Fuzzy Delphi method for evaluating hydrogen production technologies

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\textbf{A B S T R A C T}

The purpose of this research is to establish an evaluation model for selecting the most appropriate technology for development in Taiwan, based on 14 evaluation criteria. Due to the inherent uncertainty and imprecision associated with the mapping of decision makers’ perception to crisp values, linguistic variables are used to assess the weights of the criteria and the ratings of each technology with respect to each criterion. The criteria weights and technology ratings are collected through a seven-point linguistic scale using a Delphi questionnaire. The linguistic scores are then converted into fuzzy numbers, and a consensus of the decision makers’ opinions on weights and ratings is mathematically derived using fuzzy Delphi methodology. We have used the model to evaluate seven different hydrogen production technologies. The results indicate that hydrogen production via electrolysis by wind power and that via electrolysis by photovoltaic electricity are the two technologies that should be chosen for further development.

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1. 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. In general, 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\textsubscript{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 also assist local manufacturers in upgrading technology through the development of hydrogen applications.

In 2009, the Executive Yuan of Taiwan announced a new policy for renewable energy industry development called “Green Energy Industry Sunrise Project”\textsuperscript{1}, which covers the hydrogen and fuel cell industry and six other green energy industries. It is estimated that the market value of the hydrogen energy and fuel cell industry in Taiwan will increase to US $400 million in 2016 and US $3 billion in 2020. In addition, it is expected that the international market share of this industry in Taiwan will reach 5% in 2020\textsuperscript{2}. Many research institutes in Taiwan that are funded by the government have developed several hydrogen production technologies. For

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example, the Industrial Technology Research Institute (ITRI) has developed technology for producing hydrogen by reforming fossil fuels. Moreover, researchers have built a demonstration system for the production of hydrogen by renewable energy electrolysis, hydrogen storage devices, and fuel cells. Additionally, Feng Chia University [3] and other research groups in Taiwan have developed technology for hydrogen production by biological processes.

However, the funding of hydrogen-related research and development (R&D) is very limited, which means that it is critical to select the most appropriate technology for commercial development. In addition to limited support from governments, the great variations in the characteristics of various hydrogen production technologies, such as the cost and demand of hydrogen production and the volume of CO₂ emission, make it difficult to select the most appropriate technology. Further, the evaluation of hydrogen production technology should reflect any set objectives, which present 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 multi-criteria decision-making (MCDM) method to evaluate the versatility of energy system options. Konstantopoulou et al. [4] used a multi-criteria assessment method to assess six types of hydrogen production technologies. Afgan et al. [5] used the same method to assess five types of hydrogen application systems. Tzeng et al. [6] adopted the MCDM to evaluate eight new energy systems. Wang et al. [7] also adopted a fuzzy MCDM model to assess trigeneration systems. However, no study appears to use the fuzzy Delphi method (FDM) as one stream of the MCDM family specifically to evaluate hydrogen production systems.

In addition to the utilization of multi-criteria decision making (MCDM), it is recommended that information is collected through group decision making and discussions with experts, for example, by following the Delphi method [8]. The Delphi method was originally developed in the 1950s by the RAND Corporation [9]. This approach consists of a survey conducted in two or more rounds. After each round, a facilitator provides results from the previous round so that participants can revise or maintain their original assessments. A questionnaire survey is conducted anonymously, so that the participating experts are not required to meet in person. It is commonly assumed that this method makes better use of group interaction [10]. Some of the advantages of the Delphi method include the following: (1) It is effective when the past data is absent. (2) It does not require experts to meet in person. (3) It is extremely useful for the forecast of a new technology or a new product.

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 [11,12], the traditional Delphi method has been criticized for the 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. [13] combined the fuzzy set theory in the Delphi method and developed max-min and fuzzy integration algorithms to predict the diffusion of personal computers. Kaufmann et al. [14] also introduced the use of fuzzy logic in evaluating the process of design projects. Murray et al. [15] proposed improving the Delphi method in a fuzzy environment. Further, researchers have adopted this method to solve the fuzziness of a group consensus by combining the FDM and a linguistic variable [11,16–18]. Kaufmann and Gupta [19] and Kuo and Chen [16] 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 to assess various hydrogen production 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 the options among the hydrogen production technologies that are to be assessed. Section 4 discusses hydrogen production technologies to illustrate the process of using the FDM to enable field experts to determine the hydrogen production technologies with the greatest potential for development in Taiwan. The discussion and conclusion of the research findings are presented in section 5. The results are expected to provide valuable future implications for policy makers and hydrogen-related industries.

