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The future of hydrogen fueling systems for transportation: An application of perspective-based scenario analysis using the analytic hierarchy process

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Abstract

This paper integrates the analytic hierarchy process (AHP) with scenario analysis techniques to explore the commercialization of future hydrogen fuel processor technologies. AHP is a multi-attribute decision analysis tool useful for evaluating decisions with multiple criteria and alternatives. In this paper, AHP is extended using a technique called perspective-based scenario analysis (PBSA). In PBSA, scenario analysis is conducted based on potential future decision-maker perspectives that are integrated into the AHP framework. This paper discusses this method and applies it to the evaluation of hydrogen fuel processor technologies 15–20 years hence. The results provide an added layer of insight into the opportunities and barriers for the commercialization of these technologies as well as the methodological opportunities for using AHP and PBSA as a futures tool.

Keywords: Futures studies; Technology forecasting; Hydrogen; Decisions science; Technology assessment

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1. Introduction

In conducting assessments of the market potential of future technologies, one must consider a number of factors: attributes of the technology, substitutes, regulatory environment and economic considerations, among others. Future professionals apply an array of techniques to understand these factors and conjecture on the conditions under which a future technology might enter the marketplace.

A useful tool for analyses of this type is the analytic hierarchy process (AHP). AHP, developed by Dr. Tom Saaty in the early 1970s, is a multi-attribute decision analysis tool used to evaluate decisions with multiple alternatives and criteria. AHP uses "pairwise comparisons" and matrix algebra to ultimately identify and weigh the criteria that are important in a decision. Those criteria, their weights and the attributes of each technology are then applied to "rank" competing technologies according to a stated goal.

In futures research, the value of AHP can be extended by including scenario building and analysis into the AHP process. Analysts can build scenarios to depict futures that affect the criteria weights or attributes for each technology. Using these future scenarios as a guide, analysts can apply the AHP to help *quantify* the impacts of each scenario on future technology development. AHP is also flexible enough to conduct scenario analysis under various perspectives, another useful practice for the professional futurist [1,2].

This paper applies a technique dubbed "perspective-based scenario analysis" (PBSA) to conduct an assessment of future hydrogen fuel processor technologies that could be market ready in 15–20 years. In this approach, we conduct an AHP analysis on future scenarios using various decision-maker perspectives and technology attributes. Using this technique, we can evaluate, for example, technology choice under the perspective of an "environmentally conscious" society and then conduct the same analysis under the perspective of an "economically driven" society.

The usefulness of this approach is threefold. First, the AHP provides a systematic approach to identifying variables, their relationships and their weights (or *strength of influence* in the futures lexicon). This information can be fed back into a scenario-building exercise in order to make the scenario more rich and rigorous. In essence, conducting the AHP forces one to clarify variables and discern relationships that would otherwise be neglected in a less structured scenario-building process. Second, the AHP provides quantitative output that can be used with sensitivity analysis to explore how changes in variable values or weights affect scenario outcomes. Such quantification is often helpful in communicating results to decision-makers (especially when technology choice is involved). Third, the approach allows one to easily conduct backcasting assessments from a normative future and determine what conditions that must be present in order for such futures to be realized.

This paper focuses on the method itself, as applied to the evaluation of processors used to produce hydrogen for hydrogen fuel cell vehicles (FCVs) 15–20 years hence. In particular, the analysis is used to identify commercialization barriers for specific technologies under different future conditions. The paper does not attempt to exhaust all the potential uses of the method, as others will be addressed in later articles. However, the reader is encouraged to think freely and critically about this method in hopes that he/she will uncover other uses as well.

2. The AHP as a futures tool

The AHP is a powerful decision analysis technique that allows evaluators to derive solutions to complex, multicriteria problems [3]. It is especially useful when the criteria established for evaluating a problem entail a mix of quantitative and qualitative measures or when an evaluator is attempting to discern criteria weights from pooled expert opinions. Like many decision analyses, the major steps of AHP involve stating the objective, defining the criteria and selecting the alternatives. AHP is used to determine the weights of the criteria and to evaluate each of the alternatives based on these weights.

AHP has been used a number of times in the past for future-related planning. In the transportation planning field, an excellent review has been provided by Saaty [4] that explores AHP as applied to a number of future planning issues. Other applications include energy resource allocation [5], urban energy-environmental management [6], prioritizing energy and environmental research projects [7], prioritizing national electricity options [8], designing optimal renewable power systems [9], planning transportation fuel use [10] and identifying sustainable alternative transportation fuels [11], to name a few.

There are four steps that are integral to an AHP evaluation, each of which will be discussed at length below [4,12]. These steps are

1. *Decompose* the problem into a hierarchy,
2. *Prioritize* the hierarchy elements using pairwise comparisons,
3. *Synthesize* the priorities to create an evaluation of alternatives and
4. *Conduct* a sensitivity analysis on the results.

We will explore each of these steps using a case study.[1]

3. The case of hydrogen fuel processing technologies

3.1. Hydrogen as a transportation fuel

Recent interest in hydrogen as a substitute for gasoline and diesel in transportation markets is primarily due to two important realizations: (1) hydrogen fuel is essentially limitless, as hydrogen can be derived by electrolyzing water (ideally through the use of renewable energy technologies) and (2) hydrogen fuel is clean burning, as the oxidation of hydrogen yields only water. For these reasons, many organizations and governments expect hydrogen to meet a larger share of global energy needs in the coming decades [13].

In the US and many other countries, the exclusive reliance on petroleum for transportation services has repeatedly raised concerns related to energy security, economic security and environmental quality. For example, each year, the US imports 40–50% of its 19 million

[1] Although the mathematics of the AHP is beyond the scope of this paper, a very readable presentation can found in Saaty [12].

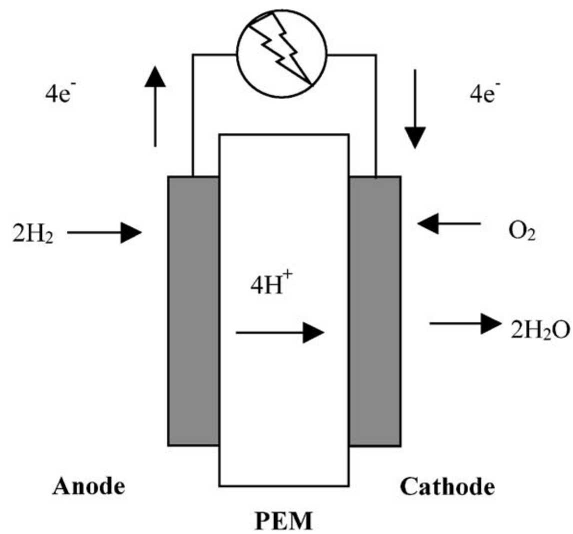

Fig. 1. Simple PEM fuel cell diagram.

barrels per day petroleum demand and spends in the range of US$6–60 billion per annum in protecting oil reserves internationally [14]. At a hypothetical cost of US$25 per barrel, oil imports alone account for over US$85 billion per year of the US trade deficit.

