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An Evaluation Model of Hydrogen Storage Technology by a Fuzzy Delphi Method

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Abstract--**Hydrogen energy is an emerging technology with benefits of energy savings and reduced carbon emissions. Development of hydrogen-related technologies is a top priority for advancing the hydrogen industry. However, hydrogen storage technologies vary based on energy savings and safety, making it difficult for decision makers to select appropriate technologies. Hence, research efforts have focused on selecting suitable hydrogen storage technologies. The purpose of this research is to develop an evaluation model to enable decision makers to select the most appropriate technology for development in Taiwan on the basis of 14 evaluation criteria. The weights of criteria and the ratings of technologies are collected by a seven-point linguistic scale using a Delphi questionnaire survey. The linguistic scores are then converted into fuzzy numbers and the consensus of decision makers' opinions on weights and ratings are derived mathematically using fuzzy Delphi methodology. We used the model to perform an evaluation of four different types of hydrogen storage technologies. The results of the assessment model revealed that chemical hydride technology is the most feasible for investment in Taiwan, and, as such, it should be given top priority for further development to realize industrialization.**

I. INTRODUCTION

Because of the impact of climate change and the demand for sustainable energy supplies, nations around the world are focusing on developing hydrogen-related technologies as a form of future sustainable energy. Several technologies are undergoing further development, including hydrogen production, storage, and transportation. The development of hydrogen-energy-related applications is beneficial to the public in two ways. Firstly, with respect to energy consumption, hydrogen production can decrease the reliance on fossil fuels and make energy supplies more sustainable. Secondly, the use of hydrogen energy will reduce emissions of greenhouse gases such as CO_2. With respect to economical and industrial benefits, the utilization of renewable energy with hydrogen production technologies will not only expand the domain of energy-related industries but will also assist local manufacturers in upgrading technology through the development of hydrogen applications.

Funding for hydrogen-related research and development (R&D) is very limited, however, which means that the selection of the most appropriate technology for commercial development is critical. In addition to limited support from governments, the characteristics of various hydrogen storage technologies, such as the cost and the volume of CO_2 emission, also vary significantly. The evaluation of hydrogen storage technology should reflect the set objectives, which presents further difficulties for decision makers. Hence, this study aims to determine the ideal technology among multiple criteria and options.

Many studies on hydrogen-related technologies have adopted a multicriteria decision-making (MCDM) method to evaluate the versatility of energy system options. Konstantopoulou et al. [1] used a multicriteria assessment method to assess six types of hydrogen production technologies. Afgan et al. [2] used the same method to assess five types of hydrogen application systems. Tzeng et al. [3] adopted the MCDM to evaluate eight new energy systems. Wang et al. [4] also adopted a fuzzy MCDM model to assess trigeneration systems. Few studies, however, have used the fuzzy Delphi method (FDM), which is one stream of the MCDM family, to specifically evaluate hydrogen storage systems.

In addition to the utilization of the MCDM, it is also recommended that information be collected by means of group decision making and discussions with experts; this can be realized utilizing the Delphi method [5]. Although the Delphi method has been widely applied in many management fields, such as forecasting public policy, the selection of alternative solutions, and project planning [6,7], the traditional Delphi method has been criticized for its low convergence in generating results, the long process of interrogation, and the loss of valuable information from expert opinions. Acknowledging the drawbacks of the traditional Delphi method, many scholars have attempted to improve it in a fuzzy environment. For instance, Ishikawa et al. [8] combined the fuzzy set theory in the Delphi method and developed max-min and fuzzy integration algorithms to predict the diffusion of personal computers. Kaufman and Gupta [9] also introduced fuzzy logic to evaluate the process of design projects. Murray et al. [10] proposed the improvement of the Delphi method in a fuzzy environment. Further, researchers have adopted this method to solve the fuzziness of group consensus by combining the FDM and a linguistic variable [6,11-13]. Kaufmann and Gupta [14] and Kuo and Chen [11] described the merits of using FDMs, such as avoiding the distortion of expert opinions, clearly expressing the semantic structure of selected options, and the consideration of fuzzy nature during the survey process.

