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Multi-Criteria Examination of Power-to-Gas Pathways under Stochastic Preferences

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Abstract: Power-to-gas is an energy storage and vector technology which can utilize off-peak power, assist in the integration of renewable power and provide needed fuel for industry and transportation. Further, power-to-gas is a useful technology for balancing surplus baseload and renewable energy generation with demand. There are numerous applications of power-to-gas in Europe, where renewable power is used to generate hydrogen for numerous applications. Examining each of these power-to-gas pathways across quantitative and qualitative criteria, this paper utilizes the stochastic fuzzy analytic hierarchy process to determine criteria weights. These weights are then fed to a multiple criteria decision analysis tool to determine the viability of each pathway for investors and policy makers. A sensitivity analysis is carried out by reprioritizing the criteria and re-evaluating the multiple criteria analysis. The two pathways that score highest under multiple criteria rankings are power-to-gas to mobility-fuel and power-to-gas-to-power, due to their established technologies, lower costs and environmental performance. By extension, both of these power-to-gas pathways are the most appropriate ways for this technology to be implemented, due to their combination of public familiarity, emissions reductions, and developed, available technologies.

Keywords: power-to-gas; energy storage; fuzzy analytic hierarchy process; renewable energy integration; imprecise pairwise comparisons; decision making

1. Introduction

Today, most developed and developing countries adopt strict strategies to utilize renewable energies as clean alternative sources of power. The widespread adoption of green electricity is spurred by the need to reduce the effects of greenhouse gases on the planet [1]. The continuous implementation of renewable energy sources worldwide will develop well-advanced and efficient technologies and reduce overall costs. Renewable energy, by its nature, is intermittent; thus, energy storage facilities are indispensable. Using renewable sources without energy storage would leave the grid prone to intermittent periods where the supply and demand for power would not match. This disjunct between supply and demand includes the situation of excess power, which must be sold at a loss to balance the system [2]. To solve these dilemmas, it is necessary to examine different energy storage solutions for each application. Common energy storage technologies, including batteries, super-capacitors, compressed air energy storage (CAES), flywheels and power-to-gas have been compared for their transport efficiency, energy density and appeal to consumers, among other criteria [3–7]. In practice, only power-to-gas energy storage is equipped for storing vast quantities of energy for months at a time and for transporting energy long distances with minimal losses [3–6].

Power-to-gas is an energy transportation and storage method, where energy produced during periods of surplus grid or by renewable energy technologies is used to produce hydrogen, which can be stored and used to produce electricity, renewable natural gas, or be used by hydrogen end users [8]. In addition, a power-to-gas system can be used to transport energy long distances using the inherent efficiency of pipelines. Such a system can interact with pre-existing infrastructure, be created as an independent micro-grid, or be used to create an urban energy network of independent energy hubs [9,10]. In Figure 1, below, the theoretical layout of a power-to-gas system is given. From left-to-right, the system components are energy supply, energy conversion, transmission/storage, distribution, conversion and final use. The hydrogen produced by electrolysis is then fed to end users or injected into natural gas pipelines. The mixed gas in the pipelines, called hydrogen enriched natural gas (HENG), can be sold directly to natural gas customers, sent through a combined cycle gas turbine (CCGT) to generate electricity, or can be separated into hydrogen and natural gas, using a pressure swing absorber, before being delivered to customers.

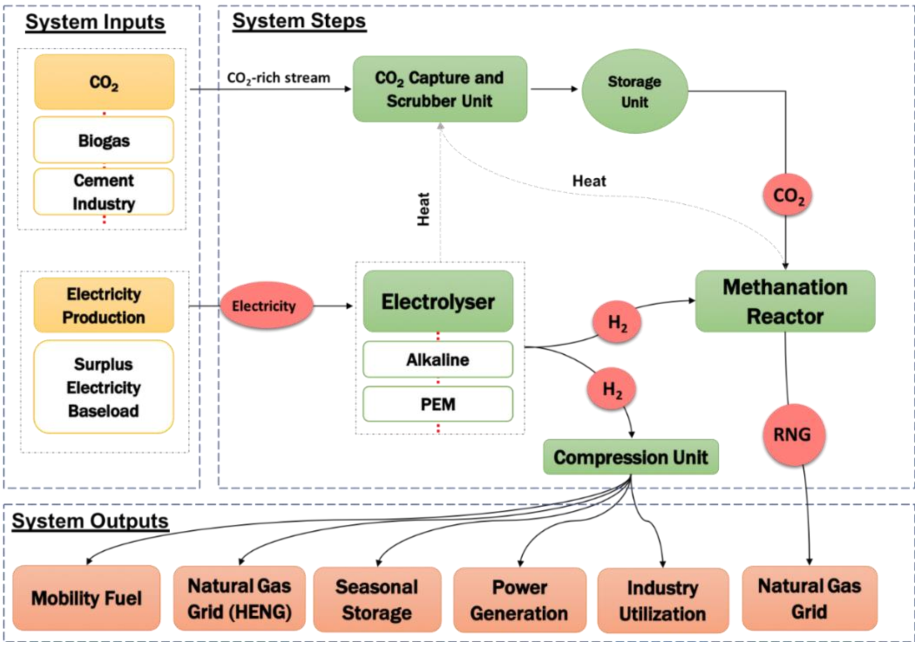

Figure 1. Power-to-gas Energy System [8,11].

In this study, multiple criteria decision analysis (MCDA), a decision support system, is employed, to determine the best power-to-gas pathways in terms of future investment suitability. This decision will be of use to utilities, technology firms, and investors. MCDA has its roots in linear optimization and the simplex method [12,13]. One of the most rigorous multiple-criteria decision making techniques is the analytic hierarchy process (AHP), which utilizes pair-wise comparisons of criteria to create criterion weighting [14]. To strengthen the application of AHP, fuzzy set theory is added to the process, yielding fuzzy analytic hierarchy process (FAHP) [15,16]. Applying FAHP for the selection of the best power-to-gas pathway is discussed in further detail in the succeeding section. Table 1, below, illustrates the examined power-to-gas pathways, which align with previously determined energy services [17].

Table 1. Power-to-gas Pathways.

