Storage costs can drastically drop in case of the presence of a geologic reservoir such as salt caverns or depleted oil and gas reservoirs (Rustagi & Soto, 2017). Storage costs in geologic structures range from 80-120 \$/Kg H_2 (at 80-160 bar) as opposed to 1100 \$/Kg H_2 at 450 bar in high pressure vessels (Ramsden et al., 2008; Rustagi & Soto, 2017). That being said, cost reductions for large-scale, high-pressure storage tanks are difficult to predict, especially that the technology has not yet been developed yet and that high-pressure tank costs are typically driven by high material costs and complex manufacturing processes with specialized equipment (Veenstra & Adams, 2017).

In the methanol production system, the most significant costs were the solar panels, system installment costs and the *ZEF* micro-plants. Methanol shipping costs are expected to remain the same, if not increase, since the shipping industry is highly influenced by the global oil and gas prices (UNCTAD, n.d.). The methanol production micro-plants are still in development, and the costs cited in this research are based on financial models developed by the company. Therefore, no long-term future costs projection are yet developed.

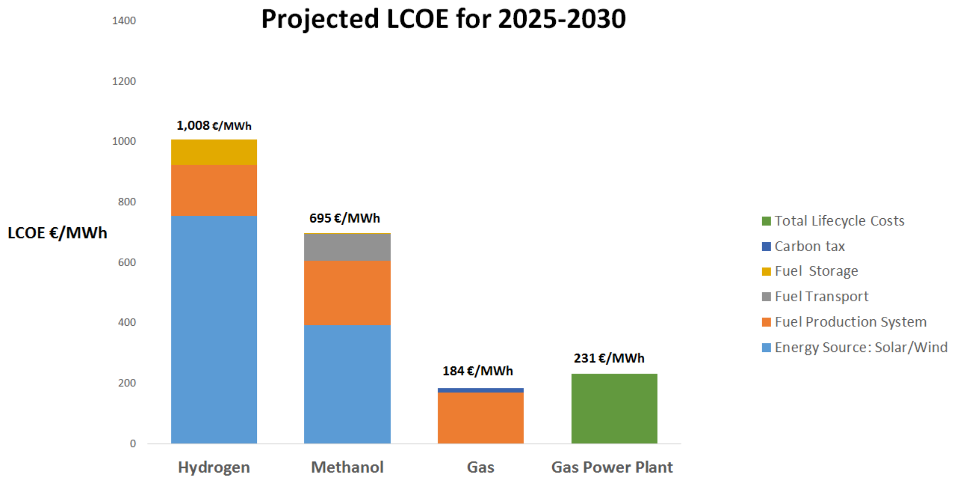

Figure 24: Projection for levelized cost of energy from both alternative fuels in 2025-2030

With regards to solar PV modules, costs have been steadily declining for several decades. Module costs have decreased by 75% from 2009 to 2014 (Van Den Akker, 2017). Mayer et al. (2015) have analyzed historic module costs since 1980, and report that historically prices have dropped by 20% for each duplication of the number of panels produced. Over the same period, this constitutes an average learning rate of 19-23% (Mayer et al., 2015). The authors predict similar future drops in module prices as the global demand forecast for PV modules continues to rise under different scenarios. A pessimistic scenario entails demand rises from 40 to 175 GW capacity from 2014-2050, corresponding to price drops of around 42%. Solar PV modules are the only relevant component for the ZEF production system since the PV system is not connected to the grid. The solar modules typically constitute 30-50 % of PV system costs, with the balance of system (BOS) constituting the rest (Van Den Akker, 2017). Van Den Akker (2017) predicts PV total system costs to drop to 1060-1380 \$/KW in the next decade. The author also predicts that the BOS has a bigger potential to drop with a larger margin. Therefore it was assumed that the PV modules would contribute to 50% of the future system costs, which would be 610 \$/KW. Site preparation costs are assumed to remain the same as in the base scenario, as they are mainly motivated by labour and land costs.

Table 24 projects the predicted levelized cost of energy from both fuel production systems. Methanol is projected to remain less expensive per MWh produced from the peak power plant. However, the difference in cost is reduced compared to the base case of current cost estimates (figure 18). The motivation behind this is the optimism in the industry for cost reductions for electrolysers and hydrogen storage tanks. Hydrogen storage can be further reduced significantly if geologic storage is used instead of high pressure storage tanks, but this is not selected in this comparison since the technology is geographically dependant. Methanol production on the other hand experiences smaller price reductions, since there is less room for technological improvements (only solar panels are projected to drop).

	Criteria weight				**Hydrogen Score**	**Methanol Score**
	Economic	*Technical*	*Environmental*	*Social*		
Equipment manufacturer	53%	30%	11%	6%	0.505	0.495
Policymaker	32%	46%	6%	16%	0.468	0.531
Fuel-producer	17%	8%	33%	42%	0.573	0.427
Investor	58%	27%	10%	5%	0.483	0.517

Table 24: Alternative fuel scores for all stakeholders (cost projections for 2025-2030)

In this scenario, only the economic criteria were altered based on realistic, future cost estimates. The scores show that the stakeholders do not agree on one alternative fuel, with policymakers and investors in favour of investing in methanol, while equipment manufacturers and fuel-producers are in favour of investing in hydrogen.

5.2.2 Fuel blending

In this scenario, half of the fuel requirements for the power plants are assumed to be provided by conventional fossil fuels. Hydrogen fuel is blended with natural gas for the hydrogen fuel case, and renewable methanol is blended with grey methanol produced from natural gas. Again, the effects on the levelized cost of energy and the environmental impact of the fuel blend are compared with using natural gas to fire the peak power plant. This scenario has several repercussions for the technical, economic and environmental criteria which will be discussed in further detail.

50-50 Natural Gas - Hydrogen

Gas turbines running on hydrogen-natural gas mixtures are already operational in several projects (Goldmeer, 2018a). Goldmeer (2018b) reports that *GE* has developed 70 gas turbines that run on hydrogen-containing fuels, with 25 of those running on fuels with at least 50% hydrogen contributing to 1 million generation hours. Therefore on the TRL scale, hybrid turbines are considered to be at TRL 9.

With regards to the economic assessment of hydrogen fuel blends, the cost estimates are based on the base cases for hydrogen and natural gas calculated in section 3.2.1 and 3.2.3. Where natural gas costs include the fuel costs and carbon tax, while the hydrogen costs cover the production, compression and storage of hydrogen. The ratio of both fuels in the gas turbine is assumed to be at 50-50.

50-50 Green and Grey methanol

Currently, conventional methanol is primarily produced using synthetic gas (syn-gas) as the main feed-stock. Syn-gas is a mixture of CO, H_2 and some CO_2 and is produced by steam reformation of natural gas, coal and increasingly biomass (Biernacki et al., 2018). When using natural gas as feed-stock, steam methane reforming (SMR) typically takes place in a nickel-based (NiO/Al_2O_3) catalytic reactor in 700–1000 °C and 10–45 bar (Lerner et al., 2018). The reaction is highly endothermic (equation 9), and is typically fired by natural gas which contributes to the carbon emissions of the chain.

$$CH_4 + H_2O \rightarrow CO + 3H_2 \tag{9}$$

At elevated temperature (250 °C) and pressure (50 bar), the syn-gas is fed into a fixed bed reactor reactor vessel in the presence of a catalyst[12] to produce methanol and water as a byproduct (Biernacki et al., 2018).

$$CO + 2H_2 \rightarrow CH_3OH \tag{10}$$

$$CO2 + 3H_2 \rightarrow CH_3OH + H_2O \tag{11}$$

The environmental impact of methanol production is obtained from Sima-pro. The included processes are the raw material use, processing energy requirement and estimated catalyst use [13]. The Ecoinvent process selected is specific for steam reforming of natural gas, and assumes the excess hydrogen is burnt in the furnace. Methanol production has a global warming potential of 0.791 Kg CO_2, and an ozone formation of 0.00101 Kg NO_x per Kg methanol produced. The GWP is validated with scientific literature, where the estimate is 0.6-1.5 Kg CO_2/Kg methanol produced (Bellotti et al., 2017).

Grey methanol can be regarded as a commodity with a stable global price (Haain, 2012). Figure 25 displays the methanol price in a variety of markets in the period 2016-2019. The contract price for methanol in the Rotterdam market was 400$/tonne (357 €/tonne) in 2019. This cost is assumed for 50% of the methanol fuel used by the turbine throughout the project lifetime. It is worth mentioning that the global price of grey methanol is not strictly tied to oil prices, and its price tends to be somewhat stable (Haain, 2012). The reason behind this being the variety of ways by which methanol can be produced from coal, natural gas, oil distillates and refuse-derived-fuels (Haain, 2012).

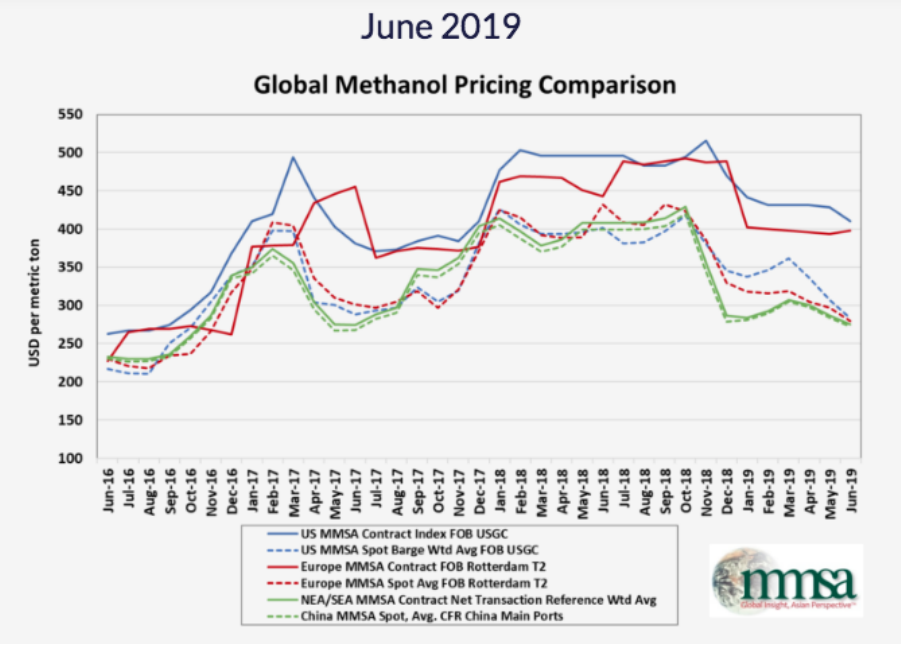

Figure 25: Methanol market price for the period 2016-2019 (MMSA, 2019)

The economic impact of fuel blending is shown in fig. 26. The analysis reveals that fuel blending of hydrogen with natural gas reduces energy generation costs significantly. While for methanol, fuel

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[12] The catalyst is typically made of $CuO/ZnO/Al_2O_3$

[13] 3 different catalysts are used for desulphurisation, steam reforming and methanol synthesis

blending with grey methanol reduces costs to some extent, however this leads to the added cost of purchasing carbon emission allowance to offset the emissions from grey methanol. No carbon emission tax is assumed for the green methanol, since the *ZEF system* is assumed to capture an equivalent amount of the carbon emitted during methanol production.

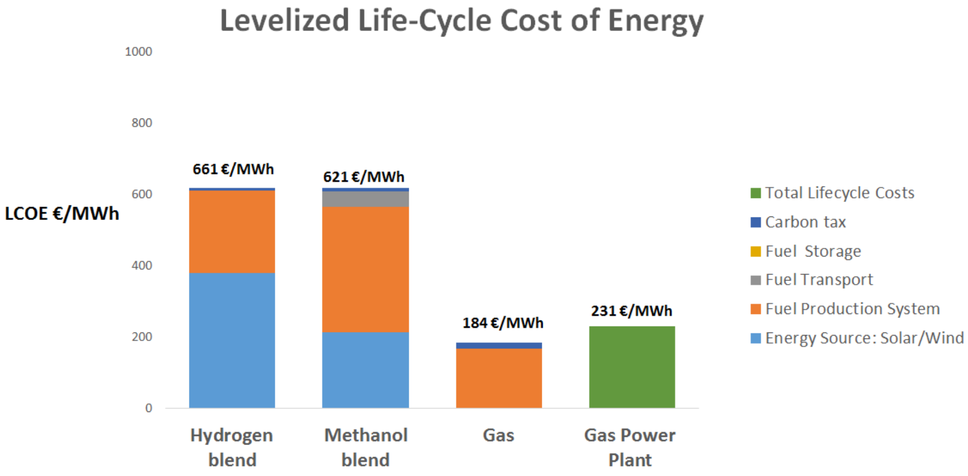

Figure 26: Comparison of levelized cost of energy from 50-50 Hydrogen-Natural gas blend 50-50 green-grey methanol blend, 100% natural gas for electricity generation from gas turbine all compared to power plant total costs

With regards to the environmental impact of fuel blending, figures 27, 28 show conflicting emissions on both environmental criteria. The assessment includes emissions from the entire value chain from production to combustion of renewable hydrogen, renewable methanol, grey methanol and natural gas. Renewable methanol blending with grey methanol (from natural gas) leads to lower NOx emissions compared to H_2-natural gas fuel blend. This is mainly due to methanol turbines releasing 80% less NOx emissions compared to natural gas (Turaga & Johnson, 2017). The GWP analysis reveals that hydrogen fuel blend is the cleanest alternative, followed by 100% natural gas, and the methanol blend being the heaviest CO_2 equiv. emitter.

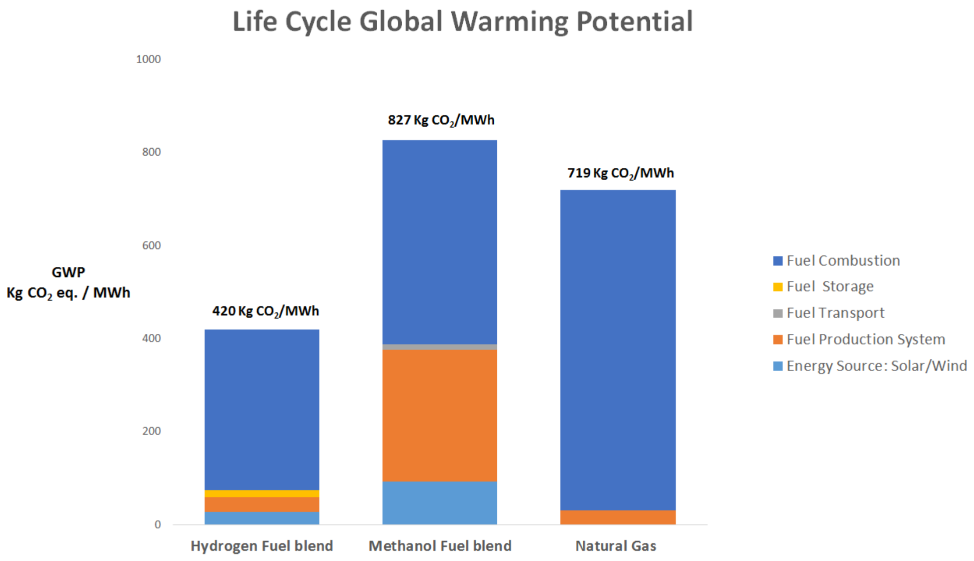

Figure 27: Life-cycle global warming potential of 50-50 Hydrogen-Natural gas blend, 50-50 green-grey methanol blend and 100% natural gas from a gas turbine

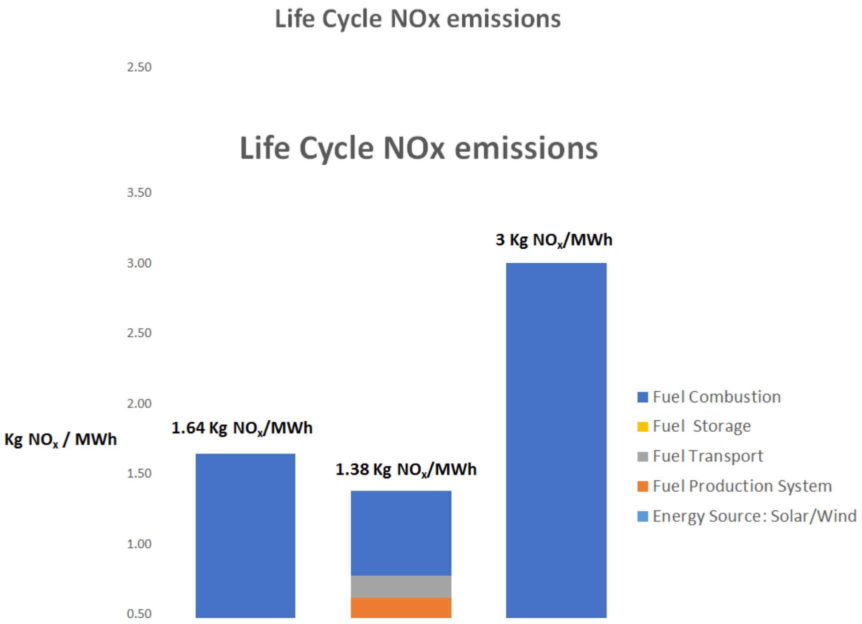

Figure 28: Life-cycle NOx of 50-50 Hydrogen-Natural gas blend, 50-50 green-grey methanol blend and 100% natural gas from a gas turbine

As for technical criteria, gas turbines running on hydrogen blends are commercially available, which raises the TRL of the turbines from level 5 (hydrogen base case) to level 9. The TRL for the rest of the components of the the hydrogen system, and the methanol system are assumed to be the same as the base case, since in both scenarios the same system components as the base case are needed to provide half of the fuel consumption.