Hence, by considering the MCDM and the Delphi method, this study utilizes the FDM as an evaluation base on which to assess various hydrogen storage technologies. This paper is organized as follows. Section 2 introduces the process of the FDM to assess the expert consensus and list the alternative options in the order of preference. Section 3 identifies the evaluation criteria and options of hydrogen storage technologies to assess. Section 4 uses hydrogen storage technologies to illustrate the process of using the FDM to enable field experts to determine the hydrogen storage technologies with greatest potential for development in

Taiwan. Discussion and conclusion of research findings are presented in section 5. The results are expected to provide valuable future implications for policy makers and hydrogen-related industries.

II. METHODOLOGY

Expert questionnaires are a useful tool for data collection in a Delphi survey when interviewing individuals is not possible because of time and group arrangement [5]. The questions were derived from related literature and suggested by experts in an open format. The process of FDM is illustrated as follows:

Step 1 Assume that K experts are invited to determine the importance of the criteria and the ratings of alternatives with respect to various criteria using linguistic variables (Table 1 and Table 2).

Step 2 Convert the linguistic variables into triangular fuzzy numbers as suggested in Table 1 and Table 2.

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, ..., m*, *j=1, ..., n*, *k=1, ..., K*

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

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

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:

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

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

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

$$a > 0$$

Step 3 For each expert, 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 $\tilde{w}_j^{k}$, $k = 1, \cdots, K$ (see Chen [15]).

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

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

Step 4 According to Cheng and Lin [16], if the distance between the average and expert's evaluation data is less than a threshold value 0.2, then all experts have achieved the consensus. Furthermore, among those $m \times n$ ratings of alternatives and *n* criteria weights, if the percentage of achieving group consensus is greater than 75% [17,18], then go to step 5, otherwise, the second round of survey is required.

Step 5 Aggregate the fuzzy evaluations by

$$\tilde{A} = \begin{bmatrix} \tilde{A}_1 \\ \tilde{A}_2 \\ \vdots \\ \tilde{A}_m \end{bmatrix}, \text{ where}$$

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

$$i = 1, \cdots, m.$$

Step 6 For each alternative option, the fuzzy evaluation $\tilde{A}_i = (a_{i1}, a_{i2}, a_{i3})$ is defuzzified by

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

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

TABLE 1 LINGUISTIC VARIABLES FOR THE IMPORTANCE WEIGHT OF CRITERIA

Linguistic variable	Fuzzy scale
Extremely unimportant (EU)	(0.0, 0.0, 0.1)
Not very important (NV)	(0.0, 0.1, 0.3)
Not important (NI)	(0.1, 0.3, 0.5)
Fair (F)	(0.3, 0.5, 0.7)
Important (I)	(0.5, 0.7, 0.9)
Very important (VI)	(0.7, 0.9, 1.0)
Extremely important (EI)	(0.9, 1.0, 1.0)

TABLE 2 LINGUISTIC VARIABLES FOR THE RATING OF ALTERNATIVES

Linguistic variable	Fuzzy scale
Very low (VL)	(0.0, 0.0, 0.1)
Medium low (ML)	(0.0, 0.1, 0.3)
Low (L)	(0.1, 0.3, 0.5)
Fair (F)	(0.3, 0.5, 0.7)
High (H)	(0.5, 0.7, 0.9)
Medium high (MH)	(0.7, 0.9, 1.0)
Very high (VH)	(0.9, 1.0, 1.0)

III. EVALUATION CRITERIA AND OPTION OF HYDROGEN STORAGE TECHNOLOGIES

Owing to the complexity of evaluating various hydrogen systems, it is not feasible to compare technologies that rely on a single aspect or only a few criteria [19]. Hence, researchers have attempted to develop a holistic view to categorize those criteria in terms of various aspects. Granovskii et al. [20] and Kothari et al. [21] assessed various methods of hydrogen production based on the aspects of environment and economy. Afgan et al. [19] categorized their criteria based on the four aspects of resources, environment, society, and efficiency in assessing selected energy systems. Petrecca and Decarli [22] examined the impact of using hydrogen systems based on technical and economic aspects. Wang et al. [4] derived their criteria from the dimensions of technology, economy, environment, and society. Hence, the present study selects criteria derived from the four aspects of environment, technology, economy, and society.