Environmentally, petroleum consumption in the transportation sector has continued to raise both local and global pollution concerns. Although significant advances have been made to reduce exhaust emissions from gasoline and diesel vehicles, mobile sources still account for a large percentage of criteria pollutants in urban centers.

In addition, transportation in the US accounts for approximately 30% of total US carbon dioxide (CO_2) emissions, an important greenhouse gas (GHG). US CO_2 emissions from transportation total over 1600 million metric tones annually, 25% higher than transportation CO_2 emissions from all other industrialized nations *combined* [14].

3.2. Hydrogen proton exchange membrane (PEM) fuel cells

In this paper, we consider hydrogen as used in a PEM FCV. FCVs are almost market ready and most automakers have prototype FCVs that they expect to offer commercially in the next 5–10 years.[2] Of all existing fuel cell technologies, PEM fuel cells are expected to serve personal transportation markets due to their high power density, quick start-up time and simple design and manufacture [15–17].

Although the technical details of PEM fuel cells can be found elsewhere [18], Fig. 1 presents a simple diagram illustrating the oxidation of hydrogen in a PEM fuel cell. In Fig. 1, hydrogen (H_2) enters the anode side of the fuel cell where it is split into hydrogen ions (i.e.,

[2] A list of companies involved in fuel cell research, development and demonstration is included in Appendix A.

protons) and electrons. The protons migrate through the PEM to the cathode, while the electrons are diverted through an electric load. At the cathode, the protons are combined with oxygen (O_2) and water (H_2O) is produced. These chemical reactions are enhanced through the use of catalysts and other design elements of the cell itself. The electricity generated by a PEM fuel cell can power either an electric motor directly or a bank of batteries that would store the electricity for later use.

There are several alternatives available for generating and delivering the hydrogen that is consumed in the PEM. These alternatives are shown in Fig. 2 and include (A) storing hydrogen (H_2) on-board the vehicle for direct use, where the hydrogen is generated at centralized reforming facilities; (B) storing hydrogen on-board where hydrogen is generated at decentralized natural gas (NG) reforming facilities; (C) storing NG on-board and reforming it using a NG steam reformer; (D) storing gasoline on-board and processing it using an autothermal reformer and (E) storing methanol (MeOH) on-board and reforming it using a MeOH steam reformer.

This paper evaluates these technology alternatives using criteria important for market success. Note that although other fuel pathways have been discussed as relevant in the literature, including naphtha and Fischer–Tropsch diesel with their associated reformers, efforts to date involve NG, MeOH and gasoline [19]. In addition, home refueling of NG

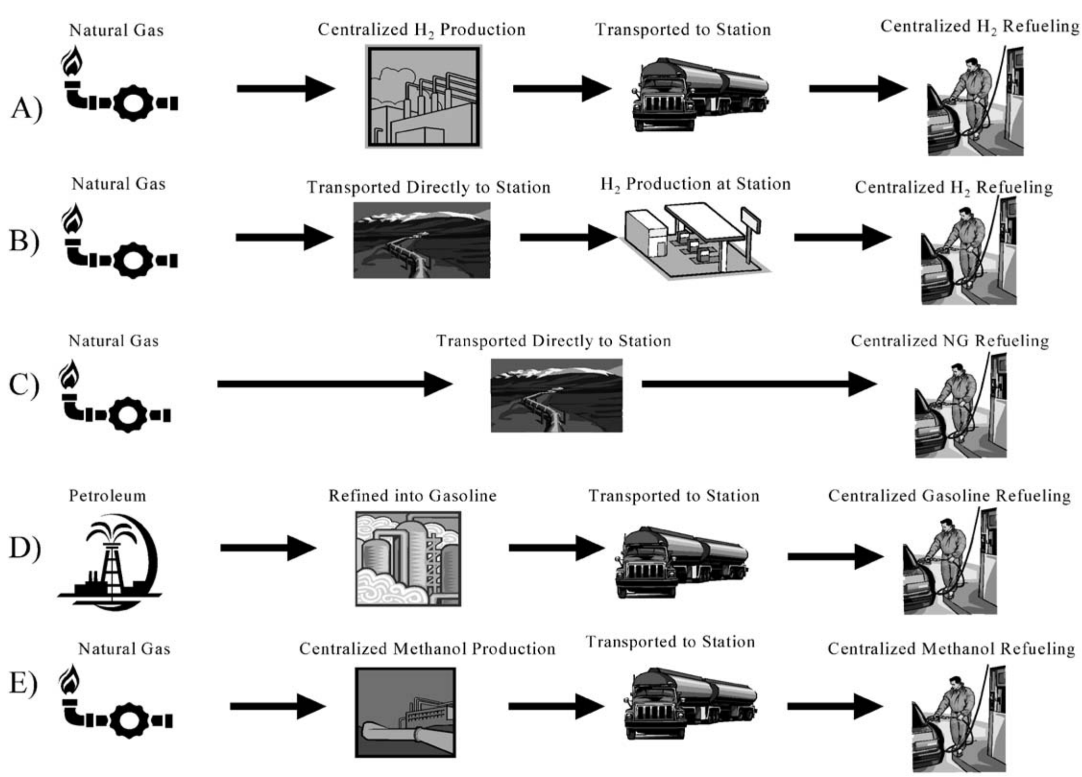

Fig. 2. Hydrogen refueling options.

is not explicitly analyzed in this paper but is discussed as a variation of the on-board NG reforming alternative.

3.3. Fuel processor options for PEM FCVs

A detailed explanation of each technology shown in Fig. 2 is beyond the scope of this paper and readers are referred to Winebrake and Creswick [20] for more information. Here, we present each alternative and briefly identify their pros/cons.

3.3.1. On-board hydrogen (no fuel processor/centralized hydrogen production)

The *on-board hydrogen* alternative (A in Fig. 2) is a technology configuration in which H_2 is stored "on-board" the vehicle. In this paper, we assume that H_2 will be produced at a large-scale production facility ("merchant H_2") using NG feedstock [21–23]. The H_2 would be transported either via pipeline or in liquid form via tanker to a decentralized refueling station. At the station, H_2 will be stored in tanks at high pressure (approximately 5000 psi) and will be dispensed directly into the vehicle.

Due to the fact that an on-board fuel processor is unnecessary, this alternative benefits from its simplicity, affordability and vehicle performance. However, a major barrier to this alternative is the H_2 distribution and storage system. Distribution of H_2 is limited (although this may be remedied by focusing on fleet markets with dedicated refueling facilities [22]). In addition, due to the low energy content of H_2 (4 MJ/l at 5000 psi versus 30 MJ/l for gasoline), a large volume of fuel is needed on-board in order to achieve acceptable vehicle ranges [21].