The AHP scores for fuel blending conclusively show that hydrogen outperforms methanol as an alternative fuel for peak power generation. The use of natural gas massively reduces the cost of energy

	Criteria weight				Hydrogen Score	Methanol Score
	Economic	*Technical*	*Environmental*	*Social*		
Equipment manufacturer	53%	30%	11%	6%	0.549	0.451
Policymaker	32%	46%	6%	16%	0.564	0.435
Fuel-producer	17%	8%	33%	42%	0.573	0.426
Investor	58%	27%	10%	5%	0.544	0.456

Table 25: Alternative fuel scores for all stakeholders (fuel blending scenario)

generation, and the negative environmental impact of natural gas is offset with the use of hydrogen. On a cost basis, the use of conventional methanol from syn-gas as fuel for power generation is more expensive than simply using natural gas, since natural gas is indeed a feed-stock for conventional methanol production. The emissions from conventional methanol production and combustion massively increase the carbon footprint for methanol fuel blends. While the costs for both fuel blends are comparable, the environmental impact and technical criteria (energy efficiency & TRL) are more in favour of hydrogen-natural gas fuel blend.

5.3 Discussion

5.3.1 Criteria Weighting

Economic and technical criteria are the most relevant criteria for *most* decision-makers when selecting an alternative fuel to invest in. Environmental criteria were surprisingly less relevant to decision-makers, with the results consistent between the equipment manufacturers, policy-makers and investors. The interviewees gave two explanations for the low relevance of the environmental impact. The first reason being that since both alternative fuels are already produced using renewable energy sources, other criteria became of more relevance. However the results form the environmental assessment prove that there are still significant differences in environmental impact depending on the renewable energy source and alternative fuel selected. The second reason for a low environmental criteria weight is the relevance of the criterion for the specific subject. For example, while policy-makers generally give high priority for the environmental impact, the actual relevance of the GWP/NOx emissions for the case of peak power plants is less relevant since they run for only a few hours per year.

This opinion was contrasted by the criteria weighting of fuel producers. The fuel producer view was represented by the commercial team of an Oil and Gas company that is actively interested in ensuring their market status as future fuel provider. When investing in an alternative fuel, the highest priority is given to the social aspect, followed by the environmental impact. The interviewees elaborated on the relevance of the ”reputational” component with high emphasis on portraying the company as an environmentally responsible partner. As of yet, alternative fuels will not present a core revenue source for fuel producers (from an Oil & Gas background), and therefore higher priority is given to safeguarding the reputation of their operations.

In the interviews performed, decision-makers were asked to mention some of these criteria. Other relevant economic criteria were the return on investment, payback period and scale. Technical criteria such as the availability and compatibility of infrastructure, R&D needs Environmental and social criteria were more or less aligned with the stakeholders’ interest,

5.3.2 Fuel selection

Short-term future

For the near future, hydrogen fuel blending with natural gas can significantly reduce the negative environmental impact of current natural gas peak power plants. Hydrogen-fuel blend outperforms a 50-50 green-grey methanol blend on the technology readiness level, total system energy efficiency and global warming potential. Moreover, the levelized cost of energy is reduced almost by half from 1138 €/MWh (100% hydrogen fuel) to 662 €/MWh which is comparable to the fuel blended methanol alternative. Gas turbines operating on high hydrogen fuel blends are at commercial levels, and can handle hydrogen percentages of 10-70% (by volume) (Goldmeer, 2018b). By varying the amount of hydrogen in the fuel blend, the overall fuel costs and environmental impact can be controlled to meet power plant targets. While for the case of methanol, fuel blending of grey and green methanol is not a promising solution. While methanol is considered as a cleaner fuel compared to natural gas, emitting as much as 80% lower NOx and SOx, the carbon footprint for synthesizing methanol from natural gas and firing it in gas turbines emits higher CO_2 equivalent per MWh compared to simply using natural gas. Not to mention that hybrid methanol fuel (50% green, 50% grey) would be more than 3 times more expensive compared to natural gas. Therefore, there is an overwhelming support for hydrogen fuel blending over methanol among all four key stakeholders. This can prove to be enough impetus to encourage investment in the alternative fuel across the value chain from production to utilization.

Long-term future

For the long-term future of peak power plant fuel where the goal would be 100% renewable fuel, the AHP results are less conclusive. With current technology and economic criteria in mind, methanol slightly outperforms hydrogen as the preferred alternative for three out of the four stakeholders. When future costs projections for the different sub-components of both systems are incorporated, stakeholders are divided in terms of their alternative fuel of choice, with two prioritizing hydrogen and two choosing methanol.

This goes to show that in the long term, both fuels can play a role as an alternative fuel for peak power plants. The fuel selection might then be more geographically dependent. For example, in regions with high solar capacity and little natural gas supplies and absence of geological reservoirs for hydrogen storage, methanol will be the clear winner. While for regions with sufficient geological structures for hydrogen storage, such as salt caverns or depleted gas reservoirs, hydrogen may prove to be economically more viable since storage costs and technology requirements would decline dramatically. The utilization of the AHP method, combined with the LCA, TRL tools, economic indicators and key stakeholder input can be flexibly implemented to aid in the assessment of the alternative fuel of choice for a case by case basis.

Role of natural gas in peak power generation

Natural gas will continue to power gas turbines due to economical reasons, even with the carbon emission floor price implemented by the Dutch government on electricity producers. The 12.30 €/ton CO_2 by 2020, raised to 31.9 €/ton CO_2 in 2030 would only represent an increase of 8.7 % of the total natural fuel costs. For reference, at current technology costs, hydrogen fuel is more than 6 times more expensive than natural gas, and green methanol is around 4 times more expensive. Therefore, a carbon tax will never be sufficient to shift the status quo and push alternative fuels to replace natural gas in power generation. Policy-makers should seek other measures to shift investor behaviour in favour of alternative fuels, especially with regards to the long-term future alternative fuels since there is no clear preference among stakeholders, and higher risk of a wait-and-see strategy to reduce investment risks.

6 Conclusion & Recommendations

The AHP method is applied to reduce future uncertainty regarding which alternative fuel could power peak power plants in Rotterdam. While several case-specific choices were made to answer this question, the proposed method is flexible and can be applied to answer similar questions in the energy sector. For the case of selecting an alternative fuel to meet peak demand, hydrogen and methanol were compared across four major criteria (economic, technical, environmental and social) which are elaborated into nine sub-criteria. Methanol production was modeled after the *ZEF* production system, which relies on solar PV to power a system of direct air capture of CO^2, water electrolysis and methanol synthesis to produce methanol. As for hydrogen production, a renewable energy source is assumed to be from the expanding offshore wind projects in the North Sea. Hydrogen is produced locally via alkaline electrolysis, compressed and stored on-site using the transmitted electricity.

Both alternatives are assessed from ”well to wheel” by including the entire fuel life-cycle from production, transportation, storage and eventually utilization in a gas turbine fuel. Experts from the energy industry representing five key stakeholders for alternative fuel adoption are interviewed in order to weigh the major and sub-criteria.

The life-cycle approach to the assessment uncovers many challenges across the value chain which decision-makers should be aware of. For example, before heavy investment in hydrogen turbines and a hydrogen economy, decision-makers should be aware of the technical status with hydrogen compression storage as well as the economic and social challenges. Similarly, a fuel producer should also understand the priorities and level of commitment of of other vital stakeholders for the adoption of the alternative fuel, these are the equipment manufacturers, investors and policy makers.

6.1 Answers to research questions

1. ***What are relevant criteria for policy makers that play a role in the decision making process?***

   Broadly speaking, multi-criteria decision making researchers have identified four major criteria groups for decision makers interested in sustainable energy systems; economic, technical, environmental and social criteria. Depending on the nature of the decision at hand, the design requirements and choices, these four major criteria can be elaborated into sub-criteria. The objective of this research is to identify which alternative fuel shapes the near and far future of peak power generation. A significant design requirements is that no special geological structure can be utilized for energy storage. Also, only technologies that are either commercially proven, at pilot demonstration stage or undergoing current research and development are assessed. This has led to the identification of two viable alternative fuels; green hydrogen produced locally, and green methanol imported from abroad.

   A literature review is carried to identify the most significant criteria for decision makers. CAPEX and OPEX indicators are consistently applied for economic assessments and are translated to LCOE to allow for a straightforward comparison. Global warming potential (CO_2 equivalent) and Nitrous oxide emissions are of high relevance in discussions on power generation from gas turbines. Also, decision makers are interested in the ”hidden” carbon footprint of renewable energy, and the improvement (if any) achieved by replacing natural gas with alternative fuels. With regards to social criteria, since fuel import is proposed in the case of methanol as opposed to local hydrogen production, this brings up questions on the significance of job creation and security of supply to the selection of an alternative fuel. System safety is also an important criterion for decision makers, especially with the ”explosive” reputation of hydrogen as a fuel. Design choices played a role in the selection of the technical sub-criteria. Since hydrogen and methanol (a liquid organic hydrogen carrier) are being compared, energy efficiency of the entire life-cycle of fuel production and eventual utilization is of interest. Also, since the design requirement allows for a range of technology maturity levels (from commercial to R&D phase), the technology readiness level becomes a relevant indicator.

2. ***How does the production, transport, storage and utilization of the selected alternative fuels perform on the relevant criteria?***

   In order to answer this question, multiple assessments are carried addressing the different dimensions of alternative fuels. An environmental life-cycle assessment reveals that hydrogen is strongly more preferred than methanol both in terms of GWP and NOx emissions. From well to wheel, the renewable energy source required for fuel production is the biggest contributor to the global warming potential indicator. Whereas methanol combustion contributes to fairly higher NOx emissions compared to hydrogen, yet both alternatives perform significantly better on GWP and NOx emissions compared to natural gas. With regards to the economic aspects, the same reasoning applies, with the energy source constituting the majority of the life-cycle costs. Hydrogen proves to be much more expensive based on the cost of offshore wind costs, which is highly influenced by the need for grid connection, expensive storage for the fuel. Methanol is the cheaper alternative due to the absence of a grid connection, and much cheaper fuel production and storage costs.

   With regards to the technical criteria, electricity generation from hydrogen is overall slightly more efficient than from methanol. The main contributor to this is the longer reaction chain for methanol production, coupled with the lower efficiency of combustion according to existing turbine technology. That being said, the technological maturity across the fuel value chain is slightly in favour of methanol fuel, due to its compatibility with existing oil infrastructure in storage, transport and combustion. Finally, the social criteria are analysed for both alternatives. In terms of safety during transport, storage and operation, both fuels are very comparable. In areas with good ventilation, gaseous hydrogen is considered safer than methanol, while the opposite is the case in enclosed areas based on their flammability range and toxicity levels.With regards to other social criteria, local hydrogen production is preferred in terms of job creation and security of supply over importing methanol fuel.

3. ***How can the criteria be weighed and combined to allow for a comparison of the alternatives?***

   This research applies the Analytical Hierarchy Process (AHP) as the multi-criteria decision-making tool, and proposes some modifications to the method. The method is popular among researchers analysing sustainable energy systems, as it can incorporate both qualitative and quantitative criteria to simplify complex decision-making problems. In the AHP method, decision-making criteria and possible alternatives are identified. Then researchers use input from decision makers to give global weights to each criterion. The performance of each alternative is assessed for each criterion, and the results of the assessment are synthesized with the criteria weights to give a final fuel score. The alternative with the highest score is then the preferred option for a a given stakeholder.

   In academic literature, the current convention is for the researcher to either carry the criteria weighting themselves, or through survey instruments distributed to energy professionals from industries and universities. In the latter case, feedback from all survey is averaged to give one set of criteria weights. This research proposes that criteria weighting should be carried by multiple stakeholder to indicate the positions of all the relevant decision-makers for the adoption of an alternative. By doing so more information can be deduced on if there is agreement/disagreement among stakeholders, and which criteria should be addressed to ensure future adoption. This research incorporated the views of 4 stakeholder groups, which are the energy policy-makers, energy companies, investors and equipment manufacturers.

   Of course, specific system boundaries and design requirements are assumed, which have implications on the design choices and fuels evaluated. The AHP fuel scores conclude that with current costs and technological advancements, three out of four stakeholders groups would prefer methanol over hydrogen as an alternative fuel for peak power plants in Rotterdam. This is driven mainly by the economic and technical advantages of utilizing methanol as a fuel.

4. ***How robust are the outcomes to the results of the analysis?***

   A sensitivity assessment is proposed to address the robustness of the results. In existing AHP literature, researchers carry sensitivity assessments by varying the subjective component of the AHP score calculation, which is the criteria weighting. So for example, carrying scenarios where all sub-criteria are given equal weights, or where one criterion is given a 60% weight each time. This research proposes implementing the sensitivity analysis on the objective part of the AHP score, i.e. the fuel performance. The scenarios are focused on the criteria with the biggest weight for most stakeholders. In the first scenario, future cost projections of both alternative fuels are incorporated. The results show that hydrogen fuel is expected to drop in costs by a bigger margin than methanol. This shift shows that stakeholders are split between supporting both alternative fuels. In the second scenario, 50:50 fuel blending is proposed, which has implications on the technical, environmental and economic criteria. Methanol is to be blended with grey methanol produced from natural gas, while hydrogen can be blended with natural gas as has been commercially proven in operating gas turbines. The AHP scores show that in this case, hydrogen fuel is fully supported by all stakeholders.

5. ***What can be recommended from this analysis for the short-term and long-term of power plant alternative fuels?***

   For the short-term, hydrogen fuel blending with natural gas can significantly reduce the negative environmental impact of current natural gas peak power plants. Hydrogen-fuel blend outperforms a 50-50 green-grey methanol blend on the technology readiness level, total system energy efficiency and global warming potential. Gas turbines operating on high hydrogen fuel blends are commercially available, and can handle hydrogen percentages of 10-70%. By varying the amount of hydrogen in the fuel blend, the overall fuel costs and environmental impact can be controlled to meet power plant targets. While for the case of methanol, fuel blending of grey and green methanol is not a promising solution. The carbon footprint for synthesizing methanol from natural gas and firing it in gas turbines emits higher CO_2 equivalent per MWh compared to simply using natural gas. The biggest challenge for the hydrogen fuel utilization in Rotterdam will be large scale storage, and should be addressed by stakeholders the Dutch energy sector. As for the long-term, future of peak power plant fuel where the goal would be 100% renewable fuel, both hydrogen and methanol can play a role as an alternative fuel. With current technology and economic criteria in mind, methanol slightly outperforms hydrogen as the preferred alternative for most stakeholders. When future costs projections for the different sub-components of both systems are incorporated, stakeholders are divided in terms of their alternative fuel of choice.

6.2 Limitations and future research

In this section, the limitations to both the assessments tools carried and the modifications proposed to the AHP method are discussed in more detail. Finally, recommendations for future research are made.

One of the limitations of the proposed method of criteria weighting, is that different stakeholder may indeed rely on different decision-making criteria to those analysed in this research. Policy makers may for instance be more interested in social factors whereas equipment manufacturers may be interested in the technical and economic criteria. This is slightly addressed with the pairwise comparison method, where if one criterion is of less interest to stakeholder, they can simply give it least priority in the decision making process. However this does not address the limitation of missing criteria. In future research, this can be addressed by carrying the criteria weighting and interviews prior to the fuel assessments. In this research, the initial criteria selection was selected by means of a literature review, to avoid overlooking any critical criteria.

With regards to the outcomes of this research, one significant shortcoming of this research is the small sample size of stakeholders that were interviewed. Since there was a constraint of time and resources during this research, the choice was made to conduct interviews with a small sample of experts from the Dutch energy sector. The interviewees are experienced in either consulting or involved in decision-making for sustainable energy projects at their companies. That being said, this research emphasises the fuel assessment on the selected criteria, rather than the conclusions from the stakeholder weightings.

Another limitation of this research is the gas turbine selection for both alternative fuels. The selection of turbine affects several decision making criteria, as it affects the amount of fuel needed for a certain energy output. This in turn has an effect on the environmental impact and fuel costs. The hydrogen turbine efficiency (35 %) in this research is significantly higher than the methanol turbine efficiency (28 %). While this is based on existing turbine technology, more research is needed on alternative fuel turbines in general in terms of their efficiency and both their CO_2 and NOx emissions.

There are several ways future research can utilize and build on the results of this research. For the case of alternative fuels for peak power generation in Rotterdam, the increased costs and improved environmental impact of carbon capture and storage, and implementing NOx control can be compared with the results of this assessment. This also reveal the role carbon capture can play . A similar comparison can be carried with the use of large scale battery storage to fulfill peak demand compared to alternative fuels.

As for the proposed modifications to the AHP method, future research should experiment with carrying the interviews prior to the assessment, in order to account for other major criteria for decision makers during the assessment. Also, the tool can be used tackle collaborative decision making problems by ensuring multiple stakeholders are engaged.