### 2. Methodology

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]. 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 evaluation criteria and the ratings of alternatives with respect to various criteria using linguistic variables (Tables 1 and 2).

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

Let fuzzy numbers $i_j^k$ be the rating of alternative $i$ with respect to criteria $j$ and $\bar{w}_j^k$ be the $j$th criteria weight of the $k$th expert for $i = 1, ..., m$, $j = 1, ..., n$, $k = 1, ..., K$.

| 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.

<table>
<thead>
<tr>
<th>Linguistic variable</th>
<th>Fuzzy scale</th>
</tr>
</thead>
<tbody>
<tr>
<td>Very low (VL)</td>
<td>(0.0, 0.0, 0.1)</td>
</tr>
<tr>
<td>Medium low (ML)</td>
<td>(0.0, 0.1, 0.3)</td>
</tr>
<tr>
<td>Low (L)</td>
<td>(0.1, 0.3, 0.5)</td>
</tr>
<tr>
<td>Fair (F)</td>
<td>(0.3, 0.5, 0.7)</td>
</tr>
<tr>
<td>High (H)</td>
<td>(0.5, 0.7, 0.9)</td>
</tr>
<tr>
<td>Medium high (MH)</td>
<td>(0.7, 0.9, 1.0)</td>
</tr>
<tr>
<td>Very high (VH)</td>
<td>(0.9, 1.0, 1.0)</td>
</tr>
</tbody>
</table>

\[
\hat{r}_j = \frac{1}{K} \left[ \frac{\hat{r}_{i1} \Theta \hat{r}_{i2} \Theta \cdots \Theta \hat{r}_{iK}}{\hat{w}_j \Theta \hat{w}_k \Theta \cdots \Theta \hat{w}_n} \right]
\]

\[
\hat{w}_j = \frac{1}{K} \left[ \hat{w}_j \Theta \hat{w}_j \Theta \cdots \Theta \hat{w}_j \right]
\]

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

\[
\bar{m} \Theta \bar{n} = (m_1 + n_1, m_2 + n_2, m_3 + n_3), \quad a \Theta \bar{m} = (am_1, am_2, am_3), \quad a > 0.
\]

Step 3. For each expert, use the vertex method to compute the distance between the average \( \hat{r}_j \) and \( \hat{r}_{ik} \) and the distance between the average \( \hat{w}_j \) and \( \hat{w}_k \), \( k = 1, \ldots, K \) (see Chen [20]).

The distance between two fuzzy numbers \( \bar{m} = (m_1, m_2, m_3) \) and \( \bar{n} = (n_1, n_2, n_3) \) is computed by

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

Step 4. According to Cheng and Lin [21], if the distance between the average and expert’s evaluation data is less than the threshold value of 0.2, then all experts are considered to have achieved a consensus. Furthermore, among those \( m \times n \) ratings of alternatives and \( n \) criteria weights, if the percentage of achieving a group consensus is greater than 75% [22,23], then go to step 5; otherwise, a second round of survey is required.

Step 5. Aggregate the fuzzy evaluations by

\[
\hat{A}_i = \begin{bmatrix} \hat{A}_{i1} \\ \hat{A}_{i2} \\ \vdots \\ \hat{A}_{im} \end{bmatrix} \quad \text{where} \quad \hat{A}_i = \hat{r}_{i1} \Theta \hat{w}_1 \Theta \hat{r}_{i2} \Theta \hat{w}_2 \Theta \cdots \Theta \hat{r}_{in} \Theta \hat{w}_n,
\]

\( i = 1, \ldots, m \)

Step 6. For each alternative option, the fuzzy evaluation \( \hat{A}_i = (a_{i1}, a_{i2}, a_{i3}) \) 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 \( a_i \).

3. Evaluation criteria and options among hydrogen production technologies

Owing to the complexity in the evaluation of various hydrogen production systems, it is not feasible to compare technologies that rely on a single aspect or only a few criteria [24]. Hence, researchers have attempted to develop a holistic view to categorize the criteria according to various aspects. Granovskii et al. [25] and Kothari et al. [26] assessed various methods of hydrogen production based on the aspects of environment and economy. Afgan et al. [24] categorized their criteria based on the four aspects of resources, environment, society, and efficiency in assessing selected energy systems. Petrecca and Decarli [27] examined the impact of using hydrogen systems based on technical and economic aspects. Wang et al. [7] 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.