3.3.2. On-site NG with direct HFCV (station reforming)

Another alternative studied in this paper is a configuration where NG is transported through pipelines to independent refueling stations (B in Fig. 2). There, the NG is reformed to H_2 using an on-site, stationary steam reformer. The H_2 is stored as a compressed gas and dispensed into direct hydrogen FCVs. From a vehicle perspective, this technology configuration is similar to the *on-board hydrogen* alternative above. However, this alternative takes advantage of the existing NG pipeline transportation network, thereby eliminating the problems associated with transporting H_2 over long distances, although it should be noted that modifying existing gasoline stations to dispense NG is an expensive endeavor. (Note that on-site production of H_2 can also occur using electrolysis, but costs, at least in the time horizon covered by this study, seem prohibitive [24].)

3.3.3. On-board NG with steam reformer

Another way to "store" H_2 on-board a vehicle is in a hydrocarbon fuel, such as NG (CH_4). The *on-board NG* alternative (C in Fig. 2) involves the on-board storage of methane (CH_4). Vehicles would fuel with NG at decentralized sites. Using storage technologies developed for NG vehicles, the NG would be stored at 3000–3600 psi. The compressed NG would be converted to H_2 using a high-temperature steam reformer on-board the vehicle.

One of the key benefits of the NG reformer is that it has the lowest carbon emissions of all the on-board fuel processor alternatives [25] and operates at the highest efficiency (over

80%). There is still the problem with NG distribution at local sites, but this problem distribution may be remedied by the development of "at-home" refueling using currently available "slow-fill" refueling units. The reforming reaction is also typically slow, so these fuel processors have poor transient response times (the time between power demand and power delivery) and long start-up times [16,17].

3.3.4. On-board gasoline with autothermal processor

Gasoline can also serve as a H_2 carrier (D in Fig. 2), and efforts are underway to develop a fuel processor that can effectively remove H_2 from the hydrocarbon constituents of unleaded gasoline. Gasoline can be processed on-board a FCV using an "autothermal reforming" process that involves a combination of oxidation reactions and reforming reactions [19,26].

There are some issues with heat management in these systems, and their costs are likely to be high (upwards of 1/3 the cost of the total fuel cell system) [27]. In addition, significant power loss in autothermal vehicles has been demonstrated [28]. Nevertheless, companies including A.D. Little (using its EPYX technology) and Xcellsis are pursuing autothermal processors [29].

3.3.5. On-board MeOH with steam reformer

This alternative (E in Fig. 2) involves fueling vehicles with MeOH (CH_3OH) and processing that fuel on-board using a MeOH steam reformer [30]. Details of this process can be found in Refs. [20,26,30].

MeOH is currently produced in abundance (over 12.5 billion gallons worldwide in 2000) at large facilities using NG as a feedstock [31]. It can be stored and transported easily in liquid form [32] and gasoline stations can easily be converted to MeOH stations, at a cost of about US$50,000 per station [33,34].

However, once again, the on-board fuel processor required to strip the H_2 from MeOH leads to a loss in vehicle efficiencies and performance [16,17,19,28].

3.4. Applying the AHP to the problem

3.4.1. Constructing hierarchies

AHP arranges the elements of a decision into a hierarchy so that the relative role of each element can be more clearly observed and evaluated.[3] Constructing a hierarchy encompasses three main steps: (1) identifying the elements of the problem, (2) grouping these elements into homogeneous sets and (3) arranging these sets in different levels of relevance.

When constructing a hierarchy, the primary goal of the decision analysis is always placed at the top of the hierarchical tree. To evaluate this goal, specific criteria that have a direct impact on the goal are then established and organized into "layers" on the tree. At the bottom of the tree, the decision alternatives are listed. In this case study, the primary goal is to identify the "best fuel processing technology" to serve hydrogen FCVs in the 15–20-year time frame.

[3] In the decision sciences, these elements are called *criteria*, while in futures studies they may be called *variables*.

Table 1
Criteria analyzed for technology alternatives

Criteria	Description
(1) Fuel production and distribution	
Production capacity	The availability of fuel as a feedstock for a given alternative. Alternatives that have large feedstock reserves and production capacity are best.
Safety and health	Health and safety issues associated with fuel production and on-site storage, including health and safety aspects of refining, transporting, storing and distributing the fuel. Alternatives that can be produced, transported and stored safely are best.
Refueling convenience	A measure of consumer access to a given fuel through the development of adequate refueling stations. Alternatives that have an existing network of fueling options are best.
(2) Vehicle operation and performance	
Start-up time	The time that it takes for a fuel system to provide enough energy to allow for vehicle propulsion. Alternatives with rapid start-up times are best.
Range	The distance (km) a vehicle can travel on a full tank of fuel. Range is strongly influenced by the weight of the vehicle and the efficiency of the fuel processor. Alternatives with high ranges are best.
Peak power	The maximum power output (kW) a vehicle can attain from the system. Alternatives with high maximum power are best.
Safety	Safety of the on-board system and the potential hazards associated with vehicle accidents. For example, fuels with low flammability characteristics are best.
Transient response	The time delay between depression of the accelerator and vehicle response (i.e., how quickly fuel is converted to mechanical energy by the fuel system). Alternatives with rapid response times are best.
(3) Environmental impacts	
GHG emissions	Emissions of GHG along the entire fuel cycle. Alternatives with the low GHG emissions (on a per mile basis) are best.
Local pollutants	Emissions of local and regional pollutants, including particulate matter (PM), oxides of nitrogen (NO_x), carbon monoxide (CO) and hydrocarbons (HC). Alternatives with low emissions (on per mile basis) are best.
Land use	A measure of the land use impacts associated with the distribution infrastructure needed for a particular alternative. Alternatives that pose little impact on land use are best.
Distribution	The environmental impacts of upstream activities, including environmental impacts of refining, transporting, storing and distributing the fuel. Distribution networks that pose little threat to ecological health are best.

Table 1 (*continued*)

Criteria	Description
(4) Resource issues	
Foreign dependence	A measure of the level of feedstock that must be imported. Alternatives with high levels of domestic feedstock reserves and production fare best.
Sustainability	A measure of feedstock supply over a long period of time (40–70 years), in amounts sufficient for supplying large market penetration of a given technology alternative. Alternatives with potentially large or renewable resource bases fare best.
(5) Economic issues	
Vehicle costs	The capital cost of the vehicle, including processor and on-board storage systems. Alternatives with low capital costs are best.
Fuel costs	The costs associated with building the refueling infrastructure needed to fuel the alternatives, including storage and distribution. Alternatives with low costs fare best.
Infrastructure costs	The costs seen by consumers (cents/mile). Alternatives with low costs fare best.

Seventeen criteria were identified to evaluate this problem. The 17 criteria were grouped into five major categories: (1) *Fuel production and distribution*, (2) *Vehicle operation and performance*, (3) *Environmental impacts*, (4) *Resource issues* and (5) *Economics*. These criteria, with a short description, are presented in Table 1.

Using the criteria in Table 1, we developed a hierarchy as shown in Fig. 3. We have segmented the hierarchy tree for this study into two levels. The first level includes the broad categories (first-level groupings). The second level includes the specific criteria. The bottom layer of the tree depicts each of the technology alternatives.