References

Aakko-Saksa, P. T., Cook, C., Kiviaho, J., & Repo, T. (2018, 8). Liquid organic hydrogen carriers for transportation and storing of renewable energy – Review and discussion. *Journal of Power Sources*, *396*, 803–823. Retrieved from `https://www.sciencedirect.com/science/article/pii/S0378775318303483` doi: 10.1016/J.JPOWSOUR.2018.04.011

Abdel-Aal, H. K., Sadik, M., Bassyouni, M., & Shalabi, M. (2005). A new approach to utilize Hydrogen as a safe fuel. *International Journal of Hydrogen Energy*. doi: 10.1016/j.ijhydene.2005.07.007

Acar, C., Beskese, A., & Temur, G. T. (2019, 3). A novel multicriteria sustainability investigation of energy storage systems. *International Journal of Energy Research*. Retrieved from `http://doi.wiley.com/10.1002/er.4459` doi: 10.1002/er.4459

Acar, C., & Dincer, I. (2014). Comparative assessment of hydrogen production methods from renewable and non-renewable sources. *International Journal of Hydrogen Energy*, *39*(1), 1–12. Retrieved from `http://dx.doi.org/10.1016/j.ijhydene.2013.10.060` doi: 10.1016/j.ijhydene.2013.10.060

Adamson, K. A., & Pearson, P. (2000). Hydrogen and methanol: A comparison of safety, economics, efficiencies and emissions. *Journal of Power Sources*. doi: 10.1016/S0378-7753(99)00404-8

Adnan, Z. A. (2018). *Renewable Power Generation Costs in 2017* (Tech. Rep.). International Renewable Energy Agency. Retrieved from `www.irena.org`

Aksyutin, O. E., Ishkov, A. G., Romanov, K. V., & Grachev, V. A. (2018). The carbon footprint of natural gas and its role in the carbon footprint of the energy production. *International Journal of GEOMATE*. Retrieved from `https://doi.org/10.21660/2018.48.59105` doi: 10.21660/2018.48.59105

Al-Yahyai, S., Charabi, Y., Gastli, A., & Al-Badi, A. (2012, 8). Wind farm land suitability indexing using multi-criteria analysis. *Renewable Energy*, *44*, 80–87. Retrieved from `https://linkinghub.elsevier.com/retrieve/pii/S0960148112000158` doi: 10.1016/j.renene.2012.01.004

Amer, M., & Daim, T. U. (2011). Selection of renewable energy technologies for a developing county: A case of Pakistan. *Energy for Sustainable Development*, *15*(4), 420–435. Retrieved from `http://dx.doi.org/10.1016/j.esd.2011.09.001` doi: 10.1016/j.esd.2011.09.001

Andersson, J., & Grönkvist, S. (2019). Large-scale storage of hydrogen. *International Journal of Hydrogen Energy*, *4*. Retrieved from `https://linkinghub.elsevier.com/retrieve/pii/S0360319919310195` doi: 10.1016/j.ijhydene.2019.03.063

Ball, M., & Weeda, M. (2015). The hydrogen economy - Vision or reality? *International Journal of Hydrogen Energy*, *40*(25), 7903–7919. Retrieved from `http://dx.doi.org/10.1016/j.ijhydene.2015.04.032` doi: 10.1016/j.ijhydene.2015.04.032

Barthelemy, H., Weber, M., & Barbier, F. (2017). Hydrogen storage: Recent improvements and industrial perspectives. *International Journal of Hydrogen Energy*, *42*(11), 7254–7262. Retrieved from `http://dx.doi.org/10.1016/j.ijhydene.2016.03.178` doi: 10.1016/j.ijhydene.2016.03.178

Beims, R., Simonato, C., & Wiggers, V. (2019). Technology readiness level assessment of pyrolysis of trygliceride biomass to fuels and chemicals. *Renewable and Sustainable Energy Reviews*. doi: 10.1016/j.rser.2019.06.017

Bellotti, D., Rivarolo, M., Magistri, L., & Massardo, A. F. (2017). Feasibility study of methanol production plant from hydrogen and captured carbon dioxide. *Journal of CO2 Utilization*, *21*(July), 132–138. Retrieved from `https://doi.org/10.1016/j.jcou.2017.07.001` doi: 10.1016/j.jcou.2017.07.001

Beylot, A., Payet, J. , Puech, C., Adra, N., Jacquin, P., Blanc, I., & Beloin-Saint-Pierre, D. (2014). Environmental impacts of large-scale grid-connected ground-mounted PV installations. *Renewable Energy*. doi: 10.1016/j.renene.2012.04.051

Biernacki, P., Röther, T., Paul, W., Werner, P., & Steinigeweg, S. (2018). Environmental impact of the excess electricity conversion into methanol. *Journal of Cleaner Production*, *191*, 87–98. doi: 10.1016/j.jclepro.2018.04.232

Brown, P., Fadok, J., Manager, P., Doe, S. ., Hydrogen, A., & Program, T. (2007). *Siemens Gas Turbine H2 Combustion Technology for Low Carbon IGCC* (Tech. Rep.). Retrieved from `https://www.globalsyngas.org/uploads/eventLibrary/29BROW.pdf`

Brunelli, M. (2015). *Introduction to the Analytic Hierarchy Process*. Springer. Retrieved from `http://dx.doi.org/10.1007/978-3-319-12502-2` doi: 10.1007/978-3-319-12502-2

Buchner, G. A., Stepputat, K. J., Zimmermann, A. W., & Schomäcker, R. (2019). Specifying Technology Readiness Levels for the Chemical Industry. *Industrial and Engineering Chemistry Research*, 6957–6969. Retrieved from `https://pubs.acs.org/doi/10.1021/acs.iecr.8b05693` doi: 10.1021/acs.iecr.8b05693

Burkhardt, J., Patyk, A., Tanguy, P., & Retzke, C. (2016). Hydrogen mobility from wind energy – A life cycle assessment focusing on the fuel supply. *Applied Energy*, *181*, 54–64. Retrieved from `http://dx.doi.org/10.1016/j.apenergy.2016.07.104` doi: 10.1016/j.apenergy.2016.07.104

Campos-Guzmán, V., García-Cáscales, M. S., Espinosa, N., & Urbina, A. (2019). Life Cycle Analysis with Multi-Criteria Decision Making: A review of approaches for the sustainability evaluation of renewable energy technologies. *Renewable and Sustainable Energy Reviews*, *104*(January), 343–366. Retrieved from `https://doi.org/10.1016/j.rser.2019.01.031` doi: 10.1016/j.rser.2019.01.031

Carpetis, C. (1988). Storage, Transport and Distribution of Hydrogen. In *Hydrogen as an energy carrier* (pp. 249–289). Berlin, Heidelberg: Springer Berlin Heidelberg. Retrieved from `http://link.springer.com/10.1007/978-3-642-61561-0_10` doi: 10.1007/978-3-642-61561-0{_}10

Castellani, B., Rinaldi, S., Bonamente, E., Nicolini, A., Rossi, F., & Cotana, F. (2018). Carbon and energy footprint of the hydrate-based biogas upgrading process integrated with CO2 valorization. *Science of the Total Environment*, *615*, 404–411. Retrieved from `https://doi.org/10.1016/j.scitotenv.2017.09.254` doi: 10.1016/j.scitotenv.2017.09.254

Castillo Ramírez, A., Mejía Giraldo, D., & Muñoz Galeano, N. (2018, 3). Large-scale solar PV LCOE comprehensive breakdown methodology. *CT&F - Ciencia, Tecnología y Futuro*, *7*(1), 117–136. doi: 10.29047/01225383.69

Chatzimouratidis, A. I., & Pilavachi, P. A. (2008). Multicriteria evaluation of power plants impact on the living standard using the analytic hierarchy process. *Energy Policy*, *36*(3), 1074–1089. doi: 10.1016/j.enpol.2007.11.028

Chatzimouratidis, A. I., & Pilavachi, P. A. (2009, 3). Technological, economic and sustainability evaluation of power plants using the Analytic Hierarchy Process. *Energy Policy*, *37*(3), 778–787. Retrieved from `https://linkinghub.elsevier.com/retrieve/pii/S0301421508005880` doi: 10.1016/j.enpol.2008.10.009

Chiesa, P., Lozza, G., & Mazzocchi, L. (2005). Using Hydrogen as Gas Turbine Fuel. *Journal of Engineering for Gas Turbines and Power*, *127*(1), 73. doi: 10.1115/1.1787513

Cook, W. D., & Kress, M. (1988, 12). Deriving weights from pairwise comparison ratio matrices: An axiomatic approach. *European Journal of Operational Research*, *37*(3), 355–362. Retrieved from `https://www.sciencedirect.com/science/article/pii/0377221788901981` doi: 10.1016/0377-2217(88)90198-1

Crawford, G., & Williams, C. (1985, 12). A note on the analysis of subjective judgment matrices. *Journal of Mathematical Psychology*, *29*(4), 387–405. Retrieved from `https://www.sciencedirect.com/science/article/pii/0022249685900021` doi: 10.1016/0022-2496(85)90002-1

Crotogino, F. (2016, 1). Larger Scale Hydrogen Storage. *Storing Energy*, 411–429. Retrieved from `https://www.sciencedirect.com/science/article/pii/B9780128034408000208` doi: 10.1016/B978-0-12-803440-8.00020-8

Curran, M. A. (2006). *Life Cycle Assessment: Principles and Practice*. National Risk Management Research Laboratory Office of research and Develeopment U.S. Environmental Protection Agency, Cincinnati, Ohio.

Daim, T., & Taha, R. (2013). Multi-Criteria Applications in Renewable Energy Analysis, a Literature Review. *Green Energy and Technology*, *60*, 17–31. doi: 10.1007/978-1-4471-5097-8

Day, W. H. (2016). *Methanol fuel in commercial operation on land and sea* (Tech. Rep.). Gas Turbine World. Retrieved from `http://www.methanol.org/wp-content/uploads/2016/12/Methanol-Nov-Dec-2016-GTW-.pdf`

De Rose, A., Buna, M., Strazza, C., Olivieri, N., Stevens, T., Leen, P., & Daniel, T.-J. (2017). *Technology Readiness Level : Guidance Principles for Renewable Energy technologies* (Tech. Rep.). doi: 10.2777/863818

Di Profio, P., Arca, S., Rossi, F., & Filipponi, M. (2009). Comparison of hydrogen hydrates with existing hydrogen storage technologies: Energetic and economic evaluations. *International Journal of Hydrogen Energy*, *34*(22), 9173–9180. Retrieved from `http://dx.doi.org/10.1016/j.ijhydene.2009.09.056` doi: 10.1016/j.ijhydene.2009.09.056

Durairaj, S., Sathiyasekar, K., & Ilangkumaran, M. (n.d.). Multi-criteria decision making approach to evaluate optimum fuel in diesel power generator. *International Journal of Applied Engineering Research*, *9*(23), 22867–22885.

Eid, C., Koliou, E., Valles, M., Reneses, J., & Hakvoort, R. (2016). Time-based pricing and electricity demand response: Existing barriers and next steps. *Utilities Policy*. doi: 10.1016/j.jup.2016.04.001

Enbar, N., Weng, D., & Klise, G. (2015). *Budgeting for Solar PV Plant Plant Operations and Maintenance: Practice and Pricing* (Tech. Rep.). he Electric Power Research Institute. Retrieved from `https://prod-ng.sandia.gov/techlib-noauth/access-control.cgi/2016/160649r.pdf`

Energy Information Administration, U. (2018). *Electric Power Annual 2017 Electric Power Annual 2017 Revision Notice* (Tech. Rep.). Retrieved from `www.eia.gov`

Erdoğan, S., Balki, M. K., Aydın, S., & Sayin, C. (2019, 4). The best fuel selection with hybrid multiple-criteria decision making approaches in a CI engine fueled with their blends and pure biodiesels produced from different sources. *Renewable Energy*, *134*, 653–668. Retrieved from `https://www.sciencedirect.com/science/article/pii/S096014811831379X` doi: 10.1016/J.RENENE.2018.11.060

EZK. (2016). *Energy Report: Transition to sustainable energy* (Tech. Rep.). The Hague: Ministry of Economic Affairs and Climate Policy. Retrieved from `https://www.government.nl/documents/reports/2016/04/28/energy-report-transition-tot-sustainable-energy`

Faunce, T. A., Prest, J., Su, D., Hearne, S. J., & Iacopi, F. (2018, 10). On-grid batteries for large-scale energy storage: Challenges and opportunities for policy and technology. *MRS Energy & Sustainability*, *5*, E11. Retrieved from `https://www.cambridge.org/core/product/identifier/S2329222918000119/type/journal_article` doi: 10.1557/mre.2018.11

Fekete, J. R., Sowards, J. W., & Amaro, R. L. (2015, 9). Economic impact of applying high strength steels in hydrogen gas pipelines. *International Journal of Hydrogen Energy*, *40*(33), 10547–10558. doi: 10.1016/j.ijhydene.2015.06.090

Ferretti, N. (2018). *PV Module Cleaning - Market Overview and Basics* (Tech. Rep.). Photovolatik-Institut Berlin, Pi AG. Retrieved from `https://www.pi-berlin.com/images/pdf/publication/White%20Paper%20-%20PV%20Module%20Cleaning%20-%20Market%20Overview%20and%20Basics.pdf`

Franza, L. (2014). *Long-term gas import contracts in Europe: The evolution in pricing mechanisms* (Tech. Rep.). Clingendael International Energy Programme (CIEP). Retrieved from `www.clingendaelenergy.com`

Gambhir, A., Few, S., Nelson, J., Hawkes, A., Schmidt, O., & Staffell, I. (2017). Future cost and performance of water electrolysis: An expert elicitation study. *International Journal of Hydrogen Energy*, *42*(52), 30470–30492. Retrieved from `https://doi.org/10.1016/j.ijhydene.2017.10.045` doi: 10.1016/j.ijhydene.2017.10.045

Ghandehariun, S., & Kumar, A. (2016a). Life cycle assessment of wind-based hydrogen production in Western Canada. *International Journal of Hydrogen Energy*, *41*(22), 9696–9704. Retrieved from `http://dx.doi.org/10.1016/j.ijhydene.2016.04.077` doi: 10.1016/j.ijhydene.2016.04.077

Ghandehariun, S., & Kumar, A. (2016b). Life cycle assessment of wind-based hydrogen production in Western Canada. *International Journal of Hydrogen Energy*, *41*(22), 9696–9704. Retrieved from `http://dx.doi.org/10.1016/j.ijhydene.2016.04.077` doi: 10.1016/j.ijhydene.2016.04.077

Gielen, D. (2012). *Rebewable Energy Technologies: Cost analysis series- Solar Photovoltaics* (Tech. Rep.). International Renewable Energy Agency. Retrieved from `www.irena.org/Publications`

Gökalp, I., & Lebas, E. (2004, 8). Alternative fuels for industrial gas turbines (AFTUR). *Applied Thermal Engineering*, *24*(11-12), 1655–1663. Retrieved from `https://www.sciencedirect.com/science/article/abs/pii/S1359431103003752` doi: 10.1016/J.APPLTHERMALENG.2003.10.035

Goldmeer, J. (2018a). *Fuel flexible gas turbines as enablers for a low or reduced carbon energy ecosystem* (Tech. Rep.). General Electric Company. Retrieved from `https://www.ge.com/content/dam/gepower/global/en_US/documents/fuel-flexibility/GEA33861%20-%20Fuel%20Flexible%20Gas%20Turbines%20as%20Enablers%20for%20a%20Low%20Carbon%20Energy%20Ecosystem.pdf`

Goldmeer, J. (2018b). Fuel Flexible Gas Turbines as Enablers for a Low or Reduced Carbon Energy Ecosystem. *Electrify Europe*(February).

Gonzalez-Rodriguez, A. G. (2017). Review of offshore wind farm cost components. *Energy for Sustainable Development*, *37*, 10–19. Retrieved from `http://dx.doi.org/10.1016/j.esd.2016.12.001` doi: 10.1016/j.esd.2016.12.001

Greunsven, J. (2017). *TenneT Market Review 2017 – Electricity market insights* (Tech. Rep.). TenneT. Retrieved from `https://www.ensoc.nl/files/20180405-market-review-2017-bron-tennet.pdf`

Grond, L., & Holstein, J. (2014). *Power-to-gas: Climbing the technology readiness ladder* (Tech. Rep.). DNV GL. Retrieved from `www.northseapowertogas.com`

Haain, Y. (2012). *Methanol - Gaining Twice: Improving both the quality of the air as well as providing a reliable electricity supply* (Tech. Rep.). Israel Electric. Retrieved from `http://www.methanol.org/wp-content/uploads/2016/06/Dor-Chemicals-Methanol-Turbine-Demo-Jerusalum-Post.pdf`

Hadjipaschalis, I., Poullikkas, A., & Efthimiou, V. (2009). Overview of current and future energy storage technologies for electric power applications. *Renewable and Sustainable Energy Reviews*, *13*(6-7), 1513–1522. doi: 10.1016/j.rser.2008.09.028

Hafizan, C., Noor, Z. Z., & Michael, F. L. (2013, 12). Energy Production from Natural Gas: Evaluation of Pontential Environmental Impacts Using Life Cycle Assesment Approach. *Advanced Materials Research*, *864-867*, 1132–1138. doi: 10.4028/www.scientific.net/amr.864-867.1132

Heslop, L. A., McGregor, E., & Griffith, M. (2001). Development of a technology readiness assessment measure: The Cloverleaf model of technology transfer. *Journal of Technology Transfer*. doi: 10.1023/A:1011139021356

Hydrogen Electrolyser, N. (2018). *The world's most efficient and reliable electrolyser* (Tech. Rep.). Retrieved from `https://nelhydrogen.com/assets/uploads/2017/01/Nel_Electrolyser_brochure.pdf`

Jin, H., & Ishida, M. (2000). Novel gas turbine cycle with hydrogen-fueled chemical-looping combustion. *International Journal of Hydrogen Energy*, *25*(12), 1209–1215. doi: 10.1016/S0360-3199(00)00032-X

Johansson, K. (2005). *Hydrogen as fuel for turbines and engines* (Tech. Rep.). Sydkraft. Retrieved from `http://ieahydrogen.org/Activities/National-Documents/Task-18/Sweden/Hydrogen-tubine-Engine.aspx`

Jones, R. K., Baras, A., Saeeri, A. A., Al Qahtani, A., Al Amoudi, A. O., Al Shaya, Y., . . . Al-Hsaien, S. A. (2016, 5). Optimized Cleaning Cost and Schedule Based on Observed Soiling Conditions for Photovoltaic Plants in Central Saudi Arabia. *IEEE Journal of Photovoltaics*, *6*(3), 730–738. doi: 10.1109/JPHOTOV.2016.2535308

Jorg, G. (2019). *Outlines of a Hydrogen Roadmap* (Tech. Rep.). TKI Nieuw Gas. Retrieved from `https://www.topsectorenergie.nl/sites/default/files/uploads/TKI%20Gas/publicaties/20180514%20Roadmap%20Hydrogen%20TKI%20Nieuw%20Gas%20May%202018.pdf`

Kahouli, S., & Martin, J. C. (2018, 6). Can Offshore Wind Energy Be a Lever for Job Creation in France? Some Insights from a Local Case Study. *Environmental Modeling and Assessment*, *23*(3), 203–227. doi: 10.1007/s10666-017-9580-4

Kahraman, C., Kaya, , & Cebi, S. (2009, 10). A comparative analysis for multiattribute selection among renewable energy alternatives using fuzzy axiomatic design and fuzzy analytic hierarchy process. *Energy*, *34*(10), 1603–1616. Retrieved from `https://linkinghub.elsevier.com/retrieve/pii/S0360544209002862` doi: 10.1016/j.energy.2009.07.008

Kling, W., Ummels, B., & Hendriks, R. (2007). *Transmission and system integration of wind power in the Netherlands.* Institute of Electrical and Electronics Engineers. Retrieved from `https://research.tue.nl/en/publications/transmission-and-system-integration-of-wind-power-in-the-netherla`