A. Selection of criteria for evaluating hydrogen storage technologies

1. Criteria from environmental aspect

i. Energy efficiency: Efficiency is the most common criterion for assessing energy-related technologies and application systems. In the study performed by Afgan et al. for the assessment of hydrogen and other renewable energy-related technologies, efficiency was the main evaluation criterion used [1,19,20,23,24]. Efficiency usually represents the ratio between the system's output power (energy) and the energy (by means of electricity or heat in general) consumed by the system. During the process of hydrogen storage, energy is needed; this energy may come from external sources (for example, electricity). In this study, the criterion of efficiency is used to evaluate the performance of hydrogen storage technology in terms of energy conservation.

ii. CO_2 emission: Similar to energy efficiency, CO_2 emission is another common criterion for evaluating energy-related technology and application systems [25,4,19,1]. Based on the Kyoto Protocol, governments from various nations have agreed to reduce greenhouse CO_2 emissions in order to mitigate the environmental impact of fossil fuel consumption. Hence, in this study, CO_2 emission is used to evaluate the performance of hydrogen storage technology in terms of reductions in carbon emissions.

2. Criteria from technological aspect

i. Volume density (g/l): From the technical issues aspect, the bottleneck of current hydrogen storage technology lies in how to develop a technique that can store the most hydrogen with the least volume and weight. Therefore, the concepts of volume density and gravimetric capacity were adopted to evaluate the hydrogen storage ability in this study. Volume density is defined as the weight of hydrogen stored (g) per unit volume of the hydrogen storage system (l).

ii. Gravimetric capacity: Gravimetric capacity is defined as the weight percentage (wt%) of the hydrogen stored in the hydrogen storage system.

iii. Technological maturity: For each piece of hydrogen storage technology, the criterion of technological maturity is identified according to the level of technological development as judged by experts [4].

iv. Technology development potential: This criterion is defined as the evaluation of each technology by its potential for future development; it is measured by its relative status (or progress).

v. Technological/industrial support: This is defined as the capability by which relevant technological or industrial support can be sought during the development of hydrogen technology.

3. Criteria from economic aspect

Cost is an essential factor when selecting a piece of technology with the greatest commercial potential for future development. In general, if the cost of hydrogen storage decreases, the penetration of hydrogen applications may increase. Hence, hydrogen storage technology with lower cost tends to have better competitiveness in general, which promotes its development as well as industrial commercialization. Besides cost, future market size is one of the important factors that government and businesses need to consider when choosing a new technology for investment. The present study uses the cost and future market size as benchmarks, which consist of the following four criteria.

i. Capital cost: This is defined as the cost of facilities and factory buildings required for storage hydrogen [25]. The assessment of investment cost is measured by the ratio of monetary cost to the capacity of H_2 storage (kg/day).

ii. Hydrogen storage cost: This is defined as the other costs incurred in the process of hydrogen storage, such as workforce salaries and energy consumption [24]. The assessment of hydrogen storage cost is measured by the total cost divided by the capacity of H_2 storage (kg/day).

iii. Domestic market demand: According to Afgan and Carvalho [26], the assessment of this criterion is described by the participation of the respective system in the total market for the specific time period. In this study, domestic market demand is defined as the capacity of demand in domestic markets in the next 10 years.

iv. Global market demand: Similar to the assessment of national market demand above, the assessment of global market demand is described in terms of the capacity of global demand in the next 10 years.

4. Criteria from societal aspect

i. Land use: This is defined as the proportion of land (acreage) required for producing H_2 [4,26,27]. Such an assessment is measured by acreage of land (km^2) divided by the capacity of hydrogen storage (kg/day).

ii. Safeguard: This is defined as whether or not the system is safe to the surroundings and people [4].

iii. Social acceptability: The factor of potential acceptability in society is described by the public's acceptance of a piece of hydrogen production technology [1].

B. Options for selecting hydrogen storage technology

The major hydrogen storage technologies currently available are [28-32]: hydrogen storage by compression (compressed hydrogen), low-temperature liquidized hydrogen storage (liquid hydrogen), solid-state hydrogen storage by hydrogen-storage alloy (metallic hydride), and chemical hydrogen storage by hydrides (chemical hydride). In addition, the use of nanotechnology to develop novel hydrogen storage materials (i.e., nanotubes) is an important topic of research. Nevertheless, the use of such nanomaterials in hydrogen storage is still in the R&D stage, and may need more time before full commercialization is realized. Only those technologies that are currently available (i.e., compressed hydrogen, liquid hydrogen, metallic hydride, and chemical hydride) were selected as the hydrogen storage technology options for assessment.