Pathways	Description
Power-to-Gas to Mobility Fuel	Hydrogen used to power hydrogen fuel cell vehicles
Power-to-gas to Hydrogen Enriched Natural Gas	Hydrogen injected into natural gas pipelines
Power-to-gas to Seasonal Storage	Hydrogen long-term storage in tanks or underground caverns
Power-to-gas to Industry	Hydrogen for use in industry
Power-to-gas to Power	Hydrogen stored in a fuel cell to produce electricity
Power-to-gas to Methanation	Hydrogen used to upgrade biogas to renewable natural gas

Review of Power-to-Gas and Decision Analysis

There are numerous global power-to-gas pilot plants, including projects in Germany where the Reichstag is planning to meet 50% of the nation's energy demand with renewable power by 2030 [18–20]. These projects demonstrate the potential for power-to-gas systems to help facilitate greater renewables penetration into the power grid. Within the power-to-gas system, the hydrogen generated by electrolysis is an energy vector—A form of energy that can be efficiently stored and transported. Even though the capital cost associated with storing and distributing hydrogen is quite high, the concept would work well in jurisdictions that can utilize an existing natural gas grid infrastructure to store and transport hydrogen. As hydrogen is an excellent energy vector with low losses in transit in comparison to the transit of electricity in the electrical grid, power-to-gas would make an excellent energy storage and transmission system to support power generation and demands and transportation fuel [21].

In each of the above described pathways, an electrolyzer is used to create hydrogen. Although the performance of power-to-gas pathways is the same for some criterion, there are many differences between them. For example, the methodology to evaluate power-to-gas to mobility fuel and power-to-gas to seasonal storage is different. For power-to-gas to seasonal storage, the electrolyzer could operate either at 100%, or whenever there is a disjunct is between the supply and demand of electricity. This hydrogen could be stored in a number of ways. For example, tanks could be used to store hydrogen on-site at utility or commercial facilities. Hydrogen could also be injected into disused underground storage areas, which previously contained natural gas, using the billions of cubic feet of vacant underground natural gas storage areas in areas like Ontario [22]. Hydrogen could be injected into the natural gas grid. Of the total volume available, hydrogen could take up 5% to 20% by volume, in order to avoid the embrittlement of natural gas pipelines [23–25]. If the conservative estimate is used, the maximum volume available for storing hydrogen would be 5% of the 155 billion cubic feet available—which is 7.75 billion cubic feet of hydrogen or 78,400 MWh of energy. This is enough to power about 3470 U.S. households for a year [26].

Energy systems are socio-technical systems and thus, it is useful to employ a socio-technical engineering tool in their evaluation [27,28]. Decision tools, such as MCDA, AHP and FAHP, are socio-technical tools for understanding and evaluating these types of complex systems. In the analysis section given below, the application of systematic decision tools for evaluating and selecting power-to-gas pathways are discussed. The six power-to-gas pathways described in Table 1 are analyzed by applying each pathway over a series of eight criteria, shown in Table 2, to evaluate their technical, societal, environmental and economic performance. The first criterion, technology prevalence, evaluates how commonly available the technology is, based on the number of operating facilities in comparison to operating substitute facilities. For example, the prevalence of hydrogen for transportation can be seen by comparing the number of hydrogen-refueling stations to the number of gasoline-refueling stations. The second criterion, pathway efficiency, is a measure of what proportion of energy delivered to the power-to-gas system arrives at the end user. The third and fourth criteria examine the environmental impact by determining the amount of greenhouse gases (GHG) and volatile organic compounds (VOC) that are reduced per unit of energy. The GHG emissions are measured in mass of carbon dioxide equivalents (CO_2e), whereby the weighted sum of all the mass of greenhouse gases are added, using global warming potentials [29]. Both the GHG and VOC reductions are calculated by examining the fuel production and use phases of the life cycle. Neither the production of the end use technology, nor the production of new equipment, is included in this assessment. The fifth criterion, capital costs of hydrogen storage and handling, is a measure of the cost of all new handling and storage equipment. For example, in the hydrogen enriched natural gas (HENG) scenario, the cost of the compressors are included, but the cost of the natural gas infrastructure is not. Profitability, the sixth criteria, is a measure of the overall profit per kg of H_2 produced per hour. The final two criteria, public acceptance and safety, are examinations of two societal questions. The first question is: will the technology by accepted by the public? The results of this criterion are closely related to the first criterion, technology prevalence, and is determined from a survey of existing corporations and systems in industry and community. In certain situations, such as power-to-gas to industry, "Public Acceptance" refers to the acceptance of technology by industries such as ammonia production and petroleum distillation. The final criterion, safety, is determined by calculating the risk to the public due to an explosion of hydrogen. Risk is calculated by multiplying the probability of an explosion event by the predicted severity of the explosion event. Although the thermodynamic properties and explosion risk of hydrogen is inherent to the material, the risk will be impacted by the temperature, pressure, mass of hydrogen stored in the application and the proximity of the application to populations of people.

Table 2. Criteria for the Analysis of power-to-gas Pathways.

Criteria	Description
Technology Prevalence	The number of existing operating facilities
Pathway Efficiency	The amount of energy delivered per unit of input energy
Reduction in Emissions of CO_2e	The mass of CO_2e emissions prevented through the use of the pathway
Reduction in Emissions of volatile organic compounds (VOC)	The mass of VOC emissions prevented through the use of the pathway
Capital Costs	The total capital cost of equipment (excluding pre-existing infrastructure)
Profitability	The total profitability per hour.
Public Acceptance	The familiarity of the public with the pathway
Safety	The calculated safety risk from system failure

Each pathway is evaluated using FAHP, a tool used in conjunction with a multiple criteria decision analysis for evaluating numerous options against a set of criteria. Previous analyses of hydrogen energy systems have examined the hydrogen fuel processors and the applications of power-to-gas [3,30]. Other analyses have examined hydrogen production methods using AHP, with an integrated decision tool and fuzzy sets [31,32]. FAHP is applied to determine the correct weighting of criteria through fuzzy stochastic pairwise comparisons and relies on expert judgments to derive priority scales [14]. The data themselves are also scaled such that when the score for each criterion is combined in a weighted sum, the magnitude of the data does not skew the analysis.

FAHP is useful for modeling complex decisions which incorporate knowledge and judgments under uncertainty. The issues involved are clearly articulated, evaluated, debated, and prioritized. The development of decision tools, often referred to as decision support systems, is concerned with weighing criteria, in order to best meet the demands of sub-objectives and higher order objectives [14,33].