Koeman, H. (2019). *High Hydrogen Gas Turbine Retrofit to Eliminate Carbon Emissions.* Retrieved from `https://www.ansaldoenergia.com/Pages/High-Hydrogen-Gas-Turbine-Retrofit-to-Eliminate-Carbon-Emissions.aspx`

Lazarevska, A. M., & Mladenovska, D. (2016). Multi-Criteria Assessment of Natural Gas Supply Options – The Macedonian Case. *International Journal of Contemporary ENERGY*, *2*(1), 54–62. doi: 10.14621/ce.20160107

Lee, H.-C., & Chang, C.-T. (2018, 9). Comparative analysis of MCDM methods for ranking renewable energy sources in Taiwan. *Renewable and Sustainable Energy Reviews*, *92*, 883–896. Retrieved from `https://www.sciencedirect.com/science/article/pii/S1364032118303435` doi: 10.1016/J.RSER.2018.05.007

Lee, K.-M., & Inaba, A. (2004). *Life Cycle Assessment: Best Practices of International Organization for Standardization (ISO) 14040 Series* (Tech. Rep. No. February). Center for Ecodesign and LCA (CEL). Retrieved from `http://publications.apec.org/publication-detail.php?pub_id=453`

Lee, M. C., Seo, S. B., Chung, J. H., Kim, S. M., Joo, Y. J., & Ahn, D. H. (2010). Gas turbine combustion performance test of hydrogen and carbon monoxide synthetic gas. *Fuel*, *89*(7), 1485–1491. Retrieved from `http://dx.doi.org/10.1016/j.fuel.2009.10.004` doi: 10.1016/j.fuel.2009.10.004

Lee, S. K., Mogi, G., Kim, J. W., & Gim, B. J. (2008). A fuzzy analytic hierarchy process approach for assessing national competitiveness in the hydrogen technology sector. *International Journal of Hydrogen Energy*. doi: 10.1016/j.ijhydene.2008.09.028

Lensink, S., & Pisca, I. (2018). *Costs of offshore wind energy 2018* (Tech. Rep.). PBL Netherlands Environmental Assessment Agency. Retrieved from `www.pbl.nl/en.`

Lerner, A., Brear, M. J., Lacey, J. S., Gordon, R. L., & Webley, P. A. (2018, 5). Life cycle analysis (LCA) of low emission methanol and di-methyl ether (DME) derived from natural gas. *Fuel*, *220*, 871–878. Retrieved from `https://www.sciencedirect.com/science/article/pii/S0016236118302278` doi: 10.1016/J.FUEL.2018.02.066

Lin, J., & Damato, G. (2011). *Energy Storage - A Cheaper and Cleaner Alternative to Natural Gas-Fired Peaker Plants* (Tech. Rep.). California Energy Storage Alliance. Retrieved from `www.storagealliance.org`

Liu, J., Zhang, J. G., Yang, Z., Lemmon, J. P., Imhoff, C., Graff, G. L., ... Schwenzer, B. (2013). Materials science and materials chemistry for large scale electrochemical energy storage: From transportation to electrical grid. *Advanced Functional Materials*. doi: 10.1002/adfm.201200690

Lozanovski, A., Schuller, O., & Faltenbacher, M. (2011). Guidance document for performing LCA on hydrogen production systems - Joint Undertaking. *FC-HyGuide*. Retrieved from `http://www.fc-hyguide.eu/documents/10156/d0869ab9-4efe-4bea-9e7a-1fb823f4fcfa`

Makridis. (2016). Hydrogen storage and compression. In *Methane and hydrogen for energy storage.* doi: 10.1049/pbpo101e{_}ch1

Mardani, A., Jusoh, A., Nor, K. M., Khalifah, Z., Zakwan, N., & Valipour, A. (2015). Multiple criteria decision-making techniques and their applications - A review of the literature from 2000 to 2014. *Economic Research-Ekonomska Istrazivanja*, *28*(1), 516–571. Retrieved from `http://dx.doi.org/10.1080/1331677X.2015.1075139` doi: 10.1080/1331677X.2015.1075139

Martín-Gamboa, M., Iribarren, D., García-Gusano, D., & Dufour, J. (2017, 5). A review of life-cycle approaches coupled with data envelopment analysis within multi-criteria decision analysis for sustainability assessment of energy systems. *Journal of Cleaner Production*, *150*, 164–174. Retrieved from `https://www.sciencedirect.com/science/article/pii/S0959652617304523?via%3Dihub` doi: 10.1016/J.JCLEPRO.2017.03.017

Mayer, J. N., Philipps, S., Hussein, N. S., Schlegl, T., & Senkpiel, C. (2015). *Current and Future Cost of Photovoltaics: Long-term Scenarios for Market Development, System Prices and LCOE of Utility-Scale PV Systems* (Tech. Rep.). Agora Energiewende. Retrieved from `https://www.ise.fraunhofer.de/content/dam/ise/de/documents/publications/studies/AgoraEnergiewende_Current_and_Future_Cost_of_PV_Feb2015_web.pdf`

Mazloomi, K., & Gomes, C. (2012). *Hydrogen as an energy carrier: Prospects and challenges.* doi: 10.1016/j.rser.2012.02.028

Medina, E., & Roberts, R. R. (2013). *Methanol Safe Handling Manual* (Tech. Rep.). The Methanol Institute. Retrieved from `www.methanol.org`

Meijer, B. (2018). *Netherlands to ban coal-fired power plants in blow to RWE - Reuters.* Retrieved from `https://www.reuters.com/article/us-netherlands-energy-coal/netherlands-to-ban-coal-fired-power-plants-in-blow-to-rwe-idUSKCN1IJ1PI`

MMSA. (2019). *Methanol Price.* Retrieved from `https://www.methanol.org/methanol-price-supply-demand/`

Moliere, M., & Hugonnetl, N. (2004). *Hydrogen-fueled gas turbines: experience and prospects* (Tech. Rep.). Power-Gen Asi. Retrieved from `https://www.researchgate.net/profile/Michel_Moliere2/publication/331298911_HYDROGEN-FUELED_GAS_TURBINES_EXPERIENCE_AND_PROSPECTS/links/5c710f99458515831f681f15/HYDROGEN-FUELED-GAS-TURBINES-EXPERIENCE-AND-PROSPECTS.pdf`

Murray, R. J., & Furlonge, H. I. (2009). Market and Economic Assessment of Using Methanol for Power Generation in the Caribbean Region. *The Journal of the Association of Professional Engineers of Trinidad and Tobago*, *38*(1), 88–99.

Namovicz, C., & Diefenderfer, J. (2016). *Capital Cost Estimates for Utility Scale Electricity Generating Plants* (Tech. Rep.). U.S. Energy Information Administration (EIA). Retrieved from `https://www.eia.gov/analysis/studies/powerplants/capitalcost/pdf/capcost_assumption.pdf`

Navajas, A., Mendiara, T., Goñi, V., Jiménez, A., Gandía, L. M., Abad, A., . . . de Diego, L. F. (2019, 10). Life cycle assessment of natural gas fuelled power plants based on chemical looping combustion technology. *Energy Conversion and Management*, *198*, 111856. doi: 10.1016/j.enconman.2019.111856

Niermann, M., Drunert, S., Kaltschmitt, M., & Bonhoff, K. (2019, 1). Liquid organic hydrogen carriers (LOHCs) – techno-economic analysis of LOHCs in a defined process chain. *Energy & Environmental Science*, *12*(1), 290–307. Retrieved from `http://xlink.rsc.org/?DOI=C8EE02700E` doi: 10.1039/C8EE02700E

Nigim, K., Munier, N., & Green, J. (2004, 9). Pre-feasibility MCDM tools to aid communities in prioritizing local viable renewable energy sources. *Renewable Energy*, *29*(11), 1775–1791. doi: 10.1016/j.renene.2004.02.012

Nugent, D., & Sovacool, B. K. (2014, 2). Assessing the lifecycle greenhouse gas emissions from solar PV and wind energy: A critical meta-survey. *Energy Policy*, *65*, 229–244. Retrieved from `https://www.sciencedirect.com/science/article/pii/S0301421513010719` doi: 10.1016/J.ENPOL.2013.10.048

Olah, G. A. (2013, 1). Towards Oil Independence Through Renewable Methanol Chemistry. *Angewandte Chemie International Edition*, *52*(1), 104–107. Retrieved from `http://doi.wiley.com/10.1002/anie.201204995` doi: 10.1002/anie.201204995

Olechowski, A., Eppinger, S. D., & Joglekar, N. (2015). Technology readiness levels at 40: A study of state-of-the-art use, challenges, and opportunities. In *Portland international conference on management of engineering and technology.* doi: 10.1109/PICMET.2015.7273196

Ozbilen, A., Dincer, I., & Rosen, M. A. (2013). Comparative environmental impact and efficiency assessment of selected hydrogen production methods. *Environmental Impact Assessment Review*, *42*, 1–9. Retrieved from `http://dx.doi.org/10.1016/j.eiar.2013.03.003` doi: 10.1016/j.eiar.2013.03.003

Papalexandrou, M., Pilavachi, P., & Chatzimouratidis, A. (2008, 9). Evaluation of liquid bio-fuels using the Analytic Hierarchy Process. *Process Safety and Environmental Protection*, *86*(5), 360–374. Retrieved from `https://linkinghub.elsevier.com/retrieve/pii/S095758200800030X` doi: 10.1016/j.psep.2008.03.003

Park, S. R., Pandey, A. K., Tyagi, V. V., & Tyagi, S. K. (2014). Energy and exergy analysis of typical renewable energy systems. *Renewable and Sustainable Energy Reviews*, *30*, 105–123. Retrieved from `http://dx.doi.org/10.1016/j.rser.2013.09.011` doi: 10.1016/j.rser.2013.09.011

Parks, G., Boyd, R., Cornish, J., & Remick, R. (2014). *Hydrogen Station Compression, Storage, and Dispensing Technical Status and Costs: Systems Integration* (Vol. 2014; Tech. Rep. No. May). National Renewable Energy Lab.(NREL), Golden, CO (United States). Retrieved from `http://www.osti.gov/servlets/purl/1130621/` doi: 10.2172/1130621

Pennington, D. W., Potting, J., Finnveden, G., Lindeijer, E., Jolliet, O., Rydberg, T., & Rebitzer, G. (2004). Life cycle assessment Part 2: Current impact assessment practice. *Environment International*, *30*(5), 721–739. doi: 10.1016/j.envint.2003.12.009

Pétron, G., Frost, G., Miller, B. R., Hirsch, A. I., Montzka, S. A., Karion, A., . . . Tans, P. (2012). *Hydrocarbon emissions characterization in the Colorado Front Range: A pilot study.* doi: 10.1029/2011JD016360

Pilavachi, P. A., Stephanidis, S. D., Pappas, V. A., & Afgan, N. H. (2009). Multi-criteria evaluation of hydrogen and natural gas fuelled power plant technologies. *Applied Thermal Engineering*, *29*(11-12), 2228–2234. Retrieved from `http://dx.doi.org/10.1016/j.applthermaleng.2008.11.014` doi: 10.1016/j.applthermaleng.2008.11.014

Raga Mexico, G., Nakajima, T., Ramanathan, V., Ramaswamy, V., Artaxo, P., Berntsen, T., . . . Averyt, K. (2007). *Changes in Atmospheric Constituents and in Radiative Forcing* (Tech. Rep.). n Climate Change 2007: The Physical Science Basis. Retrieved from `http://www.cgd.ucar.edu/events/20130729/files/Forster-Ramaswamy-etal-2007.pdf`

Ramsden, T., Kroposki, B., & Levene, J. (2008). *Opportunities for hydrogen-based energy storage for electric utilities* (Tech. Rep.). Proceedings of the NHA annual hydrogen conference. Sacramento. Retrieved from `nha.confex.com/nha/2008/recordingredirect.cgi/id/352`

Reuß, M., Grube, T., Robinius, M., Preuster, P., Wasserscheid, P., & Stolten, D. (2017, 8). Seasonal storage and alternative carriers: A flexible hydrogen supply chain model. *Applied Energy*, *200*, 290–302. Retrieved from `https://www.sciencedirect.com/science/article/pii/S0306261917305457#b0110` doi: 10.1016/J.APENERGY.2017.05.050

RIVM. (2011). *LCIA: the ReCiPe model.* Retrieved from `https://www.rivm.nl/en/life-cycle-assessment-lca/recipe`

Rustagi, N., & Soto, H. (2017). *Hydrogen Delivery Technical Team Roadmap* (Tech. Rep. No. July). United States Driving Research and Innovation for Vehicle efficiency and Energy sustainability. Retrieved from `https://www.energy.gov/sites/prod/files/2017/08/f36/hdtt_roadmap_July2017.pdf`

RVO. (2019). *Offshore Wind Energy.* Retrieved from `https://english.rvo.nl/subsidies-programmes/offshore-wind-energy`

Saaty, T. L. (2008). *Decision making with the analytic hierarchy process* (Vol. 1; Tech. Rep. No. 1). Retrieved from `http://www.rafikulislam.com/uploads/resourses/197245512559a37aadea6d.pdf`

San Cristóbal, J. R. (2011). Multi-criteria decision-making in the selection of a renewable energy project in spain: The Vikor method. *Renewable Energy*, *36*(2), 498–502. Retrieved from `http://dx.doi.org/10.1016/j.renene.2010.07.031` doi: 10.1016/j.renene.2010.07.031

Sea route map; distance - ports.com. (n.d.). Retrieved from `http://ports.com/sea-route/#/?a=16625&b=3037&c=Port%20of%20Agadir,%20Morocco&d=Port%20of%20Rotterdam,%20Netherlands`

Seebregts, A. J. (2010). *Gas-Fired Power* (Tech. Rep.). Energy Technology Systems Analysis Programme. Retrieved from `www.etsap.org`

Şengül, , Eren, M., Eslamian Shiraz, S., Gezder, V., & Şengül, A. B. (2015, 3). Fuzzy TOPSIS method for ranking renewable energy supply systems in Turkey. *Renewable Energy*, *75*, 617–625. Retrieved from `https://www.sciencedirect.com/science/article/pii/S0960148114006727` doi: 10.1016/J.RENENE.2014.10.045

Shea, G. N. (2007). NASA Systems Engineering Handbook. *Systems Engineering Handbook*, *6105 Rev1*(June), 360. Retrieved from `https://www.nasa.gov/connect/ebooks/nasa-systems-engineering-handbook%0Ahttp://adsabs.harvard.edu/full/1995NASSP6105.....S%5Cnhttps://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20080008301.pdf` doi: 10.1016/0016-0032(66)90450-9

Sheffield, J., Martin, K., & Folkson, R. (2014, 1). Electricity and hydrogen as energy vectors for transportation vehicles. *Alternative Fuels and Advanced Vehicle Technologies for Improved Environmental Performance*, 117–137. Retrieved from `https://www.sciencedirect.com/science/article/pii/B9780857095220500054` doi: 10.1533/9780857097422.1.117

Smyrnakis, C., Phocas-Cosmetatos, A., & Kynigalakis, K. (2016). A review of public desert land lease policies for concentrated solar power plants and the impact on their economic performance. *AIP Conference Proceedings*, *1734*, 50018. Retrieved from `https://doi.org/10.1063/1.4949257https://doi.org/10.1063/1.4949164https://doi.org/10.1063/1.4949116` doi: 10.1063/1.4949257

Stafford, W. H. L., Lotter, G. A., von Maltitz, G. P., & Brent, A. C. (2019). Biofuels technology development in Southern Africa. *Development Southern Africa*. doi: 10.1080/0376835X.2018.1481732

Stein, E. W. (2013). A comprehensive multi-criteria model to rank electric energy production technologies. *Renewable and Sustainable Energy Reviews*, *22*, 640–654. Retrieved from `http://dx.doi.org/10.1016/j.rser.2013.02.001` doi: 10.1016/j.rser.2013.02.001

Stevens, L., Anderson, B., Cowan, C., Colton, K., & Johnson, D. (2017). *The footprint of energy: Land use of U.S. electricity production* (Tech. Rep.). Strata. Retrieved from `https://www.eia.gov/electricity/`

Stolten, D., & Emonts, B. (2016). *Hydrogen Science and Engineering: Materials, Processes, Systems and Technology* (1st ed.; D. Stolten, Emonts, & Bernd, Eds.). John Wiley & Sons, Incorporated. Retrieved from `https://ebookcentral-proquest-com.tudelft.idm.oclc.org/lib/delft/detail.action?docID=4312659`

Taibi, E., Miranda, R., Vanhoudt, W., Winkel, T., Lanoix, J.-C., & Barth, F. (2018). *Hydrogen from renewable power: Technology outlook for the energy transition* (Tech. Rep.). International Renewable Energy Agency. Retrieved from `https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2018/Sep/IRENA_Hydrogen_from_renewable_power_2018.pdf`

Taljan, G., Cañizares, C., Fowler, M., & Verbič, G. (2008). The feasibility of hydrogen storage for mixed wind-nuclear power plants. *IEEE Transactions on Power Systems*, *23*(3), 1507–1518. doi: 10.1109/TPWRS.2008.922579

Taylor, M., & So, E. y. (2016). *Solar PV in Africa: Costs and Markets* (Tech. Rep.). Renewable Energy Agency, International. Retrieved from `www.irena.org`

Tengborg, P., Johansson, J., & Durup, J. G. (2014). Storage of highly compressed gases in underground Lined Rock Caverns – More than 10 years of experience. *World Tunnel Congress*(May 2014).