3.4.2. Performing pairwise comparisons

After the hierarchy tree is established, the next step in the AHP is to apply weights to each of the criteria. This is done through a systematic series of pairwise comparisons among the criteria. Pairwise comparisons allow the analyst to focus on only two criteria at a time, thereby translating a complex, multicriteria problem into a series of pairwise assessments. The AHP then converts these comparisons to criteria weights using a matrix algebra-based algorithm while also checking for consistency in the results.

The process is straightforward. Starting with the top level, one compares each top-level criterion to the others, reflecting each criterion's importance relative to the stated goal of the decision problem. Saaty [12] proposes the scale shown in Table 2 for this assessment, whereby the comparison of criterion X with criterion Y yields a rating ranging from 1 to 9 if X is more important in meeting the decision goal. For example, a 9 signifies that X is *extremely more important* in meeting the decision goal compared to Y, while 1 represents equal importance between X and Y.

As an example, suppose we wish to evaluate criteria on the first level of our hierarchy tree shown in Fig. 2. We start with *Vehicle operation and performance*. We then compare *Vehicle*

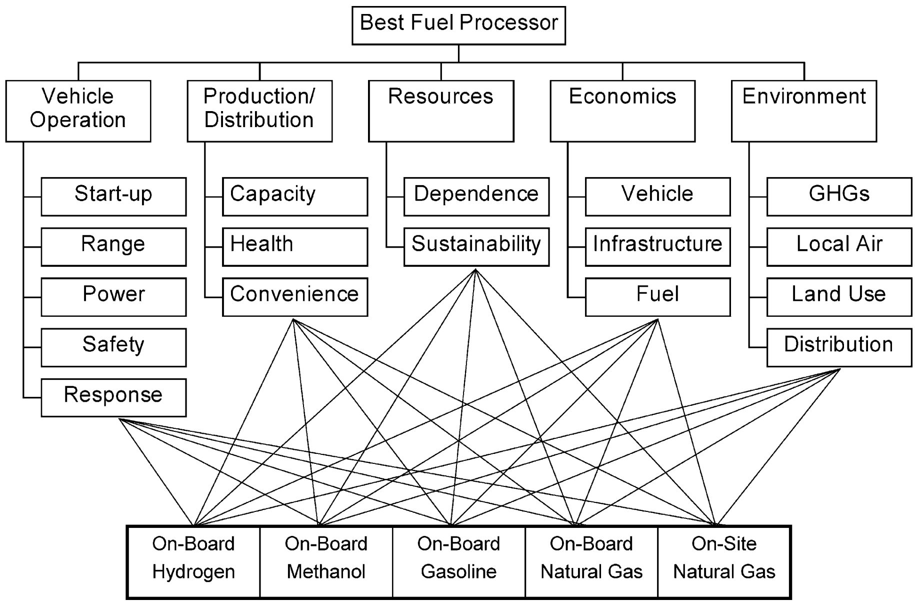

Fig. 3. Hierarchy tree for the fuel processor problem.

operation and performance with each of the other first-level attributes (i.e., *Fuel production and distribution*, *Environmental impacts*, *Resource issues* and *Economics*). Comparisons are then conducted using the scale in Table 2. Thus, if we thought *Vehicle operation and performance* was "strongly favored and its dominance demonstrated in practice" when compared to *Environmental impacts*, we would give this comparison, say, a "7."

This routine was performed for each first-level element, after which we evaluated the second-level elements in a similar manner. (For example, we conducted pairwise comparisons among *Start-up*, *Range*, *Power*, *Safety* and *Response* with respect to their relative importance toward their "parent node," in this case, *Vehicle operation and performance*.)

The comparison results are then processed to generate relative weights for each of the criteria.[4] The AHP is simplified considerably by the use of software designed to assist this process. For this work, we employed ExpertChoice 2000 software developed by Decisioneering. Fig. 4 represents a "screen shot" of the ExpertChoice 2000 input screen for evaluation of our first-level criteria. Positive numbers represent cases where the row element in the matrix is weighed more heavily than the column element. Negative numbers represent the case where the column element is weighed more heavily than the row element. Notice that only half of the matrix needs to be completed, as the *ji* matrix elements are simply the reciprocal of the *ij* elements [3]. Also note that the *ii* elements (the matrix diagonal) are not included, as these values are equal to "1" by definition.

[4] The AHP also generated an "inconsistency value" that provides the user feedback as to whether the pairwise comparisons are consistent. For example, an inconsistent result would appear if an analyst says "A" is better than "B," "B" is better than "C" and "C" is better than "A." The reader is referred to Saaty [3,12] for more information on inconsistency calculations.

Table 2
The pairwise comparison scale

Importance scale	Definition	Explanation
1	Equal importance	Two elements contribute equally
3	Moderate importance	Experience and judgment suggest that one element is slightly favored over another
5	Strong importance	Experience and judgment suggest that one element is strongly favored over another
7	Very strong importance	An element is strongly favored and its dominance is demonstrated in practice
9	Extreme importance	The evidence favoring one element over another is of the highest possible order of affirmation

3.4.3. Synthesizing the results

With the pairwise comparisons complete (in this case, about 140 pairwise comparisons were made), the mathematical evaluation begins. The first step in the evaluation is to normalize each matrix by adding the values in each *column* and then dividing each entry in each column by the total of that column. Once the matrix has been normalized, the average value of each *row* is calculated yielding a percentage of relative priority. The detailed mathematics is described in Refs. [3,12]. Fig. 5 offers a "screen shot" of the evaluation for our base case (discussed below) to give the reader an idea of AHP output. Notice the different "weightings" that have been generated for both the first- and second-level criteria as well as the overall results represented as bars in the top right of the screen.

3.4.4. Conducting sensitivity analysis and the use of PBSA

Sensitivity analysis generally involves the manipulation of model variables in an attempt to determine the degree of influence that the variable has on the overall model output. This type

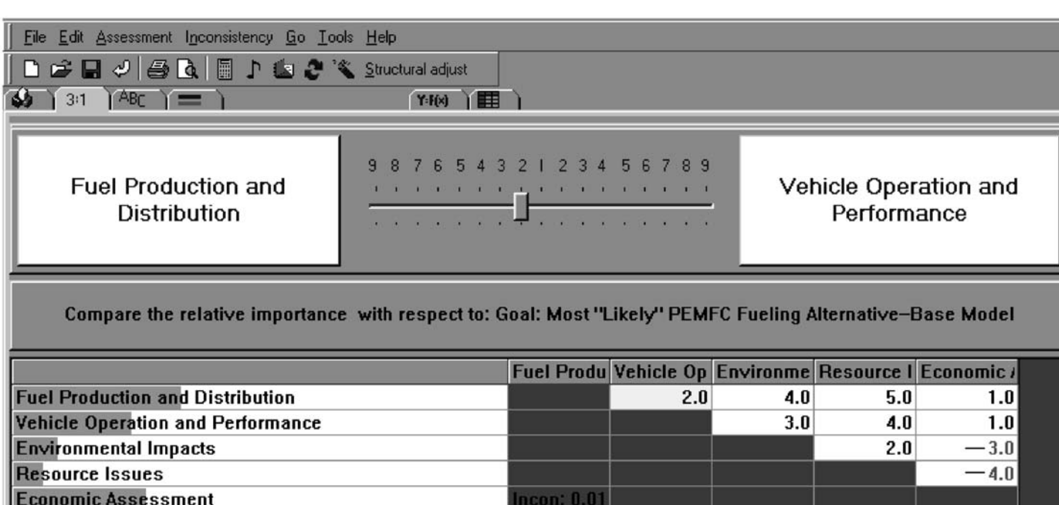

Fig. 4. "Screen shot" of pairwise comparison page for first-level criteria using ExpertChoice 2000.