2. Materials and Methods

To evaluate each of the pathways from Table 1 over the given criteria from Table 2, FAHP is applied in conjunction with a simple additive weighting (SAW) MCDA, as illustrated in Figure 2. In this analysis, these criteria are technology prevalence, pathway efficiency, reduction in greenhouse gas emissions, reduction in volatile organic compound emissions, capital costs, overall profitability, public acceptance and safety. Next, the importance of each weight is quantified as a criteria weight. In the following subsection, the analytic hierarchy process—which is used to determine the weights for each criterion—is described. Once the weights have been calculated, each of the eight criteria is evaluated for each of the 6 pathways, giving 48 data points. Next, the data points are scaled, and each pathway is evaluated using MCDA.

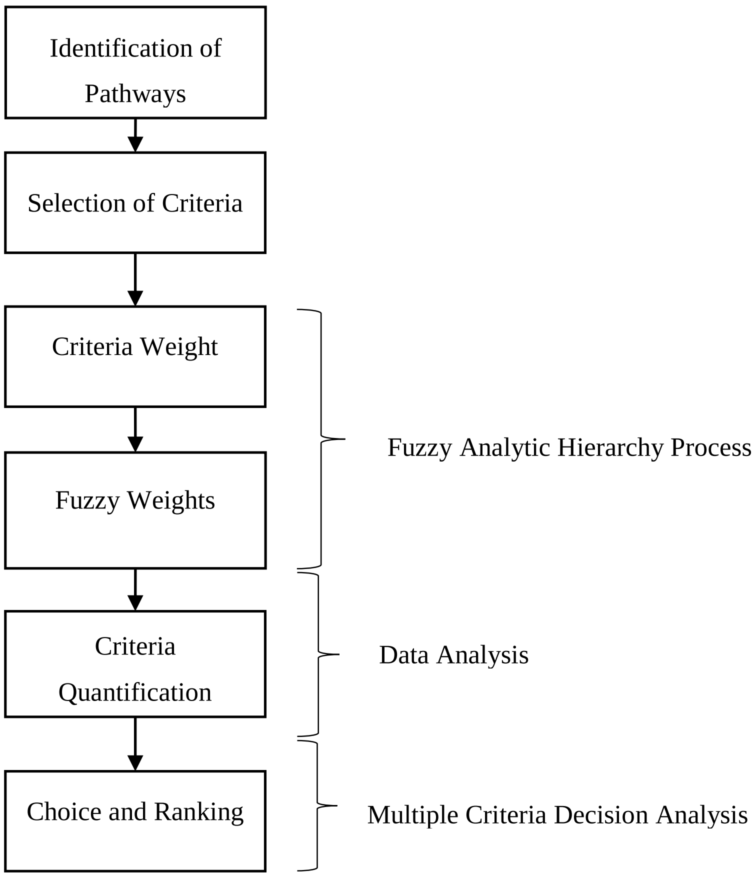

Figure 2. Application of Fuzzy Analytic Hierarchy Process for Selection of power-to-gas Pathways.

In AHP (and fuzzy AHP), a dilemma is broken down into subsystems, constructing hierarchic levels that reduce decision complexity. In this way, the complex weights are determined through the combination of numerous pairwise comparisons. Each level of the hierarchy consists of independent elements. The compulsory components of an AHP model are the goal, the alternatives to reach the goal, and the criteria to evaluate how the alternatives can satisfy the goal for each specific criterion. In every possible decision, there is a goal and a finite set of alternatives, $X = \{x_1, ..., x_n\}$, from which a decision maker may choose [14]. By individual comparisons of criteria, the complex preference relationships between each criteria are determined, using the 1 to 9 importance basis proposed by Saaty [14], whereby a value of 1 suggests an equal level of importance and a value of 9 suggests that one criteria is extremely more important than the other. The value of each entry i, j in this comparison matrix is a comparison between the criteria in row i and in column j. In the reciprocal location (j, i), the value of the comparison is always the reciprocal of the value in location (i, j).

Once a matrix of individual comparisons is created, a consistency index (*C.I.*) is calculated to insure the pairwise comparisons agree with a transitive preference structure, as shown below in Equation (1). Optimally, the value of *C.I.* will be below 0.1 for each analysis.

$$C.I. = \frac{\lambda_{max} - n}{n - 1} \tag{1}$$

where λ_{max} is the maximum eigenvalue of the pairwise comparison matrix and n is the number of criteria.

In order to accommodate uncertainty in decision making, fuzzy sets can be utilized. Specifically, fuzzy sets can be used to aid in the precision of selecting the one-to-one preferences described in Saaty's semantic scale and illustrated in Table 3 [14]. Below, some of the mathematical framework of fuzzy sets are laid out.

Table 3. Saaty's Fuzzified Semantic Scale [15].

Degree of Importance	Level of Importance	Triangular Fuzzy Number
1	Equal	(1,1,1)
2	Weak	(1,2,3)
3	Moderate	(2,3,4)
4	Moderate Plus	(3,4,5)
5	Strong	(4,5,6)
6	Strong Plus	(5,6,7)
7	Very Strong	(6,7,8)
8	Very, very strong	(7,8,9)
9	Extreme	(9,9,9)

1. A fuzzy set A in the space of points X is defined by the membership function f_A(x), which associates each point in the domain X a value in the set [0, 1]. The value of f_A(x) is the grade of membership of X to fuzzy set A, with A representing the highest such grade [16].
2. The complement of a fuzzy set A, denoted A', is such that $f_{A'}$(x) = 1 − f_A(x).
3. The union of 2 fuzzy sets A and B is $C = A \cup B$ such that $f_c(x) = Max[f_A(x), f_B(x)]$ where $x \in X$.
4. The intersection of 2 fuzzy sets A and B is $D = A \cap B$, such that $f_D(x) = Min[f_A(x), f_B(x)]$, where $x \in X$.
5. A triangular membership function for a fuzzy number between t_1 and t_3 with a peak at t_2 in the space X can be defined such that:

$$f(x) = \begin{cases} 0,\ x < t_1 \\ \frac{x-t_1}{t_2-t_1}, t_1 \le x \le t_2 \\ \frac{t_3-x}{t_3-t_2}, t_2 \le x \le t_3 \\ 0,\ x > t_3 \end{cases}$$

Additionally, the triangular membership function, or triangular fuzzy number, can be defined as a three-member point made up of the lower, middle and upper values of the function *M* = (*l*, *m*, *u*). Using this definition, Saaty's semantic system is fuzzified below in Table 3 [15].