Tsoutsos, T., Drandaki, M., Frantzeskaki, N., Iosifidis, E., & Kiosses, I. (2009). Sustainable energy planning by using multi-criteria analysis application in the island of Crete. *Energy Policy*, *37*(5), 1587–1600. doi: 10.1016/j.enpol.2008.12.011

Turaga, U., & Johnson, B. (2017). *Methanol for Power Generation: A White Paper* (Tech. Rep. No. September). ADI-Analytics. Retrieved from `http://www.methanol.org/wp-content/uploads/2017/03/Safe-Handling-Manual.pdf`

Turconi, R., Boldrin, A., & Astrup, T. (2013). *Life cycle assessment (LCA) of electricity generation technologies: Overview, comparability and limitations* (Vol. 28). Elsevier Ltd. doi: 10.1016/j.rser.2013.08.013

UNCTAD. (n.d.). *Review of Maritime Transport 2017 - Freight rates and maritime transport costs* (Tech. Rep.). United Nations Conference on Trade and Development. Retrieved from `https://unctad.org/en/PublicationChapters/rmt2017ch3_en.pdf`

Valente, A., Iribarren, D., & Dufour, J. (2017). Life cycle assessment of hydrogen energy systems: a review of methodological choices. *International Journal of Life Cycle Assessment*, *22*(3), 346–363. doi: 10.1007/s11367-016-1156-z

Valera-Medina, A., Xiao, H., Owen-Jones, M., David, W. I., & Bowen, P. J. (2018, 11). *Ammonia for power* (Vol. 69). Elsevier Ltd. doi: 10.1016/j.pecs.2018.07.001

Valpy, B., & English, P. (2017). *Future renewable energy costs: offshore wind* (Tech. Rep.). KIC InnoEnergy. Retrieved from `http://www.innoenergy.com/wp-content/uploads/2014/09/KIC_IE_OffshoreWind_anticipated_innovations_impact1.pdf`

Van Den Akker, J. H. A. (2017). *Overview of costs of sustainable energy technologies Energy production: on-grid, mini-grid and off-grid power generation and supply and heat applications* (Tech. Rep.). Retrieved from `https://jhavdakk.home.xs4all.nl/ASCENDIS%20Cost%20of%20energy%20v2a.pdf`

van Haaren, R., & Fthenakis, V. (2011, 9). GIS-based wind farm site selection using spatial multi-criteria analysis (SMCA): Evaluating the case for New York State. *Renewable and Sustainable Energy Reviews*, *15*(7), 3332–3340. Retrieved from `https://linkinghub.elsevier.com/retrieve/pii/S136403211100147X` doi: 10.1016/j.rser.2011.04.010

Varun, Bhat, I., & Prakash, R. (2009, 6). LCA of renewable energy for electricity generation systems—A review. *Renewable and Sustainable Energy Reviews*, *13*(5), 1067–1073. Retrieved from `https://www.sciencedirect.com/science/article/pii/S1364032108001093` doi: 10.1016/J.RSER.2008.08.004

Veenstra, M., & Adams, J. (2017). *Hydrogen Storage Tech Team Roadmap* (Tech. Rep.). (Driving Research and Innovation for Vehicle efficiency and Energy sustainability. Retrieved from `www.vehicles.energy.gov/about/partnerships/usdrive.htmlorwww.uscar.org.`

Vickers, J. (2017). *Hydrogen Storage Technologies Roadmap Fuel Cell Technical Team Roadmap* (Tech. Rep. No. July). U.S. Department of Energy. Retrieved from `www.uscar.org`

Wang, J.-J., Jing, Y.-Y., Zhang, C.-F., & Zhao, J.-H. (2009, 12). Review on multi-criteria decision analysis aid in sustainable energy decision-making. *Renewable and Sustainable Energy Reviews*, *13*(9), 2263–2278. Retrieved from `https://linkinghub.elsevier.com/retrieve/pii/S1364032109001166` doi: 10.1016/j.rser.2009.06.021

Warren, L. (2004). *Uncertainties in the Analytic Hierarchy Process* (Tech. Rep.). Defence Science and Technology Organisation. Retrieved from `http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.86.6240&rep=rep1&type=pdf`

Weeda, M. (2019). *Investment Agenda Hydrogen Northern Netherlands Heading for emission-free hydrogen at commercial scale* (Tech. Rep.). The Northern Netherlands Innovation Board. Retrieved from `https://www.snn.nl/sites/default/files/2019-07/Investment%20Agenda%20Hydrogen%20Northern%20Netherlands%20-%20April%202019%20%285%29.pdf`

Wolf, E. (2015, 1). Large-Scale Hydrogen Energy Storage. *Electrochemical Energy Storage for Renewable Sources and Grid Balancing*, 129–142. Retrieved from `https://www.sciencedirect.com/science/article/pii/B9780444626165000097` doi: 10.1016/B978-0-444-62616-5.00009-7

Yue, D., You, F., & Darling, S. B. (2014). Domestic and overseas manufacturing scenarios of silicon-based photovoltaics: Life cycle energy and environmental comparative analysis. *Solar Energy*. doi: 10.1016/j.solener.2014.04.008

Zabihian, F., & Fung, A. (2009). *Fuel and GHG Emission Reduction Potentials by Fuel Switching and Technology Improvement in the Iranian Electricity Generation Sector* (Tech. Rep. No. 3). Retrieved from `http://www.cscjournals.org/download/issuearchive/IJE/Volume3/IJE_V3_I2.pdf#page=78`

Zheng, J., He, Q., Gu, C., Zhao, Y., Hua, Z., Li, K., . . . Zhang, Y. (2016). High pressure 98 MPa multifunctional steel layered vessels for stationary hydrogen storage. *ASME 2016 Pressure Vessels and Piping Conference*.

Zheng, J., Liu, X., Xu, P., Liu, P., Zhao, Y., & Yang, J. (2012). Development of high pressure gaseous hydrogen storage technologies. *International Journal of Hydrogen Energy*, *37*(1), 1048–1057. Retrieved from `http://dx.doi.org/10.1016/j.ijhydene.2011.02.125` doi: 10.1016/j.ijhydene.2011.02.125

Appendix

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Multi-criteria decision making using AHP: Selection of an alternative fuel for a peak power plant in Rotterdam

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Abstract

As the energy transition evolves, more fossil-driven base-load generation is being replaced with intermittent renewable energy sources. Peak power plants will continue to play a crucial role in future renewable energy systems to complement renewable energy supply. The focus of this paper is on alternative fuels that can be utilized in conventional gas turbines. Several alternatives fuels exist, such as hydrogen, methanol and bio-fuels, and each alternative fuel has different technical, economic, social and environmental implications for the energy system and the society as a whole. Decision makers across the energy sector face difficult trade-offs between quantitative and qualitative criteria when selecting and alternative technology to invest in. This paper applies the analytical hierarchy process (AHP) to select an alternative fuel for a peak power plant in Rotterdam. The fuels analysed are methanol and hydrogen, and are ranked according to nine sub-criteria. Two contributions are proposed to improve the AHP method. Firstly, incorporating a technology readiness level indicator to quantify the technological maturity. Secondly, multiple perspectives are incorporated from key stakeholders in the criteria weighting. A sensitivity analysis is then performed on the most relevant criteria.

Keywords:
Multi Criteria Decision Making (MCDM), Analytic Hierarchy Process (AHP), Life Cycle Assessment (LCA), Technology Readiness Level (TRL), Methanol, Hydrogen, Gas Turbine.

1. Introduction

Peak power plants will continue to play an important role in future energy system. The share of intermittent renewable energy sources in the Dutch energy mix is rapidly increasing with plans for offshore wind projects of up to 6800 MW by 2023 (RVO, 2019). On the opposite end of electricity generation, two base-load coal power plants corresponding to 1875 MW capacity will be retired by 2023, and all coal plants will be shutdown by 2030 (Meijer, 2018). Peak power supply is required to be highly responsive, therefore it is conventionally fulfilled with gas or diesel turbines. Several renewable energy alternatives technologies for satisfying peak demand exist, such as Compressed Air Energy Storage (CAES) and pumped hydro (Hadjipaschalis et al., 2009). However these are often geologically dependant requiring the presence of salt caverns, abandoned mines, or proximity to a water body and elevated natural reservoirs (Hadjipaschalis et al., 2009). Storage in batteries still comes with economical challenges at large scale and faces technical challenges with efficiency, operational lifetime and self-discharge rates (Liu et al., 2013; Hadjipaschalis et al., 2009).

Renewable alternative fuels can be fired in existing gas turbines to offer dispatchable electricity generation on demand, independent of the presence of special geological structures for energy storage. Gas turbines are available for a wide range of power plant generating capacities and current gas turbines can operate on hydrogen rich fuels, bio-fuels, methanol and other alternative fuels (Gökalp y Lebas, 2004; Goldmeer, 2018; Murray y Furlonge, 2009). Decision makers across the energy sector are often faced with the challenge of selecting an alternative fuel to invest in. Alternative fuels are part of complex energy system, and their adoption requires availability of infrastructure, development of specific equipment, appropriate legislation and investment in R&D. Decision-makers can be investors, equipment manufacturers, fuel producers, policy-makers or many other possible stakeholders. In order to make a decision, stakeholders often need to balance trade-offs between multiple criteria regarding the technical, economic, social, political and environmental implications of renewable fuel alternatives (Wang et al., 2009; Campos-Guzmán et al., 2019).

Multi-criteria decision making (MCDM) tools are often employed to solve problems with contradictory objectives related to sustainable energy management (Campos-Guzmán et al., 2019; Zhou et al., 2006). MCDM tools can incorporate both quantit-

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ative and qualitative criteria to clearly and consistently evaluate choices (Daim y Taha, 2013). The Analytical Hierarchy Process (AHP) is the most popular MCDM tool in analyzing energy systems due to its simplicity, flexibility and sound mathematical principles (Campos-Guzmán et al., 2019).

This paper applies the AHP method to select an alternative fuel for a peak power plant in Rotterdam. Two contributions are proposed and applied to the AHP method. Firstly, the technology readiness level developed by NASA is utilized to quantify the technological maturity. Secondly, a new approach is proposed to the conventional criteria weighting to incorporate a wider range of stakeholders, and reduce their uncertainty in investment.

In the next section, the system boundaries for the alternative fuels are outlined, then the alternative fuels are compared using the proposed AHP method. Finally, a sensitivity analysis is performed to test the robustness of the proposed method.

2. System boundaries

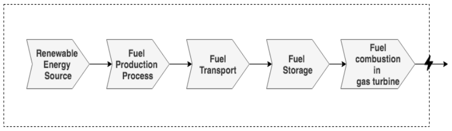

Figure 1: System boundaries

Hydrogen is widely proposed as a carbon-free energy carrier when produced from renewable electricity generation. Hydrogen is the simplest element that exists and can be remotely made by electrolysis of water. Gas turbine manufacturers, such as Siemens and GE, have been developing gas turbine running on varying mixtures of hydrogen and natural gas (from 10% to 100%) (Brown et al., 2007; Goldmeer, 2018). However, due to its physical properties, Hydrogen is a very challenging fuel to store, transport and also utilize (Wolf, 2015; Crotogino, 2016). Hydrogen can be irreversibly stored in liquid organic hydrogen carriers (LOHC) such as ammonia, formic acid and methanol (Aakko-Saksa et al., 2018). LOHC are liquid at room temperature, and exhibit similar handling, storage and utilization as well-known oil-based fuels (diesel and gasoline) (Niermann et al., 2019). Methanol and hydrogen have both been academically and experimentally fired in retrofitted gas turbines (Goldmeer, 2018; Bannister et al., 1998; Murray y Furlonge, 2009; Brown et al., 2007; Lee et al., 2010) The systems boundaries are defined to include electricity production from the renewable energy source, fuel production, fuel transport, storage and finally fuel combustion in the power plant . A 34.3 MW peak power plant in Rotterdam with a capacity factor of 5.9% is assumed based on typical capacity factors for peak power plants (Lin y Damato, 2011).

Hydrogen production system The Netherlands is rapidly expanding its offshore wind energy generating capacity (RVO, 2019). Of the planned projects, a 25 MW offshore wind farm would generate enough electricity to meet the power requirements for electrolysis and compression of hydrogen. The system specifications are summarized in table 1.

Component	Capacity	Source
Offshore wind	25 MW	(Lensink y Pisca, 2018)
Electrolysis	30 MW	(Burkhardt et al., 2016)
Compressor	99 4.3-Kg H_2/hr	(Taljan et al., 2008)
Storage	14,583 Kg H_2	(Zheng et al., 2016)

Table 1: Hydrogen production system

Methanol production system

Methanol production is based on the system developed by *Zero Emission Fuels B.V.*. In this system, a solar PV system generates the electricity required for water electrolysis, direct air capture of CO_2 from the atmosphere and the methanol synthesis reaction. The 48 MW solar farms is located in favourable conditions for maximum equivalent sun hours in Morocco. The 400 m^3 of produced methanol is shipped via oceaninc tankers to the plant location in Rotterdam. The system specifications are summarized in table 2

Component	Capacity	Source
Solar PV	48 MW	(Van Den Akker, 2017)
ZEF micro-plants	160,603	
Shipping	3356 km	(Medina y Roberts, 2013)
Storage	400 m^3	(Medina y Roberts, 2013)

Table 2: Methanol production system

3. AHP Hierarchy

In order to evaluate both alternative fuels using the AHP method, the first task is to create a top down hierarchy structure as shown in figure 2. The goal is set at the highest level according to the criteria and sub-criteria at the lower levels (Saaty, 2008). The four major criteria commonly analysed for energy systems are the economic, environmental, technical and social aspects (Campos-Guzmán et al., 2019). Major criteria are decomposed into sub-criteria that are relevant for the alternative fuel production routes being analysed. These sub-criteria will be elaborated in the following sub-section. The two alternatives are displayed at the lowest level, the 18 lines connecting the 9 sub-criteria with the 2 alternatives have been omitted for simplicity.

4. AHP method

The AHP method was developed by Saaty (2008), and has three underlying foundations. First, the problem is structured into a hierarchy of goals, criteria, sub-criteria and alternatives (as in fig. 2). Then pairwise comparative judgements are performed between elements at the same level with respect to the preceding level, in order to arrive at overall priorities for each

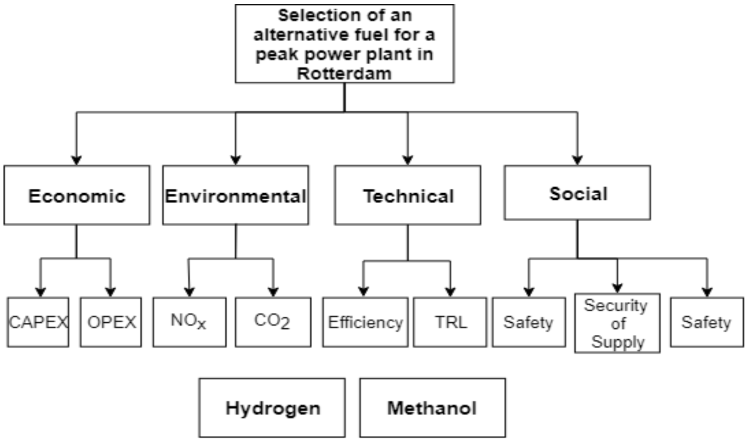

Figure 2: Analytic hierarchy tree for selecting an alternative fuel for peak power plants

alternative. Finally, the judgements over all levels of the hierarchy are synthesized to come up with a ranking of the alternatives (Campos-Guzmán et al., 2019; Papalexandrou et al., 2008).

4.1. *Evaluation of alternative fuels*

In order to compare the performance of both alternative fuels against each other, and indeed against the natural gas they are substituting, a comparison on the environmental impact and costs is provided. The environmental and economic performance of the fuel is expressed in terms of a functional unit of 1 MWh generated from the peak power plant. While the social and technical criteria are related to the fuel in general.

4.1.1. *Economic criteria*

The economic criteria are based on capital expenditure costs (CAPEX) and operation and maintenance costs (OPEX). CAPEX costs relate to long term investments whose benefits go beyond 1 year, and are assumed to be paid in the first year. OPEX costs are paid annually, and discounted at a fixed rate of 10%. The levelized cost of energy (LCOE) per MWh is calculated for each fuel alternative based on CAPEX and OPEX costs.

For the hydrogen production system, the costs are distributed among offshore wind electricity (0.0687 €/KWh) (Van Den Akker, 2017), alkaline water electrolysers (1100 €/KW) (Gambhir et al., 2017), compressor 1607 €/Kg H_2 (Parks et al., 2014) and storage tanks 982 €/Kg H_2 (Ramsden et al., 2008; Vickers, 2017). Based on these assumptions, the LCOE of hydrogen fuel is 1,138 €/MWh.

As for the methanol production system, the biggest cost contributor is the solar electricity generation (0.0259 €/KWh) (Castillo Ramírez et al., 2018; Van Den Akker, 2017), followed by the methanol production plants (230 €/plant), methanol shipping (64 €/ton.km) (UNCTAD, ????) and storage (519 €/m^3) (Medina y Roberts, 2013) at the peak power plant. This adds up to LCOE of 732 €/MWh for methanol fuel.

4.1.2. *Technical criteria*

Technical criteria are a relevant aspect for decision makers, especially for the design of future energy system. While there is extensive literature on the use of efficiency coefficients, capacity factors, resource availability and reliability, a quantitative method to incorporate the technological maturity is yet to be incorporated (Chatzimouratidis y Pilavachi, 2008; Amer y Daim, 2011). Two technical criteria ara analyzed for the alternative fuels being assessed. The total system energy efficiency, and the technology readiness level.

The system energy efficiency is the ratio between the useful energy output from the power plant, to the energy input from the renewable energy source (Amer y Daim, 2011). Hydrogen production constitutes a shorter production chain with electricity consumption for electrolysis and compression operations. 19% of the renewable energy generation from the offshore wind is generated from the peak power plant, with the losses distributed on transmission losses, electrolysis, compression and efficiency losses in the gas turbine (35% (Goldmeer, 2018)). The energy efficiency of methanol production from solar energy, and utilization in gas turbines is 19%. While no compression is required as was the case with hydrogen storage, energy is required for direct air capture and methanol synthesis. Moreover, the enrgy efficiency of the selected gas turbine is lower (28% (Murray y Furlonge, 2009)).

Technology maturity has been analysed in only very few AHP studies for sustainable energy development (Campos-Guzmán et al., 2019; Amer y Daim, 2011). Technology maturity is a measure of the operational status of a technology, whether it is experimental laboratory scale or at commercial levels and if theoretical limits of efficiency have been reached (Amer y Daim, 2011). Lee et al. (2008) proposed a technological status criterion which is quantified by the number of patents, SCI papers and paper proceedings published over a certain period of time. For example, the authors collected quantitative data on the number of paper proceedings for hydrogen storage, production and utilization (Lee et al., 2008).