1. Compressed hydrogen

Compressed hydrogen is produced by reducing the volume of hydrogen gas via a compressor under high pressure and then storing the compressed gas in a sealed high-pressure container. In this way, more hydrogen can be stored in the least amount of space. Typically, a hydrogen storage container is made of high compressive strength materials that can withstand pressure of 34－69 Mpa. However, this kind of high-pressure hydrogen storage container may give rise to safety concerns such as the risk of container explosion and leaking, which will lead to higher cost. Hydrogen storage by compression is a well-developed and widely used technology. Nevertheless, even with a high-capacity (69 MPa of pressure) hydrogen storage container, the mileage of a vehicle driven by stored hydrogen is still less than that of a conventional gasoline-powered vehicle. Therefore, the development of novel compressed hydrogen storage containers that can withstand even higher pressure is required.

2. Liquid hydrogen

When the surrounding temperature is reduced to an absolute temperature of 20 K (approximately -253°C), gaseous hydrogen becomes liquid. Because liquid hydrogen of the same mass will occupy less volume than gaseous hydrogen, a higher mass-to-volume energy density will result. Although liquid hydrogen will have higher mass-to-volume energy density, the process to cool hydrogen gas down to 20 K under one atmospheric pressure will require a tremendous amount of energy. Therefore, energy consumption will be the major obstacle in liquid hydrogen storage. Furthermore, despite the fact that liquid hydrogen storage will produce the highest energy density, more stringent requirements, such as equipment size and safety, are needed for the design of storage facilities, which will limit the application of liquid hydrogen.

3. Metallic hydrides

The use of metallic hydrides for the storage of hydrogen does not need high pressure (less than 10 atmospheric pressure) for the filling, storage, and releasing the hydrogen gas. In addition, an extremely high-pressure storage container and low-temperature operation is not necessary during metallic hydride hydrogen storage. Therefore, in general, using a container made of metallic hydride to store hydrogen is the simplest and safest way to perform hydrogen storage. The use of this method will not involve a risk of container explosion or leaking. The problem of hydrogen loss because of evaporation in low-temperature liquid hydrogen storage will also not be observed. However, because the working principle of metallic hydride hydrogen storage is to utilize the reaction between metallic alloy and hydrogen gas, a low mass-to-volume energy density will result. Many types of metallic alloys have been used for metallic hydride hydrogen storage. Currently, two types of metallic alloys, AB_5 and AB_2, which involve rare-earth elements, have most often been used for commercial production.

4. Chemical hydrides

In chemical hydride hydrogen storage, a special reactor made of a chemical hydride material is designed. Through the reaction between a catalyst and water inside the reactor, hydrogen is released. The major advantage of chemical hydride hydrogen storage is its high mass-to-volume energy density. Some of the typical chemical hydride materials used are LiH, $LiBH_4$, $LiAlH_4$, $NaBH_4$, MgH_2, and $NaAlH_4$. Compared with other hydrogen storage technologies, chemical hydride can store the most hydrogen per unit volume and unit mass. However, this technique is still far from commercial production.

C. Criteria and options of hydrogen storage technology

To summarize the above criteria obtained from the literature and industrial applications, this study constructs an assessment model based on four aspects (environment, technology, economy, and society) and 14 criteria that can be connected to assess selected hydrogen storage technologies with the greatest potential for development in Taiwan (see Figure 1).