In order to apply these triangular fuzzy numbers to the AHP pairwise comparisons, it is necessary to calculate the reciprocal of the triangular fuzzy number, as shown below in Equation (2).

$$\frac{1}{M} = M^{-1} = \left(\frac{1}{u}, \frac{1}{m}, \frac{1}{l}\right) \tag{2}$$

Once the pairwise comparison table has been converted to fuzzy sets, a selection of fuzzy weights are calculated for the triangular fuzzy selection by the following equation:

$$r_i = \left(\left(\prod_{i=1}^{n} l_i \right)^{\frac{1}{n}}, \left(\prod_{i=1}^{n} m_i \right)^{\frac{1}{n}}, \left(\prod_{i=1}^{n} u_i \right)^{\frac{1}{n}} \right) \times \left(\sum_{j=1}^{m} M \right)^{-1} \tag{3}$$

Next the, fuzzy weights are defuzzified into a singular weight using a center of area approach.

$$w_i = \frac{l_i + m_i + u_i}{3} \tag{4}$$

$$\hat{w}_i = \frac{w_i}{\sum_{i=1}^{n} w_i} \tag{5}$$

Using the above-mentioned criteria, each of the renewable power technologies is compared using a combination of fuzzy AHP and the aforementioned SAW method. The total score for each alternative under this method is calculated by Equation (6), below.

$$S_j = \sum_{i=1}^{m} \omega_j r_{ij} \tag{6}$$

here ω_i is the weight given criterion i, r_{ij} is the score for alternative j at criterion i and S_j is the total combined score for alternative j. Using the methodology, the option with the greatest score, S_i, is the selected option. As the goal of this approach to MCDA is to maximize the score, it is essential that data is quantified in such a way that a higher score is more desirable. For example, when examining the safety risk from specific pathways, it is preferable to have a lower risk number—as opposed to a higher risk number. In these cases, the scores are reordered from descending to ascending with improved performance, as given in Equation (7).

$$S_{ascending} = 1 - S_{descending}^{max} \tag{7}$$

After the scores for each of the alternatives are tabulated, the option with the maximum score is selected. In order to determine the robustness of the results to variations in the criteria, multiple scenarios of criteria weighting are evaluated.

3. Results

The criteria listed in Table 2 are sorted into four key performance areas given in Table 4: technological, environmental, economic, and social performance. The technological performance encapsulates technology readiness and pathway efficiency; the environmental performance includes greenhouse gas emissions and volatile organic compound emissions reductions; the economic performance area includes the overall capital cost and overall operating costs; and, the social performance area includes public acceptance and safety. In the tables below, each of the criteria is evaluated and tabulated to compare the six power-to-gas pathways.

Table 4. Analytic Hierarchy Process Comparison Criteria.

Performance Areas	Criteria
T: Technological	T1: Technology Readiness T2: Pathway efficiency
E: Environmental	E1: Greenhouse Gas E2: Volatile Organic Compound
C: Economic	C1: Overall capital cost (CAPEX) C2: Profitability
S: Social	S1: Public Acceptance S2: Safety

Each of the performance areas: technological, environmental, economic and social, are examined using literature values. Then, these data are used to ascertain a preferred power-to-gas pathway, using AHP and SAW MCDA as decision tools.

3.1. T1: Technology Readiness

Criterion T1 is a measure of market readiness of each power-to-gas pathway. T1 is quantified by counting the number of pilot plants and fully commercialized facilities available up to the present time via a thorough literature review, as illustrated in Table 5. The power-to-gas to mobility fuel pathway supports the use of hydrogen-powered vehicles, in which hydrogen is produced via electrolysis. Worldwide, 53 power-to-gas stations use electrolysis technology for transportation purposes: 19 in the U.S., seven in Denmark, four in England, three in Germany, three in India, three in Italy, two in Canada, one in Belgium, one in Brazil, one in China, one in Japan, one in the Netherlands, one in Norway, one in Scotland, one in South Korea, one in Spain, one in Taiwan, one in Turkey, and one in Wales [34–37]. Furthermore, two power-to-gas to HENG projects have been implemented; one in Australia, and the other one in the U.S. [38,39]. Only one power-to-gas project, in Germany, utilizes a seasonal storage facility [40]. In addition, the number of power-to-gas to industry projects are 17,000 facilities, if the use of hydrogen fuel cell forklifts is included [41,42]. Furthermore, the use of hydrogen fuel cells for power storage (power-to-power) is increasingly common, with over 100,000 in Japan and the United States alone [41]. Moreover, there are 43 power-to-gas to methanation projects around the globe [43].

Table 5. Number of power-to-gas Projects per Pathway—Readiness Score.

Power-to-Gas Pathway	Number of Projects	Order of Magnitude	Readiness Score
Power-to-Gas to Mobility Fuel	53 [34–37]	1.7	0.133
Power-to-Gas to hydrogen enriched natural gas (HENG)	2 [38,39]	0.3	0.023
Power-to-Gas to Seasonal Storage	1 [40]	0	0.000
Power-to-Gas to Industry	17,000 [41,42]	4.2	0.328
Power-to-Gas to Power	100,000+ [41]	5	0.391
Power-to-Gas to Methanation	43 [43]	1.6	0.125

3.2. T2: Pathway Efficiency

The overall efficiency of each power-to-gas pathway is evaluated by determining the amount of energy delivered and the amount that can be used as electric or fuel energy. The efficiency itself is evaluated as a range, and the average of the minimum and maximum efficiency is used. Although it is not directly related to cost or greenhouse gas emissions, efficiency is indirectly tied to these criteria. Table 6 shows the calculated efficiencies of the examined power-to-gas pathways based on previous study [44]. Power-to-gas to industry and power-to-gas to mobility fuel are, on average, the most efficient power-to-gas pathways, because there is only one energy conversion taking place. However, power-to-power pathway contains a longer energy conversion chain, i.e., electricity-to-gas-to-electricity, again, causing more energy losses. The efficiency of each of the power-to-gas streams is lower that of Li-Ion batteries (87–92%), however, the transmission of hydrogen gas is more efficient than the transmission of electricity [4,10].

Table 6. Efficiency of power-to-gas Pathways—Efficiency Score.