This paper proposes utilizing the technology readiness level (TRL framework developed by NASA to quantify the technological maturity criterion in AHP studies (Shea, 2007). The TRL is a tool used by engineers to evaluate two things: what has been demonstrated by the technology, and under what conditions (Shea, 2007). The assessment framework can be visualized in figure A.3 in the appendix. A series of questions are asked to identify where the technology lies on a TRL scale of 1 to 9, with 1 being the lowest level (basing concepts observed in the lab), and 9 being the highest (actual system proven in operational environment) (Shea, 2007). The framework is applied to each fuel's entire life-cycle from production, storage to utilization. The results are summarized in table 3 for hydrogen fuel, and table 4 for methanol fuel.

Component	TRL	Source
Electrolysis	7	(Grond y Holstein, 2014)
Compression	7	
Storage	5	(Zheng et al., 2016)
Gas turbines	5	(Goldmeer, 2018)

Table 3: Hydrogen fuel technology readiness level

Component	TRL	Source
Methanol production	2	
Transport	9	
Storage	9	(Medina y Roberts, 2013)
Gas turbines	7	(Day, 2016)

Table 4: Methanol fuel technology readiness level

4.1.3. Environmental criteria

Life-cycle assessment (LCA) is a method that provides a quantitative analysis of the environmental aspects of a product over its entire life-cycle. It is performed through a systematic set of procedures of compiling the inputs and outputs of materials, energy use and environmental impact attributable to all the stages of a system's life-cycle; from raw material extraction through material processing, manufacturing, transportation, maintenance and disposal (Lee y Inaba, 2004). Sima-pro software is used to model the environmental impact of the entire value chain for both alternative fuels. A cradle-to-grave system boundary is analysed, with the functional unit being 1 MWh generated from the peak power plant.

Global Warming Potential The global warming potential refers to the greenhouse gas (GHG) emissions during the life cycle stages of the system. GWP is expressed in equivalent tonnes of CO_2 using an integrated time horizon of 100 years; the major emissions included as GHG emissions are CO2 (GWP =1), CH4 (GWP=25), N2O (GWP=298) and chlorofluorocarbons (GWP=4750) (Raga Mexico et al., 2007). GWP is the most commonly assessed environmental indicator in sustainable energy systems (Campos-Guzmán et al., 2019). Life-cycle GWP of hydrogen fuel is 120 Kg CO_2/MWh, while for methanol 268 Kg CO_2/MWh. For reference, utilizing natural gas emits 697 Kg CO_2/MW (Aksyutin et al., 2018).

NOx emissions NOx emissions represent the amount of nitric oxides (NO) and dioxides (NO2) that is released during the production and ulitzatoin of the alternative fuel. Nox emissions are significant with natural gas, and are one of the biggest motivators to a shift to alternative fuels (Gökalp y Lebas, 2004). Methanol again emits more NOx per MWh, with 1.51 Kg NOx/MWh compared to 0.29 Kg NOx/MWh from hydrogen fuel. Both fuels are significantly cleaner that natural gas, which emits 3 Kg NOx/MWh (Aksyutin et al., 2018).

4.1.4. Social criteria

Social criteria deal with issues that affect people both directly and indirectly, and are expressed on whether they benefit or harm the population (Campos-Guzmán et al., 2019). The most commonly analysed social criterion for energy projects is job creation (Campos-Guzmán et al., 2019). Other commonly applied indicators are public acceptance, social benefit, impact on human health, resources security, national energy security, safety and expected mortality in case of an accident (Amer y Daim, 2011; Campos-Guzmán et al., 2019; Acar et al., 2019). Three social criteria selected for the analysis of the alternative fuels, which are job creation, energy security of supply and system safety. Health related criteria were not selected here to avoid overlap with the environmental criteria.

Hydrogen fuel is strongly preferred to methanol in terms of energy security of supply, and job creation. The reason being that the methanol production system is located in Morocco, while the hydrogen production system is locally situated. With regards to the safety criterion, no alternative fuel is preferred over the other (Adamson y Pearson, 2000). While hydrogen has a wider range of flammability, and highly reactive properties, it has very low density and merely escapes through air in case of a leakage, and is not inherently toxic. On the other hand methanol is a toxic fuel that can lead to partial blindness, and tends to pool around leakages judging by its higher density compared to air, yet it has a narrower range of flammability and higher ignition temperature (Medina y Roberts, 2013).

4.2. ***Criteria weighting***

Criteria weighting allocates the relative importance of major and sub criteria when synthesizing the overall scores for both alternative fuels. The weighting is carried hierarchically for each level with the respect to the preceding level (Saaty, 2008). This is inherently a subjective process since it depends on how the decision-makers prioritise the range of criteria included. The outcomes can vary significantly between stakeholders with different backgrounds, interests and objectives (Chatzimouratidis y Pilavachi, 2008).

In existing AHP studies, the criteria weighting is typically performed by the researchers themselves (Papalexandrou et al., 2008; Chatzimouratidis y Pilavachi, 2008; Pilavachi et al., 2009), or survey instruments distributed to energy professionals from industries and universities (Amer y Daim, 2011). Amer y Daim (2011) proposes to average the outcomes of all the criteria weights given in order to come up with one set of criteria weights for the alternative score calculations. Criteria weightings are highly influential on the outcomes of the AHP scores, and therefore are tested in a sensitivity analysis which are also carried by the researchers (Chatzimouratidis y Pilavachi, 2008). (Chatzimouratidis y Pilavachi, 2008) give a 60% weight to each major criterion and re-assess the AHP scores for each alternative.

This paper proposes reporting the criteria weightings from four different key stakeholders that will be crucial in the adoption and of a renewable alternative fuel. For an alternative fuel to be adopted, interest and commitment are needed across the entire life-cycle from production to utilization is necessary. This would involve investments in R&D, development of specific equipment and governmental support in some cases. Therefore, the criteria priorities are obtained from stakeholders across the value chain from fuel producers, equipment manufacturers, policy-makers and investors

	Economic	Technical	Env.	Social
Economic	1	3	4	7
Technical	1/3	1	4	6
Environmental	1/4	1/4	1	2
Social	1/7	1/6	1/2	1

Table 5: Equipment manufacturer pairwise matrix for all criteria with respect to the goal

	Economic	Technical	Env.	Social
Economic	1	1/3	5	5
Technical	3	1	5	3
Environmental	1/5	1/5	1	1/5
Social	1/5	1/3	5	1

Table 6: Policy-maker pairwise matrix for all criteria with respect to the goal

	Economic	Technical	Env.	Social
Economic	1	5	1/3	1/5
Technical	1/5	1	1/3	1/5
Environmental	3	3	1	1
Social	5	5	1	1

Table 7: Fuel producer pairwise matrix for all criteria with respect to the goal

4.3. *Alternative fuel score*

The final step of the AHP method is to synthesize the results and calculate the final score for both alternative fuels. The score for each alternative fuel is calculated by summing the product of the criteria weights multiplied by the fuel's performance on each criterion. The scores are calculated 4 times, once for each stakeholder. For three out of the four stakeholder groups, methanol is the better performing alternative fuel based on the stakeholder weightings. The main motivation being the economic and technical criteria. Although hydrogen is a cleaner fuel compared to methanol, the difference in levelized cost of energy is in favour of methanol. Hydrogen production involves the use of expensive system components for electrolysis, compression and storage, whereas methanol transport and storage is much less challenging.

	Economic	Technical	Env.	Social
Economic	1	3	7	8
Technical	1/3	1	4	6
Environmental	1/7	1/4	1	3
Social	1/8	1/6	1/3	1

Table 8: Energy investor pairwise matrix for all criteria with respect to the goal

Generally speaking, economic criteria were of more importance compared to environmental criteria. Regarding the technical criteria, hydrogen production chain is slightly more efficient, while the technology readiness level of the methanol chain is slightly more advanced. On a technical level, depending on the stakeholder, the two technical sub-criteria (efficiency and TRL) held different priorities, which in turn influenced the resulting scores. As for the social criteria, the fact that local hydrogen production system involves more job creation, and better security of supply, had almost no impact on the results since they carry a much smaller weight in the decision making process. The reason being that social criteria all together play a minor role in the decision making process (for all stakeholders but the fuel producers), and also because system safety represents the most relevant social sub-criterion according to all stakeholders.

There is no clear better fuel between the two alternatives in terms of safety, as the two fuels are similar in some aspects and outperform each other on other safety aspects. To sum up, the biggest influence on the scores are the economic and technical criteria, and for the given system boundaries, criteria selection and weightings, methanol outperforms hydrogen as an alternative fuel for gas turbines.

Stakeholder	Hydrogen Score	Methanol Score
Equipment manufacturer	0.452	0.548
Policymaker	0.436	0.543
Fuel-producer	0.565	0.434
Investor	0.425	0.575

Table 9: Alternative fuel scores for all stakeholders for the base case

5. Sensitivity Analysis

In the reviewed AHP studies, the sensitivity analysis is performed on the criteria weighting to offset the subjectivity in the pair-wise comparison process (Papalexandrou et al., 2008). This paper proposed incorporating four different stakeholders perspectives in order to test the robustness of the results of the AHP fuel scores. A sensitivity analysis is carried on the two criteria with highest priority for most stakeholders, i.e. the technical and economical criteria.

Two possible scenarios are identified that have an effect on the performance of the alternative fuel on certain criteria. In the proposed method, the criteria weightings remain constant for each stakeholder, while the fuel scores change depending on the scenario. The first scenario is related to the economic criterion and is based on the estimated future levelized cost of energy, and the second scenario analyzes the effects of fuel blending on the economic, technical and environmental criteria.

5.1. Scenario 1

The economic assessment performed in the base case, is based on capital and operational costs of commercially available technologies. Due to continued research and steep learning rates, existing literature projects price drops in some of the system components. Hydrogen production shows a steeper drop with expected 700 €/KW, OPEX of 2% of installed capacity for PEM electrolysers and 210 €/KW for stack replacements (Taibi et al., 2018). Also, electricity generation from offshore wind is projected to drop to 0.054 €/KWh (Valpy y English, 2017). As for methanol production, the biggest cost reductions are expected for the solar panels, with costs dropping to 544 €/KW by 2025 (Van Den Akker, 2017).

The AHP fuel scores are displayed in table 10. The scores show that the stakeholders do not agree on one alternative fuel, with policymakers and investors in favour of investing in methanol, while equipment manufacturers and fuel-producers are in favour of investing in hydrogen.

Stakeholder	Hydrogen Score	Methanol Score
Equipment manufacturer	0.505	0.495
Policymaker	0.468	0.531
Fuel-producer	0.582	0.417
Investor	0.483	0.517

Table 10: Alternative fuel scores for all stakeholders for the cost reduction scenario

5.2. Scenario 2

In this scenario, half of the fuel requirements for the power plants are assumed to be provided by conventional fossil fuels. Hydrogen fuel is blended with natural gas for the hydrogen fuel case, and renewable methanol is blended with grey methanol produced from natural gas. The results are shown in table 11. The AHP scores for fuel blending show that hydrogen outperforms methanol for a variety of reasons. The use of natural gas massively reduces the cost of energy generation, and the negative environmental impact of natural gas is offset with the use of hydrogen.

Stakeholder	Hydrogen Score	Methanol Score
Equipment manufacturer	0.549	0.451
Policymaker	0.564	0.435
Fuel-producer	0.580	0.420
Investor	0.544	0.456

Table 11: Alternative fuel scores for all stakeholders for the fuel blending scenario

6. Conclusions

This paper provides modifications to the AHP in order to contribute to evaluating alternatives for future sustainable energy systems. The method was applied to the selection of an alternative fuel for a peak power plant in Rotterdam. The technology readiness level developed by NASA is introduced as a technical indicator to assess the technological maturity of the entire fuel value chain. This paper proposes incorporating multiple perspectives from different stakeholders in the criteria weighting phase. By doing so, more conclusions can be made on the positions of each key stakeholder needed for the realization of the goals. Finally, a sensitivity analysis is preformed on the criteria of highest relevance for most stakeholders.

The proposed method is applied to select an alternative fuel selection for peak power plants in Rotterdam. Four different perspectives are represented in the criteria weightings which are the fuel producers, equipment manufacturers, investors and policy-makers. For the short-term there is an overwhelming support for hydrogen fuel blending over methanol among all four key stakeholders. This can prove to be enough impetus to encourage investment in the alternative fuel across the value chain from production to utilization. While for the long-term, where the goal would be 100% renewable fuel, the AHP results are less conclusive. With current technology and economic criteria in mind, methanol slightly outperforms hydrogen as the preferred alternative for three out of the four stakeholders. When future costs projections for the different sub-components of both systems are incorporated, stakeholders are divided in terms of their alternative fuel of choice, with two prioritizing hydrogen and two choosing methanol.

AHP as a decision-making tool is more commonly applied in the academic sector rather than in the industry. Further research is encouraged in incorporating AHP as a stakeholder engagement tool for early collective decision-making for sustainable energy development.

References

Aakko-Saksa, P. T., Cook, C., Kiviaho, J., Repo, T., 8 2018. Liquid organic hydrogen carriers for transportation and storing of renewable energy â Review and discussion. Journal of Power Sources 396, 803–823.
URL: https://www.sciencedirect.com/science/article/pii/S0378775318303483
DOI: `10.1016/J.JPOWSOUR.2018.04.011`

Acar, C., Beskese, A., Temur, G. T., 3 2019. A novel multicriteria sustainability investigation of energy storage systems. International Journal of Energy Research.
URL: http://doi.wiley.com/10.1002/er.4459
DOI: `10.1002/er.4459`

Adamson, K. A., Pearson, P., 2000. Hydrogen and methanol: A comparison of safety, economics, efficiencies and emissions. Journal of Power Sources.
DOI: `10.1016/S0378-7753(99)00404-8`

Aksyutin, O. E., Ishkov, A. G., Romanov, K. V., Grachev, V. A., 2018. The carbon footprint of natural gas and its role in the carbon footprint of the energy production. International Journal of GEOMATE.
URL: https://doi.org/10.21660/2018.48.59105
DOI: `10.21660/2018.48.59105`

Amer, M., Daim, T. U., 2011. Selection of renewable energy technologies for a developing county: A case of Pakistan. Energy for Sustainable Development 15 (4), 420–435.
URL: http://dx.doi.org/10.1016/j.esd.2011.09.001
DOI: `10.1016/j.esd.2011.09.001`

Bannister, R. L., Newby, R. A., Yang, W.-C., 1998. Final report on the development of a hydrogen-fueled combustion turbine cycle for power generation. Proceedings of the ASME Turbo Expo 3 (January 1999).
URL: https : / / www . scopus . com / inward / record . uri ? eid = 2 - s2 . 0 - 84971653764 & doi = 10 . 1115 % 2F98 - GT- 021 & partnerID = 40 & md5 = 094cfe288a15b2c904faeee347404eea
DOI: `10.1115/98-GT-021`

Brown, P., Fadok, J., Manager, P., Doe, S. ., Hydrogen, A., Program, T., 2007. Siemens Gas Turbine H2 Combustion Technology for Low Carbon IGCC. Tech. rep.
URL: https://www.globalsyngas.org/uploads/eventLibrary/29BROW.pdf

Burkhardt, J., Patyk, A., Tanguy, P., Retzke, C., 2016. Hydrogen mobility from wind energy â A life cycle assessment focusing on the fuel supply. Applied Energy 181, 54–64.
URL: http://dx.doi.org/10.1016/j.apenergy.2016.07.104
DOI: `10.1016/j.apenergy.2016.07.104`

Campos-Guzmán, V., García-Cáscales, M. S., Espinosa, N., Urbina, A., 2019. Life Cycle Analysis with Multi-Criteria Decision Making: A review of approaches for the sustainability evaluation of renewable energy technologies. Renewable and Sustainable Energy Reviews 104 (January), 343–366.
URL: https://doi.org/10.1016/j.rser.2019.01.031
DOI: `10.1016/j.rser.2019.01.031`

Castillo Ramírez, A., Mejía Giraldo, D., Muñoz Galeano, N., 3 2018. Large-scale solar PV LCOE comprehensive breakdown methodology. CT&F - Ciencia, Tecnología y Futuro 7 (1), 117–136.
DOI: `10.29047/01225383.69`

Chatzimouratidis, A. I., Pilavachi, P. A., 2008. Multicriteria evaluation of power plants impact on the living standard using the analytic hierarchy process. Energy Policy 36 (3), 1074–1089.
DOI: `10.1016/j.enpol.2007.11.028`

Crotogino, F., 1 2016. Larger Scale Hydrogen Storage. Storing Energy, 411–429.
URL: https : / / www . sciencedirect . com / science / article / pii / B9780128034408000208
DOI: `10.1016/B978-0-12-803440-8.00020-8`

Daim, T., Taha, R., 2013. Multi-Criteria Applications in Renewable Energy Analysis, a Literature Review. Green Energy and Technology 60, 17–31.
DOI: `10.1007/978-1-4471-5097-8`

Day, W. H., 2016. Methanol fuel in commercial operation on land and sea. Tech. rep., Gas Turbine World.
URL: http://www.methanol.org/wp-content/uploads/2016/12/Methanol-Nov-Dec-2016-GTW-.pdf

Gambhir, A., Few, S., Nelson, J., Hawkes, A., Schmidt, O., Staffell, I., 2017. Future cost and performance of water electrolysis: An expert elicitation study. International Journal of Hydrogen Energy 42 (52), 30470–30492.
URL: https://doi.org/10.1016/j.ijhydene.2017.10.045
DOI: `10.1016/j.ijhydene.2017.10.045`

Gökalp, I., Lebas, E., 8 2004. Alternative fuels for industrial gas turbines (AFTUR). Applied Thermal Engineering 24 (11-12), 1655–1663.
URL: https : / / www . sciencedirect . com / science / article / abs / pii / S1359431103003752
DOI: `10.1016/J.APPLTHERMALENG.2003.10.035`

Goldmeer, J., 2018. Fuel flexible gas turbines as enablers for a low or reduced carbon energy ecosystem. Tech. rep., General Electric Company.
URL: https://www.ge.com/content/dam/gepower/global/en_US/documents/fuel - flexibility / GEA33861 % 20 - %20Fuel % 20Flexible % 20Gas % 20Turbines % 20as % 20Enablers % 20for % 20a % 20Low % 20Carbon % 20Energy%20Ecosystem.pdf

Grond, L., Holstein, J., 2014. Power-to-gas: Climbing the technology readiness ladder. Tech. rep., DNV GL.
URL: www.northseapowertogas.com

Hadjipaschalis, I., Poullikkas, A., Efthimiou, V., 2009. Overview of current and future energy storage technologies for electric power applications. Renewable and Sustainable Energy Reviews 13 (6-7), 1513–1522.
DOI: `10.1016/j.rser.2008.09.028`

Lee, K.-M., Inaba, A., 2004. Life Cycle Assessment: Best Practices of International Organization for Standardization (ISO) 14040 Series. Tech. Rep. February, Center for Ecodesign and LCA (CEL).
URL: http://publications.apec.org/publication-detail.php?pub_id=453

Lee, M. C., Seo, S. B., Chung, J. H., Kim, S. M., Joo, Y. J., Ahn, D. H., 2010. Gas turbine combustion performance test of hydrogen and carbon monoxide synthetic gas. Fuel 89 (7), 1485–1491.
URL: http://dx.doi.org/10.1016/j.fuel.2009.10.004
DOI: `10.1016/j.fuel.2009.10.004`

Lee, S. K., Mogi, G., Kim, J. W., Gim, B. J., 2008. A fuzzy analytic hierarchy process approach for assessing national competitiveness in the hydrogen technology sector. International Journal of Hydrogen Energy.
DOI: `10.1016/j.ijhydene.2008.09.028`

Lensink, S., Pisca, I., 2018. Costs of offshore wind energy 2018. Tech. rep., PBL Netherlands Environmental Assessment Agency.
URL: www.pbl.nl/en.

