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Fuzzy Delphi Approach for Evaluating Hydrogen Fuel Cell Applications

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Abstract. The objective of this study is to develop an assessment model that can be used to evaluate hydrogen fuel cell applications and provide a screening tool for decision makers. This model operates by selecting the evaluation indicators, determining criteria weight, and assessing the performance of hydrogen fuel cell applications with respect to each criterion. The fuzzy Delphi method (FDM) was used to select the criteria and the preferred hydrogen fuel cell products based on the information collected from a group of experts. Survey questionnaires were sent out to obtain the opinions of experts in different fields. After two rounds of surveying, the group consensus, criteria weight, and ranking of options were obtained. The selected criteria included four general fields—environment, technology, economy, and society, 14 indicators such as energy efficiency and CO2 emission, and seven hydrogen fuel cell applications such as fuel cell forklifts and fuel cell backup power systems. The results show that the fuel cell backup power system ranked the highest, followed by household fuel cell electric-heat composite systems. The criteria provide a screening tool for decision makers to select appropriate hydrogen-related applications.

Keywords: Fuel cell, hydrogen, fuzzy Delphi, evaluation indicator, assessment model

1. Introduction

Hydrogen economy is based on the application of hydrogen to replace fossil energy. Hydrogen energy technology has not yet been applied on a large scale. However, because hydrogen energy technology is still emerging, transforming the current fossil-fuel based economic system into one based on hydrogen will require long-term technological developments and the related industries and social systems will need to be changed. The development of hydrogen energy technology relies on mature, reliable, and economically competitive fuel cell products to promote the growth of the hydrogen economy. In order to speed up the process of new energy technology development and product applications, many nations have adopted policies such as research incentives and demonstrative product application programs to help companies reduce development costs and to establish a preliminary product application market.

There is a wide scope for fuel cell applications, including various types of products such as transportation motorcycles and fixed and portable power systems. Owing to limited resources, the selection of suitable fuel cell products for the development and demonstrative promotion of hydrogen energy technology is necessary to implement technological and industrial government policies. By selecting the most appropriate option from an array of diverse fuel cell applications, the government of Taiwan hopes, on one hand, to promote the development of the fuel cell related industries to achieve the objectives of the energy conservation policy, and on the other hand, to apply the limited development and subsidy funds in the right direction. Therefore, the identification of an effective hydrogen application assessment model to help the government to select the most appropriate products for development has become an important research topic.

The purpose of this study is to assist the decision-making bodies of the government, concerned with the policy of energy conservation and the development of hydrogen energy industry, to establish a fuel cell

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product assessment model in order to select high-priority products for development. In this model, the assessment criteria are based on the objectives of the hydrogen energy policy development to ensure that the selected fuel cell applications are the most suitable for the fulfilment of the government's long-term objectives.

Many studies on hydrogen-related technologies have adopted a multi-criteria decision-making (MCDM) method to evaluate the options for the energy system. Afgan et al. [1] used a multi-criteria assessment method to assess five types of hydrogen application systems. Tzeng et al. [2] adopted the MCDM method to evaluate eight new energy systems. Wang et al. [3] also adopted a fuzzy MCDM model to assess trigeneration systems. Ishikawa et al. [4] combined the fuzzy set theory and the Delphi method and developed max-min and fuzzy integration algorithms to predict the diffusion of personal computers. Murray et al. [5] proposed the improvement of the Delphi method in a fuzzy environment. Further, Kaufmann and Gupta [6] and Kuo and Chen [7] described the merits of using FDMs, such as the elimination of the distortion of expert opinions, clear expression of the semantic structure of selected options, and the consideration of the fuzzy nature of the survey process. Hence, by considering the MCDM and the Delphi methods, this study employs the FDM as the basis of the evaluation to assess various fuel cell applications.

2. Fuzzy Delphi method

Expert questionnaires are a useful tool for data collection in a Delphi survey when interviewing individuals is not possible in terms of time and group arrangement [8]. Questions are derived from related literature and suggested by experts in an open format.

Assume that K experts are invited to determine the importance of the evaluation criteria and the ratings of the alternatives with respect to various criteria using linguistic variables. The linguistic variables are then converted into triangular fuzzy numbers as suggested in Tables 1 and 2.