Power-to-Gas Pathway	% Efficiency [44]	Average Efficiency	Efficiency Score
Power-to-Gas to Mobility Fuel	50–79%	64.5%	0.205
Power-to-Gas to HENG	18–83%	50.5%	0.160
Power-to-Gas to Seasonal Storage	34–68%	51%	0.162
Power-to-Gas to Industry	55–83%	69%	0.219
Power-to-Gas to Power	17–40%	28.5%	0.090
Power-to-Gas to Methanation	40–63%	51.5%	0.163

3.3. E1: Greenhouse Gas

Table 7 illustrates GHG reductions associated with each power-to-gas pathway. Each of these reductions has been calculated by comparing the use of the power-to-gas pathway with the conventional alternative. For example, the reduction for power-to-gas to mobility fuel is evaluated by comparing the emissions from traditional internal combustion engine vehicle and the hydrogen fuel cell vehicles emissions, which is almost nothing [45]. The power-to-gas to HENG reduction is calculated by comparing the emissions from hydrogen enriched natural gas with typical natural gas emissions for heating and power generation applications. The power-to-gas to power pathway greenhouse gas reduction is determined by comparing the average amount of emissions produced by the electric grid with that from renewable energy produced and stored in a hydrogen fuel cell. The power-to-gas to methanation pathway greenhouse gas emissions reduction is determined by contrasting the power-to-gas scenario with the extraction of conventional natural gas and the emissions from un-sequestered agricultural waste. Due to the high level of emissions that can be mitigated by both methanation and fuel cell vehicles, power-to-gas to methanation and power-to-gas to mobility fuel have the best GHG reduction scores.

Table 7. Greenhouse gas (GHG) Reductions for power-to-gas Pathways—GHG Reduction Score.

Power-to-Gas Pathway	g CO_2e Reduction Per kg of H_2	GHG Reduction Score
Power-to-gas to Mobility Fuel	10,143 [46]	0.845
Power-to-gas to HENG	5.64 [47]	0.000
Power-to-gas to Seasonal Storage	5.64 [47]	0.000
Power-to-gas to Industry	5.64 [47]	0.000
Power-to-gas to Power	1667 [47]	0.139
Power-to-gas to Methanation	173.4 [48]	0.014

3.4. E2: Volatile Organic Compounds

VOCs are organic compounds which are generally emitted as vapors during industrial processes. VOCs can cause allergic reactions, irritations, liver and kidney damage and, in some cases, cancer [49]. In Table 8, the mass in grams of VOCs per kg of H_2 is given for each pathway. As it is preferable to reduce the emissions of VOCs and thus their ill effects, the difference between the highest emissions factor and that of the specific pathways as expressed by Equation (7).

Table 8. VOC Emissions for power-to-gas Pathways—VOC Reduction Score.

Power-to-Gas Pathway	g VOCs Per kg of H_2	Deviation g VOCs Per kg of H_2	VOC Reduction Score
Power-to-gas to Mobility Fuel	3.4 [46]	0	0.000
Power-to-gas to HENG	0.0021 [47]	3.3979	0.211
Power-to-gas to Seasonal Storage	0.0021 [47]	3.3979	0.211
Power-to-gas to Industry	0.0021 [47]	3.3979	0.211
Power-to-gas to Power	0.1274 [47]	3.2726	0.203
Power-to-gas to Methanation	0.72435 [48]	2.6757	0.166

3.5. C1: Capital Costs

The capital costs of hydrogen storage and handling for each pathway are calculated and normalized per kg H_2/hour of capacity over the life of the technology based on the previous study [44], Table 9. The capital costs exclude the cost of the electrolyzer, as such costs are highly dependent on the type of electrolyzer used (PEM vs. alkaline), its size and thermodynamic concerns [50–52]. As a lower capital cost per capacity is preferable, Equation (3) is used to create data points that increase with decreasing cost. As can be seen in Table 10, there is an approximately equivalent maximum capital cost per capacity for the four pathways. Power-to-gas to methanation and power-to-gas to power both have lower costs as they utilize different technologies: methanation reactors and fuel cells, respectively.

Table 9. Capital Costs of Hydrogen Storage and Handling for power-to-gas Pathways.

Power-to-Gas Pathway	Components	$ Per kg H_2-h [44]	Max. $ Per kg H_2-h	Deviation Max. $ Per kg H_2 -h	Capital Cost Score
Power-to-gas to Mobility Fuel	Compressor, Tank	$8960–$13,430	$13,430	$0	0.000
Power-to-gas to HENG	Compressor	$8700–$13,000	$13,000	$430	0.017
Power-to-gas to Seasonal Storage	Compressor, Storage	$9000–$13,350	$13,350	$350	0.014
Power-to-gas to Industry	Compressor	$8700–$13,000	$13,000	$430	0.017
Power-to-gas to Power	Fuel Cell	$101–$135	$135	$13,265	0.533
Power-to-gas to Methanation	Methanation	$2500–$3000	$3000	$10,430	0.419

Table 10. Annual Profits for power-to-gas Pathways.

Power-to-Gas Pathway	Profit Per kg H_2	Profits Score
Power-to-gas to Mobility Fuel	$3.93 [42]	0.23
Power-to-gas to HENG	$0.14 [42]	0.01
Power-to-gas to Seasonal Storage	$4.68 [42]	0.27
Power-to-gas to Industry	$3.93 [42]	0.23
Power-to-gas to Power	$4.68 [42]	0.27
Power-to-gas to Methanation	−$0.05 [53,54]	0.00

3.6. C2: Profit

A project's profitability is an essential part of whether a power-to-gas pathway can be implemented. The profit, given below in USD per kg of H_2 produced, is calculated using the difference between the annual revenues and operating costs of each pathway based on previous studies [44], and tabulated in Table 10. For the pathway power-to-gas to methanation, carbon credits are part of the profit, in which carbon is priced at $30 per tonne of CO_2e reduced [53,54].

3.7. S1: Public Familiarity

Societal concerns are a key standard that should be considered for the implementation of any new project; power-to-gas pathways in this case. In this analysis, public familiarity with each power-to-gas pathway is estimated to be proportional to the first implementation of a pathway. Wherein, the older the technology, the more familiar it is with individuals who are not directly involved in the specific industry. Table 11 indicates power-to-gas pathways and the established-year associated. These data are then converted to an ascending data point using Equation (3).