Lin, J., Damato, G., 2011. Energy Storage - A Cheaper and Cleaner Alternative to Natural Gas-ÂFired Peaker Plants. Tech. rep., California Energy Storage Alliance.
URL: www.storagealliance.org

Liu, J., Zhang, J. G., Yang, Z., Lemmon, J. P., Imhoff, C., Graff, G. L., Li, L., Hu, J., Wang, C., Xiao, J., Xia, G., Viswanathan, V. V., Baskaran, S., Sprenkle, V., Li, X., Shao, Y., Schwenzer, B., 2013. Materials science and materials chemistry for large scale electrochemical energy storage: From transportation to electrical grid. Advanced Functional Materials.
DOI: `10.1002/adfm.201200690`

Medina, E., Roberts, R. R., 2013. Methanol Safe Handling Manual. Tech. rep., The Methanol Institute.
URL: www.methanol.org

Meijer, B., 2018. Netherlands to ban coal-fired power plants in blow to RWE - Reuters.
URL: https : / / www . reuters . com / article / us - netherlands - energy - coal / netherlands - to - ban - coal - fired - power - plants - in - blow - to - rwe - idUSKCN1IJ1PI

Murray, R. J., Furlonge, H. I., 2009. Market and Economic Assessment of Using Methanol for Power Generation in the Caribbean Region. The Journal of the Association of Professional Engineers of Trinidad and Tobago 38 (1), 88–99.

Niermann, M., Drunert, S., Kaltschmitt, M., Bonhoff, K., 1 2019. Liquid organic hydrogen carriers (LOHCs) â techno-economic analysis of LOHCs in a defined process chain. Energy & Environmental Science 12 (1), 290–307.
URL: http://xlink.rsc.org/?DOI=C8EE02700E
DOI: `10.1039/C8EE02700E`

Papalexandrou, M., Pilavachi, P., Chatzimouratidis, A., 9 2008. Evaluation of liquid bio-fuels using the Analytic Hierarchy Process. Process Safety and Environmental Protection 86 (5), 360–374.
URL: https://linkinghub.elsevier.com/retrieve/pii/S095758200800030X
DOI: `10.1016/j.psep.2008.03.003`

Parks, G., Boyd, R., Cornish, J., Remick, R., 2014. Hydrogen Station Compression, Storage, and Dispensing Technical Status and Costs: Systems Integration. Tech. Rep. May, National Renewable Energy Lab.(NREL), Golden, CO (United States).
URL: http://www.osti.gov/servlets/purl/1130621/
DOI: `10.2172/1130621`

Pilavachi, P. A., Stephanidis, S. D., Pappas, V. A., Afgan, N. H., 2009. Multi-criteria evaluation of hydrogen and natural gas fuelled power plant technologies. Applied Thermal Engineering 29 (11-12), 2228–2234.
URL: http://dx.doi.org/10.1016/j.applthermaleng.2008.11.014
DOI: `10.1016/j.applthermaleng.2008.11.014`

Raga Mexico, G., Nakajima, T., Ramanathan, V., Ramaswamy, V., Artaxo, P., Berntsen, T., Betts, R., Fahey, D., Haywood, J., Lean, J., Lowe, D., Myhre, G., Nganga, J., Prinn, R., Raga, G., Schulz, M., Van, R., Solomon, C., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K., 2007. Changes in Atmospheric Constituents and in Radiative Forcing. Tech. rep., n Climate Change 2007: The Physical Science Basis.
URL: http : / / www . cgd . ucar . edu / events / 20130729 / files / Forster - Ramaswamy-etal-2007.pdf

Ramsden, T., Kroposki, B., Levene, J., 2008. Opportunities for hydrogen-based energy storage for electric utilities. Tech. rep., Proceedings of the NHA annual hydrogen conference. Sacramento.
URL: nha.confex.com/nha/2008/recordingredirect.cgi/id/352

RVO, 2019. Offshore Wind Energy.

URL: https://english.rvo.nl/subsidies-programmes/offshore-wind-energy

Saaty, T. L., 2008. Decision making with the analytic hierarchy process. Tech. Rep. 1.
URL: http://www.rafikulislam.com/uploads/resourses/197245512559a37aadea6d.pdf

Shea, G. N., 2007. NASA Systems Engineering Handbook. Systems Engineering Handbook 6105 Rev1 (June), 360.
URL: https://www.nasa.gov/connect/ebooks/nasa-systems-engineering-handbook%0Ahttp://adsabs.harvard.edu/full/1995NASSP6105.....S%5Cnhttps://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20080008301.pdf
DOI: `10.1016/0016-0032(66)90450-9`

Taibi, E., Miranda, R., Vanhoudt, W., Winkel, T., Lanoix, J.-C., Barth, F., 2018. Hydrogen from renewable power: Technology outlook for the energy transition. Tech. rep., International Renewable Energy Agency.
URL: https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2018/Sep/IRENA_Hydrogen_from_renewable_power_2018.pdf

Taljan, G., Cañizares, C., Fowler, M., Verbič, G., 2008. The feasibility of hydrogen storage for mixed wind-nuclear power plants. IEEE Transactions on Power Systems 23 (3), 1507–1518.
DOI: `10.1109/TPWRS.2008.922579`

UNCTAD, ???? Review of Maritime Transport 2017 - Freight rates and maritime transport costs. Tech. rep., United Nations Conference on Trade and Development.
URL: https://unctad.org/en/PublicationChapters/rmt2017ch3_en.pdf

Valpy, B., English, P., 2017. Future renewable energy costs: offshore wind. Tech. rep., KIC InnoEnergy.
URL: http://www.innoenergy.com/wp-content/uploads/2014/09/KIC_IE_OffshoreWind_anticipated_innovations_impact1.pdf

Van Den Akker, J. H. A., 2017. Overview of costs of sustainable energy technologies Energy production: on-grid, mini-grid and off-grid power generation and supply and heat applications. Tech. rep.
URL: https://jhavdakk.home.xs4all.nl/ASCENDIS%20Cost%20of%20energy%20v2a.pdf

Vickers, J., 2017. Hydrogen Storage Technologies Roadmap Fuel Cell Technical Team Roadmap. Tech. Rep. July, U.S. Department of Energy.
URL: www.uscar.org

Wang, J.-J., Jing, Y.-Y., Zhang, C.-F., Zhao, J.-H., 12 2009. Review on multi-criteria decision analysis aid in sustainable energy decision-making. Renewable and Sustainable Energy Reviews 13 (9), 2263–2278.
URL: https://linkinghub.elsevier.com/retrieve/pii/S1364032109001166
DOI: `10.1016/j.rser.2009.06.021`

Wolf, E., 1 2015. Large-Scale Hydrogen Energy Storage. Electrochemical Energy Storage for Renewable Sources and Grid Balancing, 129–142.
URL: https://www.sciencedirect.com/science/article/pii/B9780444626165000097
DOI: `10.1016/B978-0-444-62616-5.00009-7`

Zheng, J., He, Q., Gu, C., Zhao, Y., Hua, Z., Li, K., Zhou, C., Zhong, S., Wei, C., Zhang, Y., 2016. High pressure 98 MPa multifunctional steel layered vessels for stationary hydrogen storage.

Zhou, P., Ang, B., Poh, K., 11 2006. Decision analysis in energy and environmental modeling: An update. Energy 31 (14), 2604–2622.
URL: https://www.sciencedirect.com/science/article/pii/S0360544205002264?via%3Dihub
DOI: `10.1016/J.ENERGY.2005.10.023`

Appendix A.

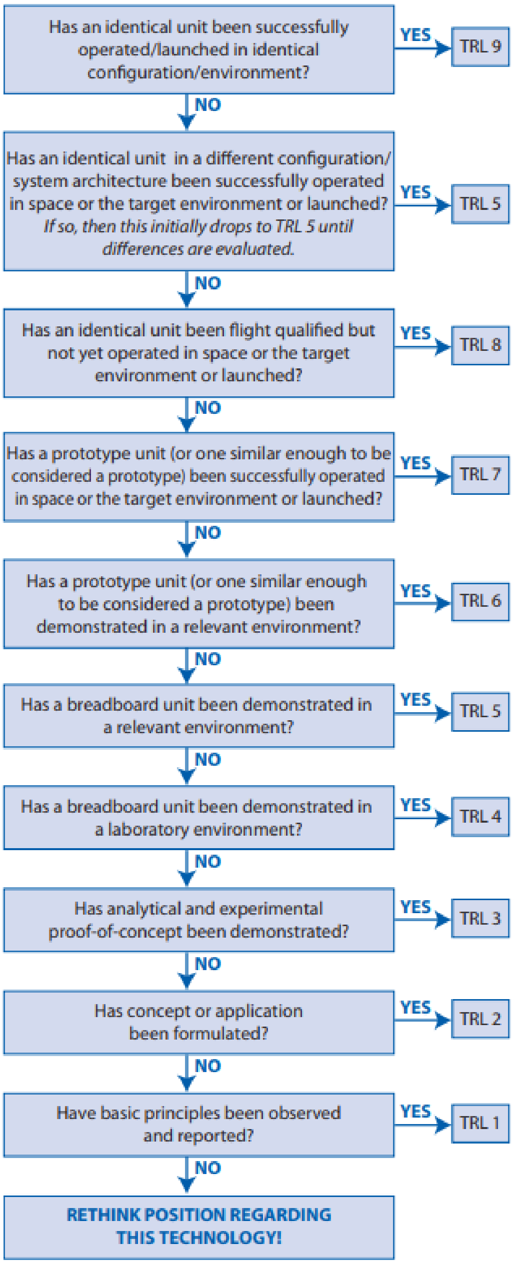

Figure G-5 The TMA thought process

Figure A.3: Technology readiness level framework (Shea, 2007)

B Peak power plants

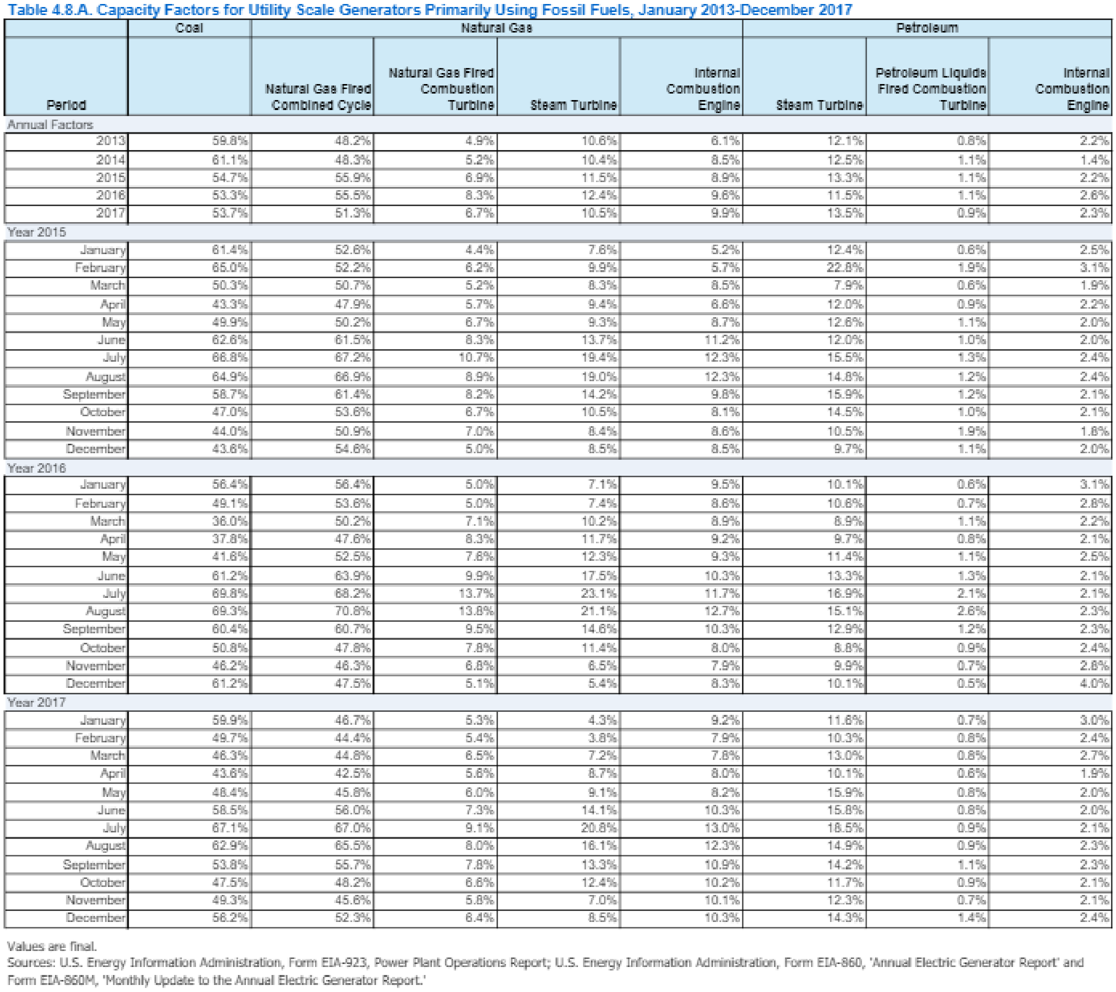

Table 4.8.A. Capacity Factors for Utility Scale Generators Primarily Using Fossil Fuels, January 2013-December 2017

Period	Coal	Natural Gas				Petroleum		
		Natural Gas Fired Combined Cycle	Natural Gas Fired Combustion Turbine	Steam Turbine	Internal Combustion Engine	Steam Turbine	Petroleum Liquids Fired Combustion Turbine	Internal Combustion Engine
Annual Factors								
2013	59.8%	48.2%	4.9%	10.6%	6.1%	12.1%	0.8%	2.2%
2014	61.1%	48.3%	5.2%	10.4%	8.5%	12.5%	1.1%	1.4%
2015	54.7%	55.9%	6.9%	11.5%	8.9%	13.3%	1.1%	2.2%
2016	53.3%	55.5%	8.3%	12.4%	9.6%	11.5%	1.1%	2.6%
2017	53.7%	51.3%	6.7%	10.5%	9.9%	13.5%	0.9%	2.3%
Year 2015								
January	61.4%	52.6%	4.4%	7.6%	5.2%	12.4%	0.6%	2.5%
February	65.0%	52.2%	6.2%	9.9%	5.7%	22.8%	1.9%	3.1%
March	50.3%	50.7%	5.2%	8.3%	8.5%	7.9%	0.6%	1.9%
April	43.3%	47.9%	5.7%	9.4%	6.6%	12.0%	0.9%	2.2%
May	49.9%	50.2%	6.7%	9.3%	8.7%	12.6%	1.1%	2.0%
June	62.6%	61.5%	8.3%	13.7%	11.2%	12.0%	1.0%	2.0%
July	66.8%	67.2%	10.7%	19.4%	12.3%	15.5%	1.3%	2.4%
August	64.9%	66.9%	8.9%	19.0%	12.3%	14.8%	1.2%	2.4%
September	58.7%	61.4%	8.2%	14.2%	9.8%	15.9%	1.2%	2.1%
October	47.0%	53.6%	6.7%	10.5%	8.1%	14.5%	1.0%	2.1%
November	44.0%	50.9%	7.0%	8.4%	8.6%	10.5%	1.9%	1.8%
December	43.6%	54.6%	5.0%	8.5%	8.5%	9.7%	1.1%	2.0%
Year 2016								
January	56.4%	56.4%	5.0%	7.1%	9.5%	10.1%	0.6%	3.1%
February	49.1%	53.6%	5.0%	7.4%	8.6%	10.6%	0.7%	2.8%
March	36.0%	50.2%	7.1%	10.2%	8.9%	8.9%	1.1%	2.2%
April	37.8%	47.6%	8.3%	11.7%	9.2%	9.7%	0.8%	2.1%
May	41.6%	52.5%	7.6%	12.3%	9.3%	11.4%	1.1%	2.5%
June	61.2%	63.9%	9.9%	17.5%	10.3%	13.3%	1.3%	2.1%
July	69.8%	68.2%	13.7%	23.1%	11.7%	16.9%	2.1%	2.1%
August	69.3%	70.8%	13.8%	21.1%	12.7%	15.1%	2.6%	2.3%
September	60.4%	60.7%	9.5%	14.6%	10.3%	12.9%	1.2%	2.3%
October	50.8%	47.8%	7.8%	11.4%	8.0%	8.8%	0.9%	2.4%
November	46.2%	46.3%	6.8%	6.5%	7.9%	9.9%	0.7%	2.8%
December	61.2%	47.5%	5.1%	5.4%	8.3%	10.1%	0.5%	4.0%
Year 2017								
January	59.9%	46.7%	5.3%	4.3%	9.2%	11.6%	0.7%	3.0%
February	49.7%	44.4%	5.4%	3.8%	7.9%	10.3%	0.8%	2.4%
March	46.3%	44.8%	6.5%	7.2%	7.8%	13.0%	0.8%	2.7%
April	43.6%	42.5%	5.6%	8.7%	8.0%	10.1%	0.6%	1.9%
May	48.4%	45.8%	6.0%	9.1%	8.2%	15.9%	0.8%	2.0%
June	58.5%	56.0%	7.3%	14.1%	10.3%	15.8%	0.8%	2.0%
July	67.1%	67.0%	9.1%	20.8%	13.0%	18.5%	0.9%	2.1%
August	62.9%	65.5%	8.0%	16.1%	12.3%	14.9%	0.9%	2.3%
September	53.8%	55.7%	7.8%	13.3%	10.9%	14.2%	1.1%	2.3%
October	47.5%	48.2%	6.6%	12.4%	10.2%	11.7%	0.9%	2.1%
November	49.3%	45.6%	5.8%	7.0%	10.1%	12.3%	0.7%	2.1%
December	56.2%	52.3%	6.4%	8.5%	10.3%	14.3%	1.4%	2.4%

Values are final.
Sources: U.S. Energy Information Administration, Form EIA-923, Power Plant Operations Report; U.S. Energy Information Administration, Form EIA-860, 'Annual Electric Generator Report' and Form EIA-860M, 'Monthly Update to the Annual Electric Generator Report.'