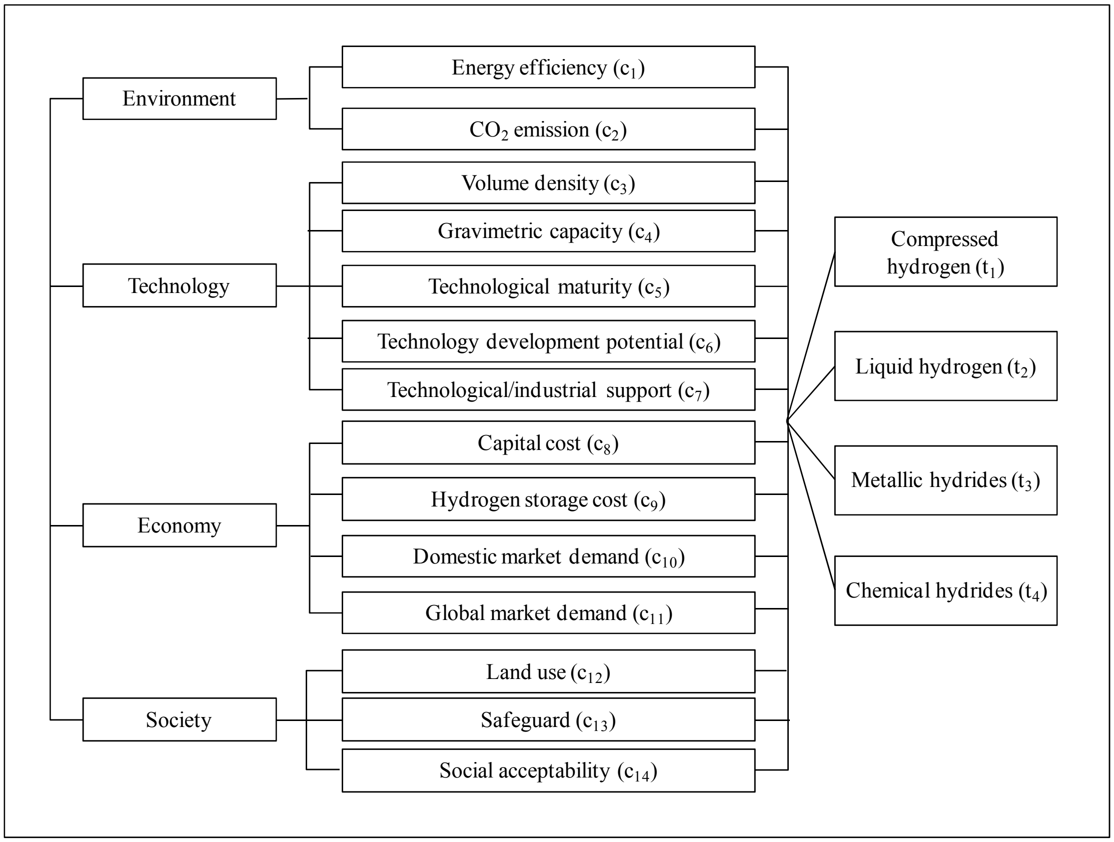

Fig. 1: Criteria and options of hydrogen storage technologies

IV. EVALUATION OF HYDROGEN STORAGE TECHNOLOGIES

Because of the complexity of selecting the best option among the various hydrogen storage technologies, this study used 14 criteria from four aspects to assess four hydrogen storage technologies. A panel was formed of nine experts from various fields, including academia and the hydrogen industry. The evaluation procedures are described as follows.

Experts' information was collected by survey questionnaires. In all, nine questionnaires were successfully returned and validated. The criteria weight for the 14 criteria and ratings of four hydrogen storage technologies were converted into fuzzy sets based on experts' responses on a 7-point Likert scale (Table 3). The scales for four criteria, i.e., CO_2 emission, capital cost, hydrogen storage cost, and land use, were reversed based on actual responses because the value of these four criteria should be as small as possible.

The group consensus was estimated. The distance between two fuzzy numbers was calculated by measuring the deviation between the average fuzzy evaluation and the experts' evaluation data. For instance, for expert 1, under the criterion of energy efficiency (c_1), the average fuzzy weight is (0.79, 0.92, 0.98) and the original evaluation data is (0.90, 1.00, 1.00). Hence, the distance between these two fuzzy numbers is given by:

$$\sqrt{\frac{1}{3}[(0.90-0.79)^2+(1.00-0.92)^2+(1.00-0.98)^2]} = 0.08 \quad < 0.2$$