Table 11. Year of First Use for power-to-gas Pathways.

Power-to-Gas Pathway	Year of 1st Use	Deviation from Latest	Familiarity Score
Power-to-gas to Mobility Fuel	1967 [55] (1st FCV)	27	0.134
Power-to-gas to HENG	1975 [56]	19	0.095
Power-to-gas to Seasonal Storage	1994 [40]	0	0.000
Power-to-gas to Industry	1932 [55] (1st fuel cell)	62	0.308
Power-to-gas to Power	1932 [55]	62	0.308
Power-to-gas to Methanation	1973 [57] (Coal-to-gas)	31	0.154

3.8. S2: Safety

A power-to-gas plant's safety level can be determined by calculating the risk related, based on the following risk relationship, Equation (8) [59]:

$$Risk = Probability \times Severity \quad (8)$$

In the case of hydrogen utilization, the critical risk which must be guarded against is that of an explosion. In this analysis, the risk of a hydrogen tank or pipeline rupturing is combined with an average severity to determine the average risk number [58]. Table 12 shows explosion severity ratings: EXP1, EXP2, EXP3, EXP4, and EXP5 [58]. The average explosion severity calculation takes into account the likelihood of an event. An EXP1 event occurs when there is possible damage to equipment or injuries to personnel. The severity of the events increases incrementally until EXP5, at which point, the explosion causes fatalities to those in the accident region, severe damage to the environment and injuries up to 100 km away.

Table 12. Hydrogen Explosion Scenarios [58].

Name	Description
EXP1	• damage to property and injuries in accident area due to fire
EXP2	• damage to property and injuries in accidental zone of 10 m due to fire and overpressure
EXP3	• fire from accident or external reasons in combination with hydrogen • destruction of equipment, damage of surrounding property in the accidental zone • severe injuries of all individuals in the immediate vicinity
EXP4	• explosion by high pressure • destruction of equipment • damage of property in the accidental zone of 80 m • all individuals killed within 10 m due to overpressure; 80 m due to projectiles
EXP5	• explosion in open environment, consecutive fire/explosion of other stored H_2 • destruction of equipment, damage of property in the accidental zone of within 100 m and kill the people in the accidental zone

The risk numbers, calculated and tabulated in Table 13, consider the size of the application in addition to the type of container, fuel cell, pipeline or tank, and thus, can be used to determine the overall risk, by incorporating both the severity and probability. As illustrated in Table 13, the maximum risk comes from the potential application of power-to-gas to seasonal storage. The reason for the increased risk is that the storage of high quantities of hydrogen leads to an increased probability for an EXP5 occurrence.

Table 13. Risk Number for power-to-gas Pathways.

Power-to-Gas Pathway	Average Risk Number	Deviation from Max Risk	Risk Score
Power-to-gas to Mobility Fuel	7.25×10^{-5} [58]	9.775×10^{-4}	0.237
Power-to-gas to HENG	2.82×10^{-4} [59]	7.68×10^{-4}	0.186
Power-to-gas to Seasonal Storage	1.05×10^{-3} [59]	0	0.000
Power-to-gas to Industry	2.82×10^{-4} [59]	7.68×10^{-4}	0.186
Power-to-gas to Power	2.82×10^{-4} [59]	7.68×10^{-4}	0.186
Power-to-gas to Methanation	2.1×10^{-4} [59]	$\times 10^{-4}$	0.204

3.9. Application of FAHP

The optimal or best power-to-gas pathway is determined by incorporating the previously discussed results for each criteria. In Table 14, below, the raw data for each of the six power-to-gas pathways across all of the aforementioned criteria are compiled.

Table 14. Raw Data for power-to-gas Pathways.

Pathway	# of Projects	Avg. Efficiency	g CO_2e Red. Per kg H_2	g VOCs Per kg of H_2	Price Per kg H_2 Per h	Profit Per kg H_2	Year of First Use	Average Risk Number
Mobility Fuel	53	64.5%	10,143	3.4	$13,430	$3.93	1967	7.25×10^{-5}
HENG	2	50.5%	5.64	0.0021	$13,000	$0.14	1975	2.82×10^{-4}
Seasonal Storage	1	51%	5.64	0.0021	$13,350	$4.68	1994	1.05×10^{-3}
Industry	17,000	69%	5.64	0.0021	$13,000	$3.93	1932	2.82×10^{-4}
Power	100,000+	28.5%	1667	0.1274	$135	$4.68	1932	2.82×10^{-4}
Methanation	43	51.5%	173.4	0.72435	$3000	−$0.05	1973	2.1×10^{-4}

In order to use the AHP and SAW approach, the data in Table 14 is modified. First, the data are normalized so that the sum of each criterion score column must equal one. Next, the data are also modified such that increasing scores correspond to increasing performance to a given criterion. For example, the average efficiency increases as performance increases, thus, there is no need to modify it. However, it is preferred that a system have a lower risk number than a higher risk number. Thus, the risk numbers must be modified in order to create a useable risk score, Table 15.

Table 15. Normalized Scores for power-to-gas Pathways.

Pathway	Technology Readiness	Pathway Efficiency	Greenhouse Gas Red	VOC Emissions	Capital Cost	Profit	Familiarity	Safety
Mobility Fuel	0.133	0.205	0.845	0.000	0.000	0.230	0.134	0.237
HENG	0.023	0.160	0.000	0.211	0.017	0.011	0.095	0.186
Seasonal Storage	0.000	0.162	0.000	0.211	0.014	0.273	0.000	0.000
Industry	0.328	0.219	0.000	0.211	0.017	0.230	0.308	0.186
Power	0.391	0.090	0.139	0.203	0.533	0.273	0.308	0.186
Methanation	0.125	0.163	0.014	0.166	0.419	0.000	0.154	0.204

Using the data given in Table 15, it is possible to apply an AHP to determine the pathway that meets the preferences of a given decision maker. As described in Section 2, pairwise comparisons are made between different criteria to determine the weights. In Table 16, a set of pairwise comparisons are proposed for a decision maker that is concerned most about greenhouse gas emissions, profitability and public safety concerns, in order of increasing importance. As expected, the weights in the righthand column of Table 16 reflect this.

Table 16. Analytic Hierarchy Process Comparisons for Focus on GHG Reductions and Safety (Source: own results).