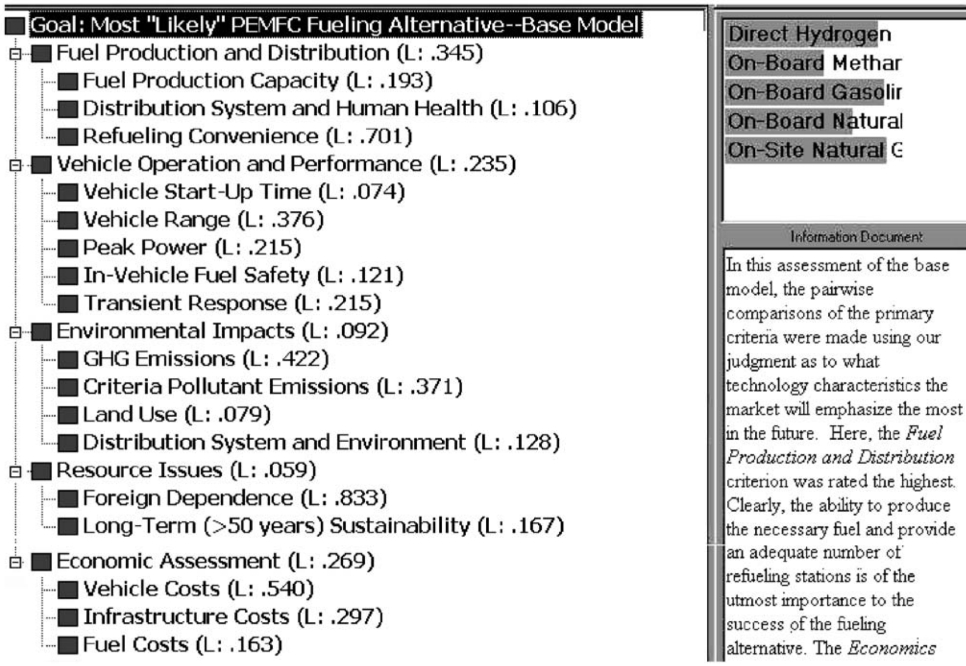

Fig. 5. "Screen shot" of typical output of AHP using ExpertChoice 2000.

of analysis is useful in that it allows for an understanding of the different outcomes that could arise given a certain amount of variation in the model assumptions. In AHP, sensitivity analysis involves the systematic adjustment of criteria and attribute weights.

As discussed in Section 1, we have extended this sensitivity analysis using a scenario-building approach. To illustrate this method, we defined three possible future scenarios and adjusted the model according to a decision-maker "living" in each scenario. The scenarios are the following:

- *Likely market conditions*. This scenario represents the status quo development of hydrogen FCV markets and our expectations about likely market conditions and consumer preferences.
- *Environmental milieu*. This scenario represents a future in which environmental issues, either through consumer preference or regulation, become a major driver in the technological development of fuel processor systems.
- *Economic milieu*. This scenario represents a future in which economics almost solely drive the decisions that will affect market entry and success.

These scenarios are not presented here in great detail, as in this paper we wish to focus on the usefulness of the AHP method for conducting quantitative PBSA. Prior to the AHP analysis (or in conjunction with it), scenarios like the ones identified above should be clearly outlined and fleshed out using principles described in the literature [2,35,36].

We performed the AHP analysis for each scenario, keeping the hierarchy constant but modifying our pairwise comparisons based on the perspective of a decision-maker "living" in the scenario's future.[5] For each scenario, we obtained synthesized results that "ranked" the alternatives in light of our pairwise judgments. The results of this analysis are presented in Section 4.

4. Results

4.1. Scenario 1: likely market conditions

As stated above, this scenario represents what we believe will be the likely market conditions in the US for fuel processors in the time frame of this analysis (15–20 years hence).[6]

Table 3 identifies each of the attributes of the AHP tree in rows and the technology alternatives in columns.[7] The numbers along the *Goal* row represent the overall "score" for each alternative based on the criteria weighting and our assessment of each alternative's performance vis-a-vis these criteria. The alternative with the highest score is considered "best." In this case, that alternative is *On-site NG* (23.0), closely followed by *On-board gasoline* (22.8), *On-board hydrogen* (21.8) and *On-board NG* (18.3). *On-board MeOH* (14.1) is the least preferred option.

Before engaging in a discussion of these results, it is instructive to review Table 3 more closely. Each first-level category in this table has an associated percentage next to it. This represents the contribution of category to the overall goal. These values are also depicted in Fig. 6. The *Fuel production and distribution* attribute leads all others, with *Economics* and *Vehicle operation and performance* next. *Environment* and *Resource issues* lag further behind. This ranking, which emerged from our pairwise comparison analysis, seems reasonable given observations in current markets for alternative fuels. In such markets, distribution networks have been the "thorn in the side" of the alternative fuel industry, preventing the widespread adoption of NG, MeOH and ethanol vehicles, even though vehicle performance and costs are comparable to gasoline vehicles.

In addition, Table 3 identifies second-level attributes and the "scores" associated with them. These scores represent the contributions that the second-level attributes have *toward their first-level parent node*. For example, *Convenience* (70.1) is the dominant attribute affecting approximately 70% of the score in the *Fuel production and distribution* category.

[5] As the reader will soon see, we only adjusted the weights to each of the first-level elements in the PBSA presented here. This assumes that the technical attributes of the alternatives (i.e., the second-level elements) remain constant under each scenario. This analysis then focuses on scenarios in which consumer preferences change over time. One could easily adjust second-level elements as well, which would imply that the technical aspects of each of the alternatives also change over time.

[6] Although we have conducted the analysis with the US in mind, the results may apply well, but not uniformly, to other industrialized countries.

[7] Actual matrix entries for our *Likely market* scenario are included in Appendix B.