Figure 29: Typical capacity factors of natural gas peak power plant (Energy Information Administration, 2018)

C Environmental Assessment

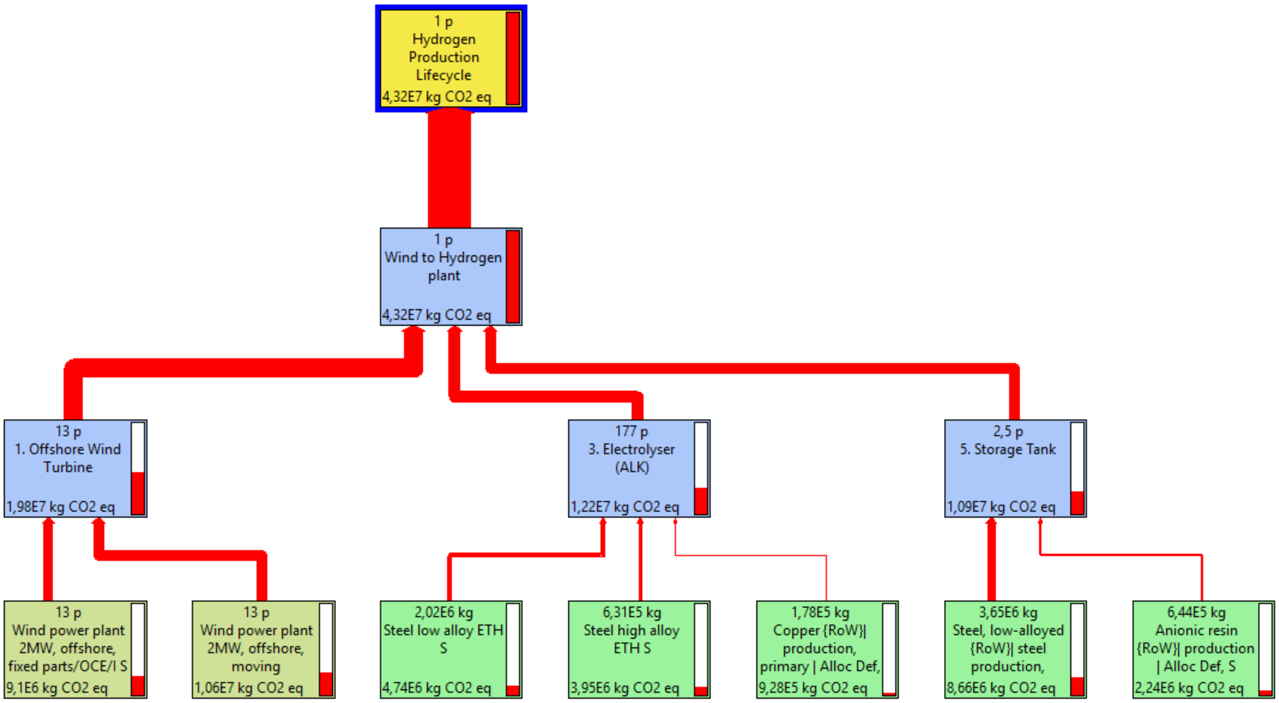

Figure 30: Network impact assessment for Hydrogen production

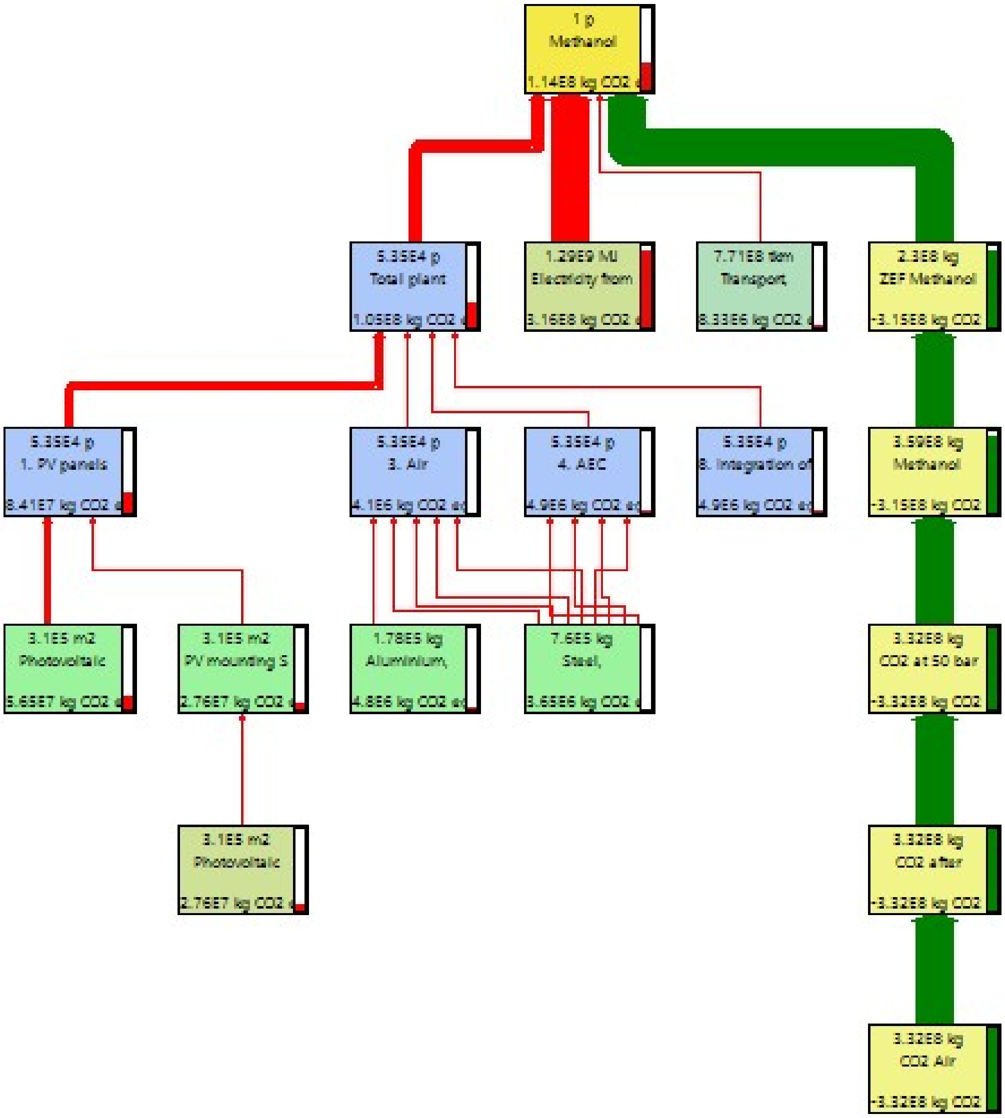

Figure 31: Network impact assessment for Methanol production

D Technology Readiness Level

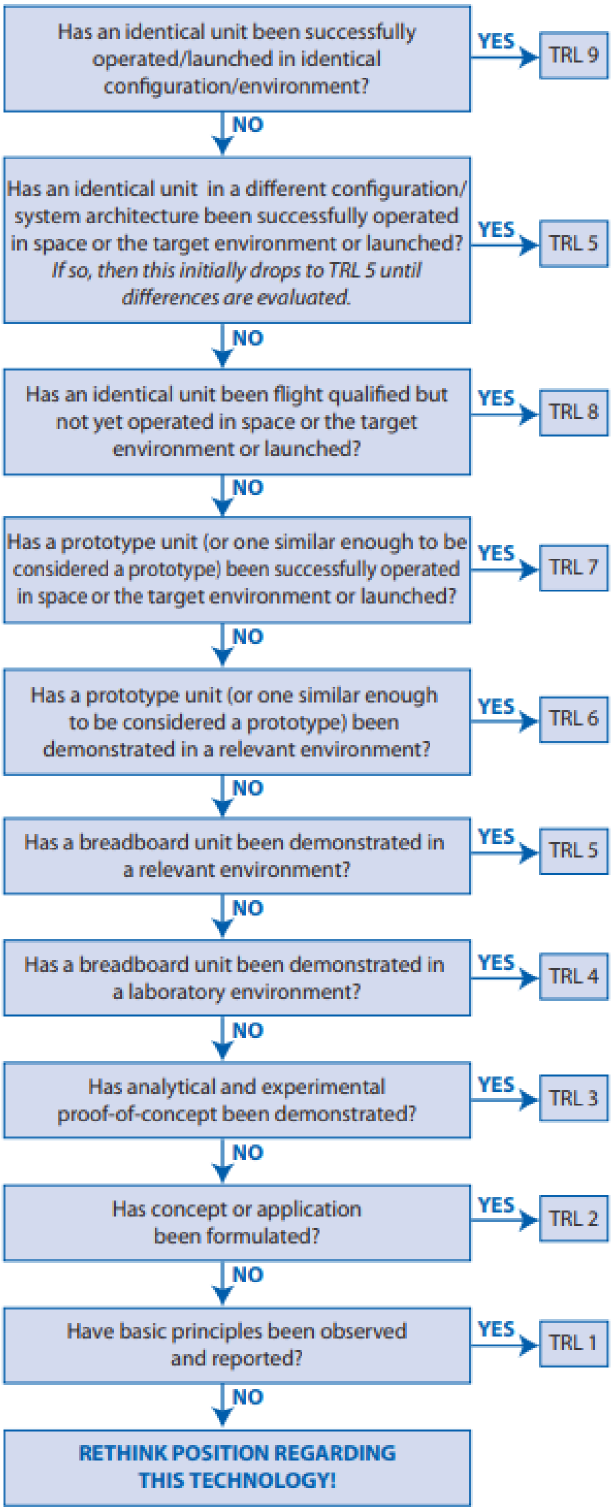

Figure G-5 The TMA thought process

Figure 32: Technology readiness level identification process (Shea, 2007)

E Survey tool

Please Fill out this survey

Name:

Position:

Multi-criteria weighting

Economic criteria are ……………………. to **Environmental** criteria:

☐ Extremely less important
☐ Very strongly less important
☐ Strongly less important
☐ Slightly less important
☐ Equally important
☐ Extremely more important
☐ Very strongly more important
☐ Strongly more important
☐ Slightly more important

Economic criteria are ……………………. to **Technical** criteria:

☐ Extremely less important
☐ Very strongly less important
☐ Strongly less important
☐ Slightly less important
☐ Equally important
☐ Extremely more important
☐ Very strongly more important
☐ Strongly more important
☐ Slightly more important

Economic criteria are ……………………. to **Social** criteria:

☐ Extremely less important
☐ Very strongly less important
☐ Strongly less important
☐ Slightly less important
☐ Equally important
☐ Extremely more important
☐ Very strongly more important
☐ Strongly more important
☐ Slightly more important

Technical criteria are ……………………. to **Environmental** criteria:

☐ Extremely less important
☐ Very strongly less important
☐ Strongly less important
☐ Slightly less important
☐ Equally important
☐ Extremely more important
☐ Very strongly more important
☐ Strongly more important
☐ Slightly more important

Technical criteria are ……………………. to **Social** criteria:

☐ Extremely less important
☐ Very strongly less important
☐ Strongly less important
☐ Slightly less important
☐ Equally important
☐ Extremely more important
☐ Very strongly more important
☐ Strongly more important
☐ Slightly more important

Environmental criteria are ……………………. to **Social** criteria:

☐ Extremely less important	☐ Equally important	☐ Extremely more important
☐ Very strongly less important		☐ Very strongly more important
☐ Strongly less important		☐ Strongly more important
☐ Slightly less important		☐ Slightly more important

<u>Economic Analysis:</u>

CAPEX costs are ……………………. to **OPEX costs**:

☐ Extremely less important	☐ Equally important	☐ Extremely more important
☐ Very strongly less important		☐ Very strongly more important
☐ Strongly less important		☐ Strongly more important
☐ Slightly less important		☐ Slightly more important

<u>Environmental Assessment</u>

Global Warming Potential (CO_2 equiv.) is ……………………. to **NOx** emissions:

☐ Extremely less important	☐ Equally important	☐ Extremely more important
☐ Very strongly less important		☐ Very strongly more important
☐ Strongly less important		☐ Strongly more important
☐ Slightly less important		☐ Slightly more important

<u>Social Assessment</u>

System safety is ……………………. to **Job creation** criteria:

☐ Extremely less important	☐ Equally important	☐ Extremely more important
☐ Very strongly less important		☐ Very strongly more important
☐ Strongly less important		☐ Strongly more important
☐ Slightly less important		☐ Slightly more important

System Safety is ……………………. to **Security of Supply**:

☐ Extremely less important	☐ Equally important	☐ Extremely more important
☐ Very strongly less important		☐ Very strongly more important
☐ Strongly less important		☐ Strongly more important
☐ Slightly less important		☐ Slightly more important

Security of Supply is ……………………. to **Job creation**:

☐ Extremely less important
☐ Very strongly less important
☐ Strongly less important
☐ Slightly less important

☐ Equally important

☐ Extremely more important
☐ Very strongly more important
☐ Strongly more important
☐ Slightly more important

Technical Assessment

Technology Readiness Level is ……………………. to **Energy efficiency** criteria: [Not sure about this one too]

☐ Extremely less important
☐ Very strongly less important
☐ Strongly less important
☐ Slightly less important

☐ Equally important

☐ Extremely more important
☐ Very strongly more important
☐ Strongly more important
☐ Slightly more important

Questions

As a decision maker, what **other sub-criteria** are relevant to you (if any) when investing in an alternative renewable fuel?

Economic	Environmental	Social	Technical
CAPEX *OPEX*	*CO_2* *NOx*	*Safety* *Security of Supply* *Job Creation*	*Technology Readiness* *Energy Efficiency*

As a decision maker, what **other criteria** are relevant to you when investing in an alternative renewable fuel? (*Other than economic, environmental, social and technical criteria*)

F Criteria Weighting

	Economic	Technical	Env.	Social
Economic	1	1/3	5	5
Technical	3	1	5	3
Environmental	1/5	1/5	1	1/5
Social	1/5	1/3	5	1

Table 26: Policy-maker pairwise matrix for all criteria with respect to the goal

	Economic	Technical	Env.	Social
Economic	1	9	1	1
Technical	1/9	1	1/7	1/7
Environmental	1	7	1	1
Social	1	7	1	1

Table 27: Electricity company pairwise matrix for all criteria with respect to the goal

	Economic	Technical	Env.	Social
Economic	1	5	1/3	1/5
Technical	1/5	1	1/3	1/5
Environmental	3	3	1	1
Social	5	5	1	1

Table 28: Fuel producer pairwise matrix for all criteria with respect to the goal

	Economic	Technical	Env.	Social
Economic	1	3	7	8
Technical	1/3	1	4	6
Environmental	1/7	1/4	1	3
Social	1/8	1/6	1/3	1

Table 29: Energy investor pairwise matrix for all criteria with respect to the goal

	Equipment Manufacturer	**Policy Maker**	**Energy Company**	**Energy Investor**
Economic				
CAPEX	26.5 %	15.8%	13%	29.0%
OPEX	26.5 %	15.8%	13%	29.0%
Technical				
TRL	12.2%	42%	3%	19.1%
Efficiency	18.2%	5%	3%	8.2%
Environmental				
CO2	8%	4.1%	22.4%	6.9%
NOx	3%	1.8%	9.6%	2.9%
Social				
System safety	4%	12.0%	27.7%	3.7%
Security of Supply	1.1%	2.9%	6.7%	0.9%
Job Creation	0.4%	1.1%	2.6%	0.4%

Table 30: Global criteria weights for all stakeholders

G Sensitivity Analysis

Fuel performance for both scenarios

Table 31: Summary of alternative fuel performance for cost reduction scenario

Criteria						**Outcome**						
	HYDROGEN	**9**	**7**	**5**	**3**	**1**		**3**	**5**	**7**	**9**	**METHANOL**
Economic												
CAPEX							✔					
OPEX							✔					
Technical												
TRL								✔				
Efficiency					✔							
Environmental												
CO2				✔								
NOx				✔								
Social												
System safety						✔						
Security of Supply		✔										
Job Creation		✔										

Table 32: Summary of alternative fuel performance for fuel blending scenario

Criteria	**Outcome**												
	HYDROGEN	**9**	**7**		**5**	**3**	**1**		**3**	**5**	**7**	**9**	**METHANOL**
Economic													
CAPEX								✔					
OPEX							✔						
Technical													
TRL									✔				
Efficiency						✔							
Environmental													
CO2				✔									
NOx									✔				
Social													
System safety							✔						
Security of Supply		✔											
Job Creation		✔											