Pathway	Technology Readiness	Pathway Efficiency	Greenhouse Gas Red.	VOC Emissions	Capital Cost	Profit	Familiarity	Safety
Tech Readiness	1	1	0.2	0.33	0.33	0.33	1	0.2
Pathway Eff	1	1	0.2	0.33	0.33	0.33	1	0.2
GHG Red	5	5	1	3	1	3	5	1
VOCs	3	3	0.33	1	1	1	3	0.2
Cap. Cost	3	3	1	3	1	1	3	0.2
Profit	3	3	0.33	1	1	1	3	0.2
Familiar	1	1	0.2	0.33	0.33	0.33	1	0.2
Safety	5	5	1	5	5	5	5	1

The C.I. from the above pairwise comparisons is found to be 0.075 and thus below the threshold of 0.1. Using the fuzzy triangular numbers defined previously, Fuzzy AHP relationships are defined. Preference relationships are quantified by a set of low, middle and upper values for each pairwise comparison, as illustrated in Table 17.

Table 17. Fuzzy AHP Comparisons for Focus on GHG Reductions and Safety (Source: own results).

	Tech. Read.	**Pathway Efficiency**	**Greenhouse Gas Red**	**VOC Emissions**	**Capital Cost**	**Profit**	**Famil.**	**Safety**
Tech Readiness	(1,1,1)	(1,1,1)	$\left(\frac{1}{6},\frac{1}{5},\frac{1}{4}\right)$	$\left(\frac{1}{4},\frac{1}{3},\frac{1}{2}\right)$	$\left(\frac{1}{4},\frac{1}{3},\frac{1}{2}\right)$	$\left(\frac{1}{4},\frac{1}{3},\frac{1}{2}\right)$	(1,1,1)	$\left(\frac{1}{6},\frac{1}{5},\frac{1}{4}\right)$
Pathway Eff	(1,1,1)	(1,1,1)	$\left(\frac{1}{6},\frac{1}{5},\frac{1}{4}\right)$	$\left(\frac{1}{4},\frac{1}{3},\frac{1}{2}\right)$	$\left(\frac{1}{4},\frac{1}{3},\frac{1}{2}\right)$	$\left(\frac{1}{4},\frac{1}{3},\frac{1}{2}\right)$	(1,1,1)	$\left(\frac{1}{6},\frac{1}{5},\frac{1}{4}\right)$
GHG Red	(4,5,6)	(4,5,6)	(1,1,1)	(2,3,4)	(1,1,1)	(2,3,4)	(4,5,6)	(1,1,1)
VOCs	(2,3,4)	(2,3,4)	$\left(\frac{1}{4},\frac{1}{3},\frac{1}{2}\right)$	(1,1,1)	(1,1,1)	(1,1,1)	(2,3,4)	$\left(\frac{1}{6},\frac{1}{5},\frac{1}{4}\right)$
Cap. Cost	(2,3,4)	(2,3,4)	(1,1,1,)	(2,3,4)	(1,1,1)	(1,1,1)	(2,3,4)	$\left(\frac{1}{6},\frac{1}{5},\frac{1}{4}\right)$
Profit	(2,3,4)	(2,3,4)	$\left(\frac{1}{4},\frac{1}{3},\frac{1}{2}\right)$	(1,1,1)	(1,1,1)	(1,1,1)	(2,3,4)	$\left(\frac{1}{6},\frac{1}{5},\frac{1}{4}\right)$
Familiar	(1,1,1)	(1,1,1)	$\left(\frac{1}{6},\frac{1}{5},\frac{1}{4}\right)$	$\left(\frac{1}{4},\frac{1}{3},\frac{1}{2}\right)$	$\left(\frac{1}{4},\frac{1}{3},\frac{1}{2}\right)$	$\left(\frac{1}{4},\frac{1}{3},\frac{1}{2}\right)$	(1,1,1)	$\left(\frac{1}{6},\frac{1}{5},\frac{1}{4}\right)$
Safety	(4,5,6)	(4,5,6)	(1,1,1)	(4,5,6)	(4,5,6)	(4,5,6)	(4,5,6)	(1,1,1)

Next, the triangular fuzzy numbers are converted into a set of fuzzy weights, with a low, middle and upper value, as shown in Equations (2) and (3), and finally into defuzzified weights. Now, the optimal power-to-gas pathway is determine based on the weights from Table 16, the normalized scores from Table 15, and the fuzzy AHP shown in Table 17. Table 18 shows the resultant scores and calculated fuzzy weights that indicate the best option looking at the highest score. Therefore, for this case, the optimal pathways are power-to-gas to mobility fuel and power-to-gas to power.

Table 18. Application of simple additive weighting (SAW) Method to Selection of power-to-gas Pathways (Source: own results).

Pathway	**Mobility Fuel**	**HENG**	**Seasonal Storage**	**Industry**	**Power**	**Methan.**
Tech Read	0.13	0.02	0	0.33	0.39	0.13
Weight			0.0244			
Path Effi	0.205	0.16	0.162	0.219	0.09	0.163
Weight			0.0250			
GHG Red.	0.845	0	0	0	0.139	0.014
Weight			0.1347			
VOC Emiss	0	0.21	0.21	0.21	0.2	0.17
Weight			0.0731			
Capital Cost	0	0.02	0.01	0.02	0.53	0.42
Weight			0.1054			
Profit	0.23	0.01	0.27	0.23	0.27	0
Weight			0.1180			
Familiarity	0.134	0.095	0	0.308	0.308	0.154

Table 18. *Cont.*

Pathway	Mobility Fuel	HENG	Seasonal Storage	Industry	Power	Methan.
Weight			0.0469			
Safety	0.237	0.186	0	0.186	0.186	0.204
Weight			0.4725			
Score	0.268	0.115	0.053	0.16	0.236	0.169

The weights are then recalibrated to give emphasis on profit and secondly on safety; a new set of FAHP pairwise comparisons must be made, as illustrated in Tables 19 and 20.

Table 19. Pairwise Comparisons for Focus on Profitability and Safety (Source: own results).