TABLE 3 RATINGS OF FOUR HYDROGEN STORAGE TECHNOLOGIES (ONE EXPERT'S RATINGS IS GIVEN AS AN EXAMPLE)

	c_1	c_2	c_3	c_4	c_5	c_6	c_7	c_8	c_9	c_{10}	c_{11}	c_{12}	c_{13}	c_{14}
t_1	F	F	F	F	MH	H	H	H	H	H	MH	H	F	F
t_2	F	H	F	F	H	F	F	H	H	L	L	H	H	F
t_3	F	F	H	H	F	MH	H	F	F	H	H	F	MH	H
t_4	H	H	H	H	H	MH	F	F	F	F	H	F	MH	H

The value of 0.08 is less than the threshold value of 0.2 set by this research and is thus acceptable for group consensus. The same rule is applied to the rating of hydrogen storage options. For evaluating the option of compressed hydrogen (t_1) under the criterion of energy efficiency, the average fuzzy rating is (0.32, 0.52, 0.71) and the original evaluation data is (0.30, 0.50, 0.70). Hence, the deviation is 0.02, which means that group consensus is achieved on this item.

In this study, the criterion used to evaluate group consensus was based on 85% group agreement. In the first round, the average criteria weight is 90.48% and the rating average is 79.96%. Owing to the unsatisfactory results obtained in the first round, the results were sent back to the experts for re-evaluation or revision in the second round. The estimation of group consensus in the second round was 90.48% in average criteria weight and 87.50% in rating average, which is acceptable. Hence, no further questioning was required after the second survey round.

After confirming group consensus, an average fuzzy weight was formed by each criteria respectively. (Table 4).

Four technologies (t_1, t_2, t_3, t_4) were rated by the same experts by taking into account the 14 criteria (c_1, c_2, …, c_{14}). The average fuzzy ratings are presented in Table 5.

The experts' preferences for hydrogen storage technologies were assessed by combining the fuzzy ratings and the fuzzy weights. The assessment of various hydrogen storage technologies was conducted by defuzzifying the fuzzy evaluation. Hydrogen storage technologies are thus listed by order of priority (t_1, t_2, t_3, t_4) via their score rankings (Table 6).

TABLE 4 AVERAGE FUZZY WEIGHTS OF 14 CRITERIA

Label	Indicator	Fuzzy weight
C_1	Energy efficiency	(0.79,0.92,0.98)
C_2	CO_2 emission	(0.63,0.81,0.93)
C_3	Volume density	(0.81,0.94,0.99)
C_4	Gravimetric capacity	(0.81,0.94,0.99)
C_5	Technological maturity	(0.61,0.80,0.94)
C_6	Technology development potential	(0.72,0.90,0.99)
C_7	Technological/industrial support	(0.57,0.76,0.91)
C_8	Capital cost	(0.59,0.79,0.94)
C_9	Hydrogen storage cost	(0.59,0.78,0.93)
C_{10}	Domestic market demand	(0.66,0.86,0.98)
C_{11}	Global market demand	(0.77,0.92,0.99)
C_{12}	Land use	(0.46,0.66,0.84)
C_{13}	Safeguard	(0.66,0.84,0.97)
C_{14}	Social acceptability	(0.59,0.79,0.94)

TABLE 5 AVERAGE FUZZY RATINGS

	c_1	c_2	c_3	c_4	c_5	c_6	c_7	c_8	c_9	c_{10}	c_{11}	c_{12}	c_{13}	c_{14}
t_1	0.32	0.30	0.30	0.23	0.68	0.31	0.43	0.21	0.23	0.50	0.54	0.23	0.23	0.32
	0.52	0.50	0.50	0.43	0.88	0.50	0.63	0.41	0.43	0.70	0.74	0.43	0.41	0.52
	0.71	0.70	0.70	0.63	0.99	0.70	0.82	0.61	0.63	0.87	0.89	0.63	0.61	0.72
t_2	0.24	0.21	0.37	0.28	0.52	0.24	0.29	0.14	0.10	0.17	0.23	0.17	0.32	0.26
	0.43	0.41	0.57	0.48	0.72	0.43	0.48	0.32	0.28	0.34	0.41	0.37	0.52	0.46
	0.62	0.61	0.77	0.68	0.89	0.63	0.68	0.52	0.48	0.54	0.61	0.57	0.72	0.66
t_3	0.43	0.32	0.43	0.28	0.32	0.63	0.31	0.23	0.30	0.39	0.57	0.28	0.61	0.52
	0.63	0.52	0.63	0.48	0.52	0.83	0.50	0.43	0.50	0.59	0.77	0.48	0.81	0.72
	0.83	0.72	0.83	0.68	0.72	0.97	0.69	0.63	0.70	0.79	0.93	0.68	0.96	0.90
t_4	0.52	0.26	0.48	0.39	0.27	0.70	0.30	0.23	0.32	0.39	0.66	0.28	0.59	0.50
	0.72	0.46	0.68	0.59	0.46	0.89	0.50	0.43	0.52	0.59	0.84	0.48	0.79	0.70
	0.91	0.66	0.87	0.79	0.66	0.99	0.69	0.63	0.72	0.79	0.97	0.68	0.94	0.88