Table 3
Results of the likely market scenario

	O-B H_2	O-B MeOH	O-B Gas	O-B NG	O-S NG
Goal: best PEM FCV fuel	21.8	14.1	22.8	18.3	23.0
Fuel production/distribution (34.5%)	4.5	11.1	39.6	30.0	14.8
Capacity (19.3)	3.1	10.1	40.9	22.9	22.9
Safety (10.6)	11.8	7.5	4.6	38.1	38.1
Convenience (70.1)	3.5	22.9	49.6	14.5	9.5
Vehicle operation/performance (23.5%)	25.8	13.1	19.1	16.1	25.8
Start-up time (7.4)	37.4	10.4	4.4	10.4	37.4
Range (37.6)	9.6	17.7	45.4	17.7	9.6
Peak power (21.5)	34.8	12.0	6.5	12.0	34.8
Safety (12.1)	26.0	8.2	13.8	26.0	26.0
Transient response (21.5)	34.9	12.6	5.0	12.6	34.9
Environment (9.2%)	34.4	11.1	6.9	20.9	26.7
GHG (42.2)	38.0	9.8	5.3	21.0	25.9
Local (37.1)	42.1	10.9	2.9	16.8	27.3
Land use (7.9)	3.5	25.6	41.9	14.5	14.5
Distribution (12.8)	21.8	7.9	3.5	33.4	33.4
Resources (5.9%)	31.5	11	3.4	27.1	27.1
Dependence (83.3)	28.7	10.5	3.3	28.7	28.7
Sustainability (16.7)	60.9	16.2	4.2	9.4	9.4
Economics (26.9%)	36.0	12.0	4.0	12.0	36.0
Vehicle (54.0)	39.2	8.9	3.9	8.9	39.2
Infrastructure (29.7)	6.5	18.4	50.2	18.4	6.5
Fuel (15.3)	42.7	5.9	9.6	26.0	15.8

O-B H_2 = On-board hydrogen; O-B MeOH = On-board MeOH; O-B Gas = On-board gasoline; O-B NG = On-board NG; O-S NG = On-site NG.

Finally, each cell in Table 3 identifies "scores" for each alternative by attribute. These scores represent the performance distribution of a particular attribute across alternatives. For example, in the *Fuel production and distribution* first-level attribute, *On-board gasoline* (39.6%) performs best, followed by *On-board NG* (30.0%).

Several important observations can be made regarding the results of our *likely market* scenario. These are the following:

1. There is no single dominant technology. Four of the five technologies have scores ranging from 18% to 24%. Only *On-board MeOH* seems to lag, performing near the low end for most criteria. This implies that there is an opportunity for competition and diversity among fueling options.

2. *On-site NG* has the highest score despite difficulties in *Fuel production and distribution* (where *Convenience* negatively affects it most). However, this FCV alternative tends to have the best of both worlds: it embodies the simplicity and low-cost operation of direct H_2 FCVs yet avoids some of the distribution hurdles faced by direct H_2 fuel. In addition, one can envision small-scale NG reformers located in homes connected to the NG distribution grid. If such reformers become economic, this alternative would perform even better.

3. *On-board gasoline* performs well, driven primarily by its ability to rely on the existing ubiquitous gasoline infrastructure. Although gasoline fuel processors are still expensive and

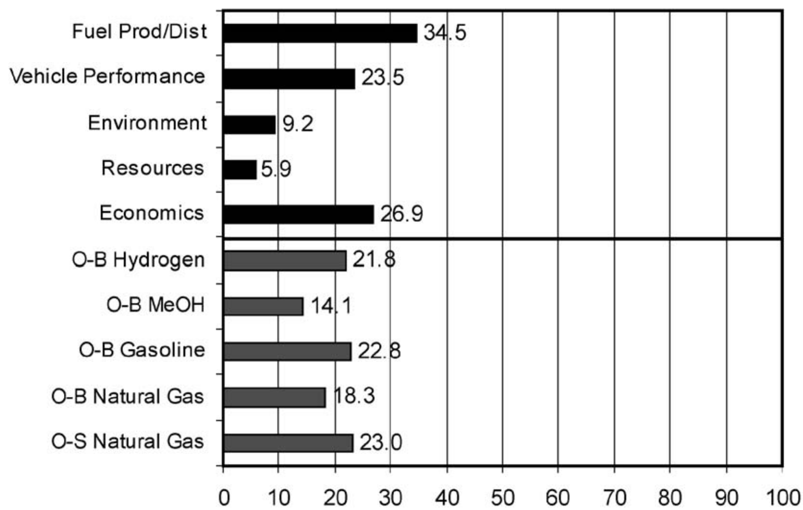

Fig. 6. Relative weighting for first-level attributes and final scores for each technology alternative (based on pairwise comparisons for the *Likely market* scenario).

must overcome several technical problems, several companies are aggressively pursuing gasoline FCVs as a transitional technology.

4. *On-board NG* performs moderately well for several reasons. First, as mentioned above, we assume that there is the potential for home refueling with NG FCVs. Technologies that can pressurize at-home NG for vehicle use are already available. The opportunity for widespread distribution of NG outweighs some of the costs and performance losses associated with methane reforming on-board a vehicle.

4.1.1. Scenario 2: economic milieu

In this scenario, we adjusted the *Economics* first-level attribute to be the dominant attribute (comprising approximately 75% of the total weight of the decision). Other first-level attributes were reduced proportionately. Although the weight placed on economics under this scenario may seem extreme at first, it allows us to test the robustness of the final results. One could just as easily craft a scenario in which economics was weighted less importantly. Fig. 7 shows our overall results.

Technology alternatives that are penalized by a higher weighting of economic factors include *On-board gasoline* and *On-board NG*. This is primarily due to the higher costs for vehicles outfitted with on-board fuel processors. *On-site NG* and *On-board hydrogen* are the two dominant technology alternatives under an *Economic-driven* scenario.

4.1.2. Scenario 3: the environmental milieu

In the third scenario, we increased the relative weights given to the *Environment* first-level attributes. As shown in Fig. 8, environmental attributes now compose 50% of the decision weighting under this scenario.

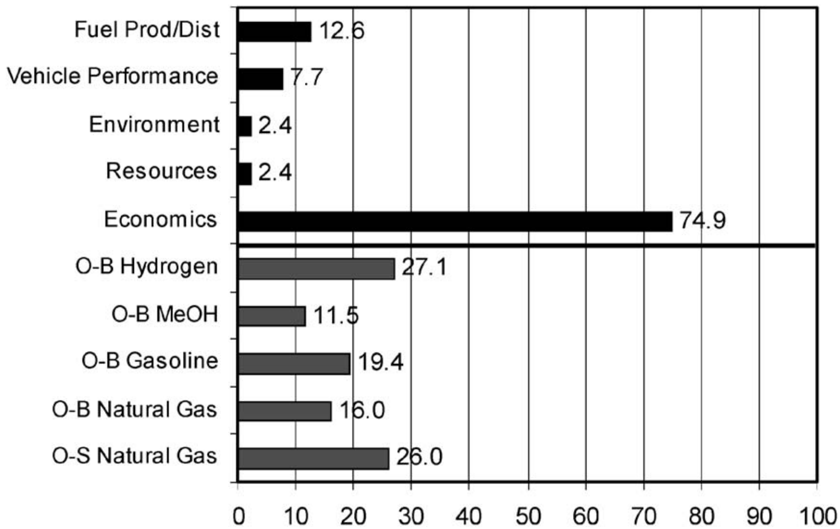

Fig. 7. Results of the *Economics milieu* scenario.