Table 1: Linguistic variables for the importance weight of criteria

Linguistic variable	Fuzzy scale
Extremely unimportant	(0.0, 0.0, 0.1)
Not very important	(0.0, 0.1, 0.3)
Not important	(0.1, 0.3, 0.5)
Fair	(0.3, 0.5, 0.7)
Important	(0.5, 0.7, 0.9)
Very important	(0.7, 0.9, 1.0)
Extremely important	(0.9, 1.0, 1.0)

Table 2: Linguistic variables for the rating of alternatives

Linguistic variable	Fuzzy scale
Very low	(0.0, 0.0, 0.1)
Medium low	(0.0, 0.1, 0.3)
Low	(0.1, 0.3, 0.5)
Fair	(0.3, 0.5, 0.7)
High	(0.5, 0.7, 0.9)
Medium high	(0.7, 0.9, 1.0)
Very high	(0.9, 1.0, 1.0)

Let fuzzy numbers $\tilde{r}_{ij}^{k}$ be the rating of alternative *i* with respect to criteria *j* and $\tilde{w}_{j}^{k}$ be the j[th] criteria weight of the k[th] expert for $i = 1, \ldots, m$, $j = 1, \ldots, n$, and $k = 1, \ldots, K$,

and $$\tilde{r}_{ij} = \frac{1}{K} \otimes \left[\tilde{r}_{ij}^{1} \oplus \tilde{r}_{ij}^{2} \oplus \cdots \oplus \tilde{r}_{ij}^{K}\right];$$

$$\tilde{w}_{j} = \frac{1}{K} \otimes \left[\tilde{w}_{j}^{1} \oplus \tilde{w}_{j}^{2} \oplus \cdots \oplus \tilde{w}_{j}^{K}\right],$$

where the operation laws for two triangular fuzzy numbers $\tilde{m} = (m_1, m_2, m_3)$ and $\tilde{n} = (n_1, n_2, n_3)$ are as follows:

$$\tilde{m} \oplus \tilde{n} = (m_1 + n_1, m_2 + n_2, m_3 + n_3),$$

$$\tilde{m} \otimes \tilde{n} = (m_1 n_1, m_2 n_2, m_3 n_3),$$

$$a \otimes \tilde{m} = (am_1, am_2, am_3),\ a > 0.$$

For each expert, we use the vertex method to compute the distance between the average $\tilde{r}_{ij}$ and $\tilde{r}_{ij}^{k}$ and the distance between the average $\tilde{w}_{j}$ and $\tilde{w}_{j}^{k}$; $k = 1, \ldots, K$ (see Chen [9]). This distance is used to measure the deviation between the average fuzzy evaluation and the experts' evaluation. The distance between two fuzzy numbers $\tilde{m} = (m_1, m_2, m_3)$ and $\tilde{n} = (n_1, n_2, n_3)$ is computed by using

$$d(\tilde{m},\tilde{n}) = \sqrt{\frac{1}{3}\left[(m_1 - n_1)^2 + (m_2 - n_2)^2 + (m_3 - n_3)^2\right]}.$$

According to Cheng and Lin [10], if the distance between the average and the expert's evaluation data is less than the threshold value of 0.2, then all the experts are considered to have achieved a consensus. Furthermore, among the $m \times n$ ratings of alternatives and n criteria weights, if the percentage of achieving a consensus is greater than 75% [11,12], then we calculate the fuzzy evaluation of each alternative. Otherwise, a second survey round is required.

The fuzzy evaluation of alternative i is given by

$$\tilde{A}_i = \tilde{r}_{i1} \otimes \tilde{w}_1 \oplus \tilde{r}_{i2} \otimes \tilde{w}_2 \oplus \cdots \oplus \tilde{r}_{in} \otimes \tilde{w}_n, \quad i = 1, \cdots, m.$$

For ranking the alternatives, the fuzzy evaluation

$\tilde{A}_i = (a_{i1}, a_{i2}, a_{i3})$ is defuzzified [13] by using

$$a_i = \frac{1}{4}(a_{i1} + 2a_{i2} + a_{i3}).$$

The ranking order of alternatives can be determined according to the values of a_i.

3. The options and evaluation criteria for fuel cell applications

3.1. Selection of options for fuel cell application

The purpose of establishing a fuel cell application assessment model in this study is to assist governmental decision-making bodies in selecting suitable products for development and demonstrative promotion. Therefore, the fuel cell products of future application markets are currently not included in the assessment options, and selections are mostly made from amongst the products from the early or developing application markets. In this study, assessment options from the early application market include fuel cell forklifts, backup power systems, household electric-heat composite systems, portable power installations, and distributed power generation systems. Options from the developing application market were limited to fuel cell motorcycles and power modules for computer, communication, and consumer (3C) products. Taiwan currently has over 10 million gasoline-powered motorcycles, a complete motorcycle industry chain, and has produced world-class achievements in the development of fuel cell motorcycles. In addition, Taiwan is the world's leading center for the development and production of 3C products, and several companies have begun their developing. On the other hand, although the commercialization of fuel cell vehicles, a major hydrogen energy application, is imminent, their development has been limited in Taiwan due to their complex technologies, high development costs, and industry threshold requirements. Therefore, fuel cell vehicles have not been included in the selected options of this study.