TABLE 6 ASSESSMENT OF HYDROGEN STORAGE TECHNOLOGIES

Technology potion	Fuzzy value	Score	Ranking
Compressed hydrogen	(3.83,7.03,10.00)	6.97	3
Liquid hydrogen	(2.80,5.74,8.78)	5.76	4
Metallic hydrides	(4.44,7.77,10.79)	7.69	2
Chemical hydrides	(4.64,7.97,10.92)	7.88	1

Chemical hydrides are revealed to be the best option for future development, followed by metallic hydrides and compressed hydrogen.

V. DISCUSSION AND CONCLUSION

Because of the infancy of hydrogen energy technology, a strongly supportive policy is needed from the government to accelerate the technology and industrial development. However, the resources and research budget of the government are generally limited. Therefore, it is essential to develop a model that enables the selection of suitable technology for future development. In this study, an assessment model of evaluating hydrogen storage technology based on the MCDM method was constructed. This model can act as a screening tool for government policy-makers, enabling them to select the hydrogen storage technologies that conform to the objectives of energy conservation and industrial development promotion. The research findings indicate that chemical hydride technology should be the top-priority hydrogen storage technology that Taiwan participates in the research, development, and commercialization of.

The major achievements of the studies on chemical hydrogen storage technology currently in Taiwan include the following. (1) The use of sodium borohydride ($NaBH_4$)-based chemical hydrogen storage material for military applications, developed by the Chung-Shan Institute of Science and Technology. (2) The development of a sodium borohydride ($NaBH_4$)-based chemical hydrogen storage system by the Industrial Technology Research Institute (ITRI) under the financial support of the Bureau of Energy, Ministry of Economic Affairs. A gravimetric capacity of 4 wt% and a sodium borohydride recycling rate of greater than 76% can be realized by this system. In addition, this hydrogen storage system has been demonstrated together with the hydrogen fuel cell for civilian applications. A portable chemical hydrogen storage system was demonstrated as well. (3) Tatung System Technology Inc. has collaborated with ITRI to develop hydrogen storage－related products. (4) Because of the tremendous amount of research on ammonia borane (NH_3BH_3) around the world, ITRI has collaborated with National Cheng Kung University to carry out preliminary studies regarding ammonia borane－based chemical hydrogen storage materials.

In general, the development of various hydrogen storage technologies in Taiwan lags behind the international level. For instance, the gravimetric capacity of chemical hydrogen storage achieved internationally is 4.2 wt%, whereas that in Taiwan is 4.0 wt%. This indicates that if Taiwan wishes to develop hydrogen storage technologies that are internationally competitive, continuous efforts and investments in the development of related technologies will be required. A roadmap for the development of chemical hydrogen storage in Taiwan was described in the 2010 Energy Technology White Paper announced by the Bureau of Energy, Ministry of Economic Affairs. Based on the roadmap, the emphasis of development before 2015 will be on the R&D of niche product technologies, whereas the main development from 2015 to 2025 will be focused on the R&D of commercial-scale chemical hydride recycling technology to reduce the overall cost.

In past years, Taiwan has exerted great efforts in the development of the petroleum and plastic industries. Therefore, many talented individuals with chemistry and chemical engineering backgrounds have been cultivated. Moreover, most companies in Taiwan are highly experienced in areas such as manufacturing, mass production, and cost reduction. These will serve as Taiwan’s strengths in the development of chemical hydrogen storage technology. In the future, if more resources and time were provided and if supportive policies were made, the development of large-scale chemical hydrogen storage technologies in Taiwan would advance with even great success.

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