Pathway	Technology Readiness	Pathway Efficiency	Greenhouse Gas Red	VOC Emissions	Capital Cost	Profit	Familiarity	Safety
Tech Readiness	1	1	0.33	0.33	0.5	0.2	1	0.2
Pathway Eff	1	1	0.33	0.33	0.5	0.2	1	0.2
GHG Red	3	3	1	1	0.5	0.2	1	0.2
VOCs	3	3	1	1	0.5	0.2	1	0.2
Cap. Cost	2	2	2	2	1	1	2	0.2
Profit	5	5	5	5	1	1	5	1
Familiar	1	1	1	1	0.5	0.2	1	0.2
Safety	5	5	5	5	5	1	5	1

Table 20. Fuzzy AHP Comparisons for Focus on Profitability and Safety (Source: own results).

	Pathway	Technology Readiness	Pathway Efficiency	Greenhouse Gas Red	VOC Emissions	Capital Cost	Profit	Familiarity
Tech Readiness	(1,1,1)	(1,1,1)	$\left(\frac{1}{4},\frac{1}{3},\frac{1}{2}\right)$	$\left(\frac{1}{4},\frac{1}{3},\frac{1}{2}\right)$	$\left(\frac{1}{3},\frac{1}{2},1\right)$	$\left(\frac{1}{6},\frac{1}{5},\frac{1}{4}\right)$	(1,1,1)	$\left(\frac{1}{6},\frac{1}{5},\frac{1}{4}\right)$
Pathway Eff	(1,1,1)	(1,1,1)	$\left(\frac{1}{4},\frac{1}{3},\frac{1}{2}\right)$	$\left(\frac{1}{4},\frac{1}{3},\frac{1}{2}\right)$	$\left(1,\frac{3}{2},2\right)$	$\left(\frac{1}{6},\frac{1}{5},\frac{1}{4}\right)$	(1,1,1)	$\left(\frac{1}{6},\frac{1}{5},\frac{1}{4}\right)$
GHG Red	(2,3,4)	(2,3,4)	(1,1,1)	(1,1,1)	(1,1,1)	$\left(\frac{1}{6},\frac{1}{5},\frac{1}{4}\right)$	(1,1,1)	$\left(\frac{1}{6},\frac{1}{5},\frac{1}{4}\right)$
VOCs	(2,3,4)	(2,3,4)	(1,1,1)	(1,1,1)	$\left(\frac{1}{4},\frac{1}{3},\frac{1}{2}\right)$	$\left(\frac{1}{6},\frac{1}{5},\frac{1}{4}\right)$	(1,1,1)	$\left(\frac{1}{6},\frac{1}{5},\frac{1}{4}\right)$
Cap. Cost	(1,2,3)	(1,2,3)	(1,2,3)	(1,2,3)	(1,1,1)	(1,1,1)	(1,2,3)	$\left(\frac{1}{6},\frac{1}{5},\frac{1}{4}\right)$
Profit	(4,5,6)	(4,5,6)	(4,5,6)	(4,5,6)	(1,1,1)	(1,1,1)	(4,5,6)	(1,1,1)
Familiar	(1,1,1)	(1,1,1)	(1,1,1)	(1,1,1)	$\left(\frac{1}{3},\frac{1}{2},1\right)$	$\left(\frac{1}{6},\frac{1}{5},\frac{1}{4}\right)$	(1,1,1)	$\left(\frac{1}{6},\frac{1}{5},\frac{1}{4}\right)$
Safety	(4,5,6)	(4,5,6)	(4,5,6)	(4,5,6)	(4,5,6)	(1,1,1)	(4,5,6)	(1,1,1)

In this set of pairwise comparisons, the C.I. is found, using Equation (1), to be 0.066 and thus below the 0.1 threshold of consistency. Using the same method is in the previous run, the table above is converted into a set of fuzzy comparisons using TFN representations of the pairwise comparisons.

Finally, these pairwise comparisons are converted into fuzzy weights represented by their own TFNs and from there into the weights shown in Table 21 using Equations (2) through (6). Applying Equation (7) gives a score for the performance of each option.

Table 21. Scores for Profitability Scenario (Source: own results).

Pathway	Mobility Fuel	HENG	Seasonal Storage	Industry	Power	Methan.
Tech Read	0.13	0.02	0	0.33	0.39	0.13
Weight			0.028704			
Path Effi	0.21	0.16	0.16	0.22	0.09	0.16
Weight			0.050427			
GHG Red	0.85	0	0	0	0.14	0.01
Weight			0.050427			
VOC Emiss	0	0.21	0.21	0.21	0.2	0.17
Weight			0.053759			
Capital Cost	0	0.02	0.01	0.02	0.53	0.42
Weight			0.088575			
Profit	0.23	0.01	0.27	0.23	0.27	0
Weight			0.212335			
Familiarity	0.13	0.1	0	0.31	0.31	0.15
Weight			0.074940			
Safety	0.24	0.19	0	0.19	0.19	0.2
Weight			0.463487			
Score	0.225	0.117	0.078	0.191	0.248	0.165

The scores in Tables 19 and 21 show that, power-to-gas to mobility Fuel, and to a lesser extent power-to-gas to power, are optimal pathways where the objective is to reduce greenhouse gas emissions or to generate a profit. The consistency of the selection of these two pathways over the two scenarios with fuzzy weights to capture uncertainty suggest that these are robust results.

4. Conclusions

The best pathway for future investment was determined using the fuzzy analytic hierarchy process and simple additive weight. Eight unique environmental, economic and technical criteria were applied to examine 6 distinct power-to-gas pathways. Two scenarios were followed, to provide a sensitivity analysis, which put the emphasis on profitability and greenhouse gas reductions. Under each of these scenarios, the application of systems tools find that the two best pathways are power-to-gas to mobility fuel and power-to-gas to power. Each of these technologies utilize hydrogen fuel cells to convert chemical energy to electricity to replace typical fossil fuel applications. These particular pathways are selected because of their performance under specific criteria that are stressed under the three scenarios, including efficiency, greenhouse gas emissions, technological readiness and profitability. The use of the fuzzy analytic hierarchy process accounted for the uncertainty in the selection of specific pairwise comparisons across a broad range of criteria.

For policymakers, going forward, the two most suitable power-to-gas pathways for investment in implementation right now are power-to-gas to mobility fuel and power-to-gas to power. Each of these pathways is technically ready to be implemented in practice, with plenty of research into their feasibility already accomplished. Two other power-to-gas streams, power-to-gas to industry and power-to-gas to methanation, scored as the 3rd and 4th highest, respectively, in each of the analyses. These pathways—industry and methanation—are also feasible sources of investment which are technologically ready, but have lower greenhouse gas reductions and are less familiar to society.

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