This study used the following seven types of fuel cell products as options: (1) Fuel cell motorcycles; (2) Fuel cell forklifts; (3) Fell cell backup power systems; (4) Household fuel cell electric-heat composite systems; (5) Portable fuel cell power facilities; (6) Distributed fuel cell power generation systems; and (7) 3C product fuel cell power modules.

3.2. Selection of criteria for evaluating fuel cell applications

Afgan et al. [14] categorized their evaluation criteria based on four aspects—resources, environment, society, and efficiency—while assessing the selected energy systems. Wang et al. [3] derived their criteria based on the aspects of technology, economy, environment, and society. Hence, this study selected the criteria derived from four aspects—environment, technology, economy, and society.

3.2.1. Evaluation criteria from an environmental perspective

(1) Energy efficiency: Afgan and Carvalho [15] evaluated the sustainability of new and renewable energy power plants; energy efficiency was one of the assessment criteria. In this study, energy efficiency is defined as the ratio between the energy efficiency of the fuel cell product and the traditional energy product.

(2) CO_2 emission: This criterion has been used by many scholars studying hydrogen energy and new

energy technologies/products [16]. In this study, carbon emission is defined as the ratio between the CO_2 emitted by fuel cell products and the CO_2 emitted by traditional energy products.

3.2.2. Evaluation criteria from a technological perspective

(1) Reliability: Jacobs [17] used system reliability as an assessment criterion. Fuel cell products are newly developed products and there is much room for improvement in their system reliability. In this study, reliability is defined as the ratio between the fuel cell product's reliability and the traditional energy product's reliability.

(2) System performance: Afgan and Carvalho [18] used this indicator as an assessment criterion for hydrogen energy systems. In this study, system performance is defined as the ratio between the overall performance of the fuel cell product and that of the traditional energy product.

(3) Product maturity: Konstantopoulou et al. [19] used this indicator as an assessment criterion for energy technology. In this study, product maturity is defined as the relative level of technological and systematic maturity of a certain type of fuel cell product compared to that of other products.

(4) Product development potential: Konstantopoulou et al. [19] used this indicator as an assessment criterion for energy technology. In this study, product development potential is defined as the relative level of product development potential of a certain type of fuel cell product compared to that of other products.

(5) Domestic technological ability: In this study, domestic technological ability is defined as the relative level of domestic technological ability of a certain type of fuel cell product compared to that of other products.

3.2.3. Evaluation criteria from an economic perspective

(1) Acquisition cost: Pilavachi et al. [20] used the acquisition cost of energy systems as an assessment criterion. In this study, acquisition cost is defined as the ratio between the acquisition cost of fuel cell products and that of traditional energy products.

(2) Use cost: Afgan et al. [1] used this indicator as an assessment criterion for hydrogen systems. In this study, use cost is defined as the ratio between the use cost of fuel cell products and that of traditional energy products.

(3) Domestic market demand: Afgan and Carvalho [18] used the European market demand for hydrogen energy systems over the next 10 years as an economic evaluation index. In this study, domestic market demand is defined as the domestic market demand for a certain type of fuel cell product over the next 10 years.

(4) Global market demand: Afgan and Carvalho [18] used the global market demand for hydrogen systems over the next 10 years as an economic evaluation index. In this study, global market demand is defined as the global market demand for a certain type of fuel cell product over the next 10 years.

3.2.4. Evaluation criteria from a social perspective

(1) Safeguard: Wang et al. [3] used the safeguarding of surroundings for residents as an assessment criterion for new energy systems. In this study, safeguard is defined as the relative level of safety while using a certain type of fuel cell product compared to that of other products.

(2) Use environment maturity: Wang et al. [3] used this indicator as an assessment criterion for new energy systems. In this study, use environment maturity is defined as the relative level of environment maturity of a certain type of fuel cell product compared to that of other products.

(3) Social acceptability: Konstantopoulou et al. [19] used the level of public willingness to use a new energy system as an assessment criterion. In this study, social acceptability is defined as the relative level of social acceptability of a certain type of fuel cell product compared to that of other products.

