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Energy Policy 00 (2019) 1–8

www.elsevier.es/RII

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

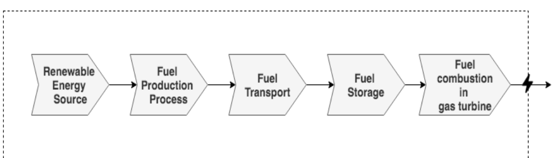

Figure 1: System boundaries

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

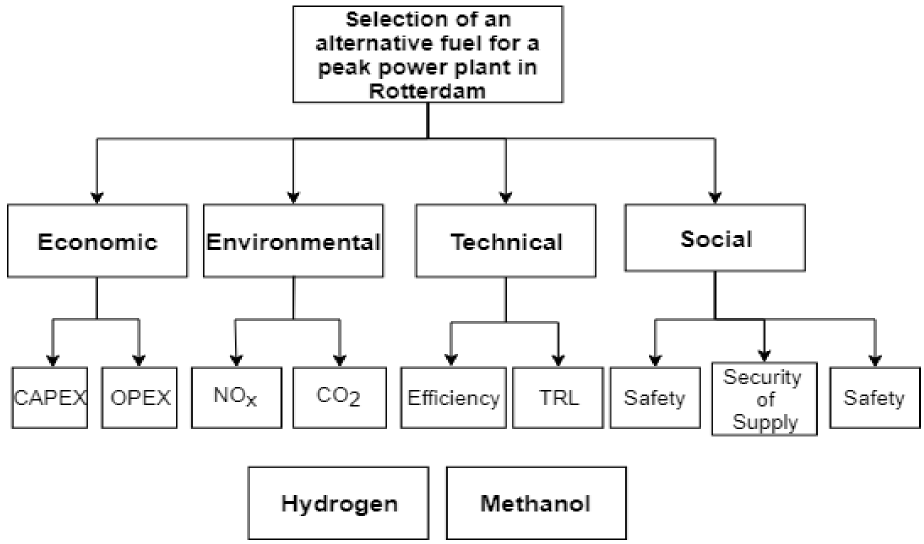

Figure 2: Analytic hierarchy tree for selecting an alternative fuel for peak power plants

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

	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

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.

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.

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Appendix A.

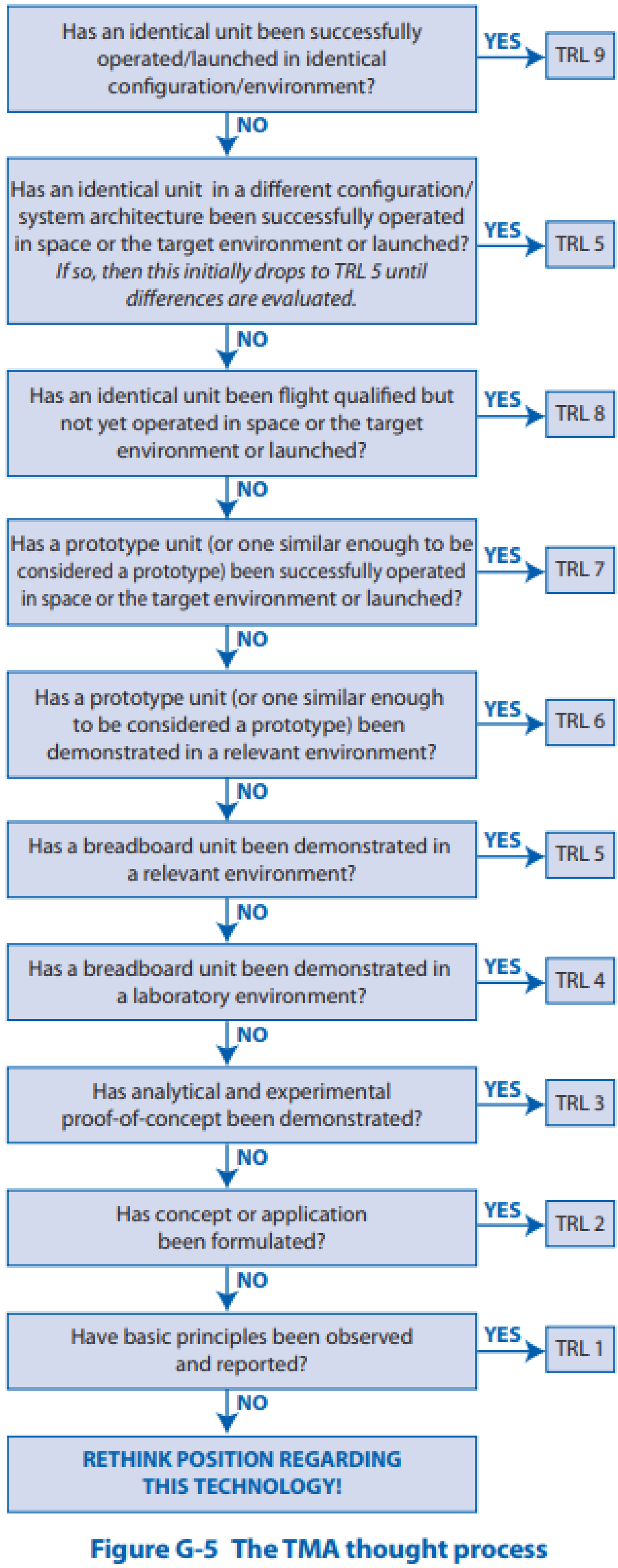

Figure A.3: Technology readiness level framework (Shea, 2007)