Here, *On-board gasoline* is penalized due to environmental and resource problems associated with petroleum importation, refining and fuel processing. Indeed, from an "environmental values" point of view, *On-board gasoline* FCVs would offer little improvement over the conventional gasoline vehicle milieu we see today. Instead, hydrogen and NG FCVs would define the future transportation landscape.

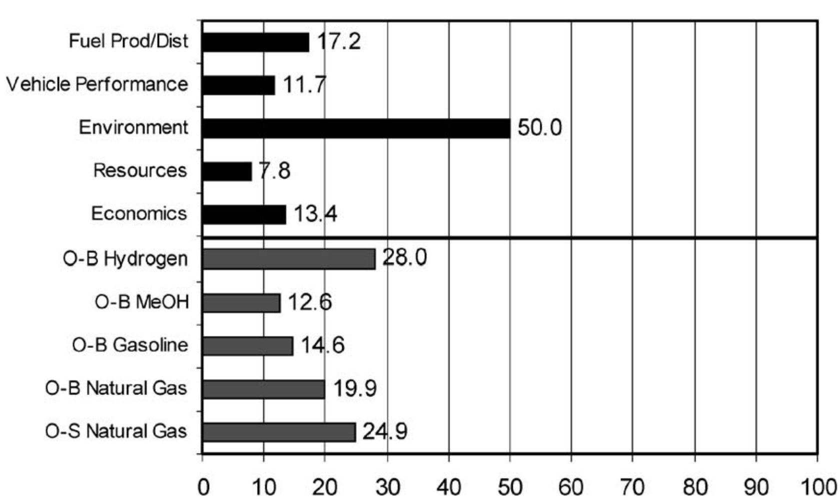

Fig. 8. Results of the *Environmental milieu* scenario.

4.2. Benefits of the PBSA methodology using AHP

It should be stressed that the example scenarios depicted here are only for illustrative purposes, and we have not applied probability functions to them (although these can be applied and the results adjusted by these probabilities in order to provide a wide-spectrum quantitative result to the user).

It must also be mentioned that the strategy used here is not a linear one. Indeed, the pairwise comparisons of the AHP force the analyst to carefully describe and outline their scenarios. So, although the analyst may have a number of scenarios in mind or built when beginning the AHP process, these will likely be modified and enhanced as the AHP process takes shape. By identifying all the important variables in the AHP process, structuring them in a hierarchy and then conducting pairwise comparisons to highlight importance, the analyst is forced to think carefully through each scenario. This process also helps the analyst evaluate the *plausibility* of each scenario; a scenario that requires implausible pairwise comparisons is likely to be an implausible scenario.

Another attribute of this process is its usefulness in focus groups or with pooled expert opinions. Conducting pairwise comparisons in groups forces participants to discuss each of the problem elements and their comparative weights. These discussions often generate self-awareness in the group regarding what the group values.

5. Conclusion

This paper examined the fuel processor technologies that will be available to serve transportation markets 15–20 years hence. The paper applied the AHP in conjunction with a scenario-building exercise (PBSA) to evaluate five technology alternatives with respect to numerous criteria and decision-maker perspectives. The results indicate that in the *Likely market scenario*, the *On-site NG* alternative scores highest, closely followed by *On-board gasoline*, *On-board NG* and *Direct hydrogen*. The *On-board MeOH* alternative scored lowest of all technologies. Our analysis also reveals that under all three cases evaluated (the *Likely market case*, the *Economics-driven scenario* and the *Environmental-driven scenario*), the *On-site NG* alternative performs extremely well. This alternative may likely be the technology that is best able to weather the uncertainty in the FCV landscape in 15–20 years. These conclusions have been supported by other studies that have identified on-board fuel processing as problematic from an economic and environmental perspective [26].

Although the range of scenarios presented in this paper is limited, we have demonstrated the usefulness of AHP-PBSA to explore future scenarios and to assist in technology and policy decision-making. Extending the method further, the AHP-PBSA analysis can be used as a backcasting tool. One could identify the technology alternative that is desired under a normative future and then adjust the AHP parameters until that technology scores highest.[8]

[8] In many cases, there will be an unlimited number of "solutions," and the decision-maker will have to narrow the scope to include only those that are possible or feasible.

This process helps decision-makers and planners focus on the issues that must be addressed today in order to achieve a desired future.

The AHP-PBSA is also useful in *constructing* scenarios, as the feedback received from the hierarchy development and the pairwise comparisons is useful information for scenario building. Ideally, one would work with a group of experts or stakeholders to formulate the hierarchy, develop pairwise comparisons and construct different scenarios in an iterative process.

The AHP-PBSA model can also be used to explore the impacts of specific policies and decisions. For example, one could use the model presented here to explore the potential FCV market impacts associated with a national GHG regulatory policy. In this case, by increasing the importance of the GHG criteria, one could see how technology alternatives might be affected.

We are only at the beginning of understanding the full range of uses for AHP-PBSA. Future research will include refinement of the methodological steps involved and explorations into the integration of stakeholder and expert groups in the process. We also believe there is a need to examine the AHP-PBSA under more complex, holistic and/or non-technology-based decisions. Finally, we would like to include probabilistic assessments in the AHP-PBSA model and present our results with appropriate probability statements. In the end, we believe AHP-PBSA will be a useful tool for future researchers and analysts that can complement the many other tools in the future toolbox.

Appendix A. FCV activities for various companies

Table A1: Companies and activities related to FCV system production and development.

FCV development	
Ford, General Motors, Honda, Nissan, Volkswagen	Direct hydrogen systems
General Motors, Toyota	On-board gasoline fuel processing
DaimlerChrysler, Hyundai, Mazda, Mitsubishi, Nissan	On-board MeOH fuel reforming
Fuel cell stack production	
Ballard Power Systems, DCH Technology, ElectroChem, H Power, International Fuel Cells (ICF), Proton Energy Systems, XCELLIS	PEM fuel cell (PEMFC) development
Fuel processor development	
General Motors, ExxonMobil	Gasoline fuel processors
International Fuel Cells	Flex fuel processor to reform traditional fuels to hydrogen
Johnson Matthey	Flex fuel processor used for on-board NG fuel reforming
Kosan	Petroleum-based fuel processors
NUVERA Fuel Cells	Gasoline fuel processors