4. Evaluation of fuel cell applications

The experts' assessment was collected via survey questionnaires. In all, 20 questionnaires were successfully returned and validated. The criteria weight for the 14 criteria and the ratings for the seven fuel cell applications were converted into fuzzy sets based on the experts' responses on a 7-point Likert scale. The scales for three criteria (CO_2 emission, acquisition cost, and use cost) were reversed based on actual responses, because the value of these three criteria should be as small as possible.

In this study, the criterion for the evaluation of group consensus was the agreement of more than 75% of the group. [11,12]. In the first round, the average of criteria weight was found to be 75.71%, and the rating average was 61.68%. Owing to the unsatisfactory result obtained from the first round, the results were sent back to the experts for re-evaluation or revision in the second round. The estimation of the group consensus for the average criteria weight in the second round was 84.29%, and the rating average was 75.05%, which was acceptable. Hence, no further questioning was required after the second round of surveying.

After confirming the group consensus, an average fuzzy weight was formed for each respective criterion (Table 3).

Table 3: Average fuzzy weights of 14 criteria

Label	Indicator	Fuzzy weight ($\tilde{w}_j$)	Label	Indicator	Fuzzy weight ($\tilde{w}_j$)
c_1	Energy efficiency	(0.68,0.87,0.98)	c_8	Acquisition cost	(0.64,0.81,0.92)
c_2	CO_2 emission	(0.56,0.74,0.89)	c_9	Use cost	(0.62,0.80,0.92)
c_3	Reliability	(0.55,0.74,0.89)	c_{10}	Domestic market demand	(0.57,0.77,0.92)
c_4	System performance	(0.54,0.73,0.89)	c_{11}	Global market demand	(0.63,0.82,0.95)
c_5	Product maturity	(0.53,0.72,0.87)	c_{12}	Safeguard	(0.60,0.79,0.93)
c_6	Product development potential	(0.63,0.83,0.96)	c_{13}	Use environment maturity	(0.65,0.83,0.94)
c_7	Domestic technological ability	(0.57,0.77,0.92)	c_{14}	Social acceptability	(0.56,0.76,0.91)

Seven fuel cell applications (t_1, t_2, t_3, …, t_7) were rated by the same experts based on 14 criteria (c_1, c_2, …, c_{14}). The average fuzzy ratings were obtained. The experts' preferences among the selected fuel cell applications were assessed by combining the fuzzy ratings and the fuzzy weights. The various fuel cell applications were assessed by defuzzifying the fuzzy evaluation. Fuel cell applications are thus listed in Table 4 in order of priority according to their score rankings.

Table 4: Assessment of fuel cell applications

Option	Fuzzy evaluation ($\tilde{A}_i$)	Score (a_i)	Ranking
Fuel cell motorcycles	(2.76, 5.51, 8.75)	5.63	7
Fuel cell forklifts	(3.27, 6.38, 9.81)	6.46	5
Fuel cell backup power systems	(3.49, 6.70, 10.13)	6.76	1
Household fuel cell electric-heat composite systems	(3.55, 6.71, 10.01)	6.74	2
Portable fuel cell power facilities	(3.28, 6.43, 9.95)	6.53	4
Distributed fuel cell power generation systems	(3.42, 6.54, 9.88)	6.60	3
3C product fuel cell power modules	(2.84, 5.74, 9.11)	5.86	6

5. Discussion and conclusion

This study used four fields—environment, technology, economy, and society—and 14 assessment indicators for determining the fuel cell product selection criteria. Results from the FDM showed that out of the 14 indicators, the most highly weighted were c_1 (energy efficiency), c_6 (product development potential), c_{13} (use environment maturity), and c_{11} (global market demand). These four indicators were part of the categories of environment (c_1), technology (c_6), social (c_{13}), and economy (c_{11}). The lower weighted indicators included c_5 (product maturity) and c_4 (system performance).

The study results showed that from the seven hydrogen fuel cell application products, backup power systems were the best choice, followed by household fuel cell electric-heat composite systems. Their assessment scores were very close: 6.76 and 6.74, respectively. On the other hand, among the seven types of products, fuel cell motorcycles had the lowest overall assessment score because they had very low c_8 (acquisition cost), c_9 (use cost), and c_{13} (use environment maturity) scores, and did not score high on the other indicators either.

This is a preliminary study that employs the FDM for the assessment of hydrogen fuel cell applications. In this study, a model was constructed for evaluating hydrogen fuel cell applications based on an analysis of the FDM and the experts' opinions. The 20 experts invited to participate in this study have in-depth knowledge and practical experience in the field of hydrogen energy. This study provides valuable suggestions for policy making through a systematic analysis and group consensus. The results of this study indicated that the fuel cell backup power system is the most appropriate fuel cell application for Taiwan and should be chosen for further development.

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