Methanex and Misui & Company	MeOH fuel processors
Hydrogen generation systems	
Proton Energy Systems	Producing, purifying and compressing low-cost hydrogen using its HOGEN 40 on-site hydrogen generators
Stuart Energy Systems	Marketing its Electrolyser TTR Hydrogen Generator (which has the capacity to produce 1350 ft^3 hydrogen/hour)
Tathacus Resources	Hydrogen generation from water
Teledyne Energy Systems	Marketing its Titan HP Series Hydrogen Gas Supply System
Via-Tech	Hydrogen generation from water through a time-release alkaline metal emulsion released into a water reservoir
Hydrogen storage systems	
Dynetek Industries	High-pressure hydrogen storage tanks
IMPCO Technologies	High-pressure hydrogen storage tanks
Shell Hydrogen	Metal hydride storage systems
Texaco Energy Systems and Energy Conversion Devices	Metal hydrides storage systems

Appendix B. Pairwise comparison results for the “likely market” base case

Pairwise comparisons were based on literature studies and the expert opinion of these authors. The numbers below represent the relative ‘‘weight’’ given to the row vs. column using the standard AHP approach. Positive numbers represent a greater weighting to the row category, while negative numbers represent a greater weighting to the column category. Blank cells in the tables (row and column) represent the corollary of the cell’s matched pair (column and row) and are excluded for simplicity in presentation. ‘‘Inconsistency’’ ratings are provided either below the tables or in parentheses after each stated criteria. Inconsistencies of less than 0.05 are deemed appropriate for the AHP [3].

Table B1: Pairwise comparisons for first-level criteria

	Fuel production/ distribution	Vehicle performance	Environmental	Resource	Economics
Fuel production/ distribution	1	2	4	5	1

Vehicle performance	1	3	4	1
Environment		1	2	− 3
Resources			1	− 4
Economics				1

Inconsistency: 0.01.

Table B2a–e: Pairwise comparisons for second-level criteria
Table B2a: Fuel production and distribution.

	Production capacity	Distribution system	Refueling convenience
Production capacity	1	2	− 4
Distribution system		1	− 6
Refueling convenience			1

Inconsistency: 0.01.

Table B2b: Vehicle operation and performance

	Start-up	Range	Peak power	Safety	Transient
Start-up	1	− 4	− 3	− 2	− 3
Range		1	2	3	2
Peak power			1	2	1
Safety				1	− 2
Transient					1

Inconsistency: 0.01.

Table B2c: Environmental impacts

	GHG	Local pollutants	Land use	Distribution
GHG	1	1	5	4
Local pollutants		1	4	3
Land use			1	− 2
Distribution				1

Inconsistency: 0.01.

Table B2d: Resource issues

	Dependence	Sustainability
Dependence	1	5
Sustainability		1

Inconsistency: 0.00.

Table B2e: Economics

	Vehicle	Infrastructure	Fuel
Vehicle	1	2	3
Infrastructure		1	2
Fuel			1

Inconsistency: 0.01.

Table B3a–e: Pairwise comparison for technology alternatives by criteria
Table B3a: Fuel production and distribution

	Direct H_2	On-board MeOH	On-board gasoline	On-board NG	On-site NG
Production capacity (0.03)					
Direct H_2	1	−6	−9	−7	−7
On-board MeOH		1	−5	−3	−3
On-board gasoline			1	2	2
On-board NG				1	1
On-site NG					1
Distribution system (0.01)					
Direct H_2	1	2	3	−4	−4
On-board MeOH		1	2	−5	−5
On-board gasoline			1	−7	−7
On-board NG				1	1
On-site NG					1
Refueling convenience (0.03)					
Direct H_2	1	−6	−9	−5	−4
On-board MeOH		1	−3	2	3
On-board gasoline			1	4	5
On-board NG				1	2
On-site NG					1

Table B3b: Vehicle operation and performance

	Direct H_2	On-board MeOH	On-board gasoline	On-board NG	On-site NG
Start-up time (0.01)					
Direct H_2	1	4	7	4	1
On-board MeOH		1	3	1	−4

On-board gasoline			1	− 3	− 7
On-board NG				1	− 4
On-site NG					1
Range (0.01)					
Direct H_2	1	− 2	− 4	− 2	1
On-board MeOH		1	− 3	1	2
On-board gasoline			1	3	4
On-board NG				1	2
On-site NG					1
Peak power (0.00)					
Direct H_2	1	3	5	3	1
On-board MeOH		1	2	1	− 3
On-board gasoline			1	− 2	− 5
On-board NG				1	− 3
On-site NG					1
Safety (0.00)					
Direct H_2	1	3	2	1	1
On-board MeOH		1	− 2	− 3	− 3
On-board gasoline			1	− 2	− 2
On-board NG				1	1
On-site NG					1
Transient response (0.01)					
Direct H_2	1	3	6	3	1
On-board MeOH		1	3	1	− 3
On-board gasoline			1	− 3	− 6
On-board NG				1	− 3
On-site NG					1

Sources include Refs. [37,38].

Table B3c: Resource issues

	Direct H_2	On-board MeOH	On-board gasoline	On-board NG	On-site NG
Foreign dependence (0.00)					
Direct H_2	1	3	8	1	1
On-board MeOH		1	4	− 3	− 3
On-board gasoline			1	− 8	− 8
On-board NG				1	1
On-site NG					1
Sustainability (0.02)					
Direct H_2	1	5	9	7	7
On-board MeOH		1	4	2	2

On-board gasoline			1	− 3	− 3
On-board NG				1	1
On-site NG					1

Table B3d: Environmental impacts

	Direct H_2	On-board MeOH	On-board gasoline	On-board NG	On-site NG
GHG emissions (0.02)					
Direct H_2	1	3	6	2	2
On-board MeOH		1	2	− 2	− 4
On-board gasoline			1	− 4	− 5
On-board NG				1	1
On-site NG					1
Local pollutants (0.03)					
Direct H_2	1	4	9	3	2
On-board MeOH		1	6	− 2	− 3
On-board gasoline			1	− 7	− 9
On-board NG				1	− 2
On-site NG					1
Land use (0.01)					
Direct H_2	1	− 7	− 9	− 5	− 5
On-board MeOH		1	− 2	2	2
On-board gasoline			1	3	3
On-board NG				1	1
On-site NG					1
Distribution system (0.02)					
Direct H_2	1	4	7	− 2	− 2
On-board MeOH		1	3	− 4	− 4
On-board gasoline			1	− 8	− 8
On-board NG				1	1
On-site NG					1

Sources include Refs. [23,25,39].

Table B3e: Economic assessment

	Direct H_2	On-board MeOH	On-board gasoline	On-board NG	On-site NG
Vehicle costs (0.00)					
Direct H_2	1	3	9	3	1
On-board MeOH		1	− 3	1	− 3
On-board gasoline			1	− 3	− 9

On-board NG				1	−3
On-site NG					1
Infrastructure costs (0.00)					
Direct H_2	1	−3	−7	−3	1
On-board MeOH		1	−3	1	3
On-board gasoline			1	3	7
On-board NG				1	3
On-site NG					1
Fuel costs (0.01)					
Direct H_2	1	6	4	2	3
On-board MeOH		1	−2	−4	−3
On-board gasoline			1	−3	−2
On-board NG				1	2
On-site NG					1

Sources include Refs. [24,27,37,40].

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