3.1. Selection of criteria for evaluating hydrogen production technologies

3.1.1. Criteria from an environmental perspective

i. Energy efficiency: This criterion is often described by comparing the system output with energy consumption. The energy required for hydrogen production comprises the energy stored in feedstock (e.g., natural gas or biomass) and the energy from external transformation (e.g., electricity and heat). As noted, energy efficiency is the most common criterion for assessing energy-related technologies and application systems [24,27]. In the present study, the criterion of energy efficiency is used to evaluate the performance of hydrogen production technology in terms of energy conservation.

ii. CO2 emission: Similar to energy efficiency, CO2 emission is another common criterion for evaluating energy-related technology and application systems [4,7,24,28]. Based on the Kyoto Protocol, governments from various nations have agreed to reduce greenhouse CO2 emissions in order to mitigate the environmental impact of fossil fuel consumption. Hence, in this study, CO2 emission is used to evaluate the performance of hydrogen production technology in terms of reduction in carbon emissions.

iii. Fossil fuel consumption: This criterion is measured in terms of the amount of fossil fuels used in the process of hydrogen production and applications. Fossil fuels are usually derived from petroleum, coal, or natural-gas [5]. Hence, the amount of fossil fuel consumption is often measured in units of kiloliters of oil equivalent (KLOE) in order to compare the energy converted from various sources.

3.1.2. Criteria from a technological perspective

i. Technological maturity: For each piece of hydrogen production technology, the criterion of technological
maturity is identified according to the level of technological development as judged by experts [7].

ii. Technology development potential: This criterion is defined as the evaluation of each technology with regard to its potential for future development and measured by its relative status (or progress).

iii. Technological/industrial support: Defined as the capability by which relevant technological or industrial support can be sought during the development of hydrogen technology.

3.1.3. Criteria from an economic perspective

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 production decreases, the penetration of hydrogen applications may increase. Hence, hydrogen production technology with lower cost tends to have better competitiveness in general, which promotes their development as well as industrial commercialization. The hydrogen production process may incur various costs such as fuel cost, electricity cost, capital cost, cost of operation & maintenance, production cost, investment cost, and cost of feedstock [24]. The present study uses the total production cost as the benchmark, which consists of the following five criteria.

i. Capital cost: Defined as the cost of facilities and factory buildings required for producing hydrogen [28]. The investment cost is assessed in terms of the ratio of monetary cost to the capacity of hydrogen production (kg/day).

ii. Feedstock cost: Defined as the cost of importing primary material used in the production of hydrogen [28]. The assessment of feedstock cost is evaluated by dividing the cost of importing raw material by the capacity of hydrogen production (kg/day).

iii. Hydrogen production cost: Defined as the other costs incurred in the process of hydrogen production, such as workforce salaries and energy consumption [29]. The hydrogen production cost is assessed in terms of dividing the total cost by the capacity of hydrogen production (kg/day).

iv. Domestic market demand: According to Afgan and Carvalho [30], the assessment of this criterion is described by the participation of the respective systems in the total market for a specific time period. In this study, domestic market demand is defined as the capacity of demand in domestic markets in the next 10 years.

v. 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.

3.1.4. Criteria from societal perspective

i. Land use: Described as the proportion of land (acreage) required for producing hydrogen [7,30,31]. For instance, a proportion of land may be required to install a solar-energy system to generate electricity and use it to electrolyze water and produce hydrogen. Such an assessment is measured by dividing the acreage of land (km²) by the capacity of hydrogen production (kg/day).

ii. Safeguard: Defined as whether the system is safe to the surroundings and people [7].

iii. Social acceptability: The factor of potential acceptability in society is described by the public's acceptance of a piece of hydrogen production technology [4].

3.2. Selection of options for hydrogen production technologies

A wide range of technologies is available for producing hydrogen. Some are still at the pilot stage. Hence, some researchers have conducted comparative studies and selected hydrogen production technologies with the greatest commercial potential [4,32,33]. Afgan et al. [24] described several methods of producing hydrogen, such as hydrogen production via the electrolysis of water, splitting of water, light photolysis, and reforming gas from biomass, natural gas, or any other fossil fuel. These energy sources can be utilized to provide electricity at a low cost. The characteristics of energy production systems are as follows:

i. Natural-gas reforming (SMR) technology includes natural-gas reforming and natural-gas reforming with CO₂ capture and storage.

ii. Biomass energy is mainly extracted from agricultural waste. There are two methods of producing hydrogen from biomass. The first is to transform biological compounds or agricultural waste through a thermochemical process and produce hydrogen through gasification, degradation, and reforming. This method is similar to hydrogen production through fossil fuel reforming. The second technique is to choose a biological process linked to the utilization of microorganisms that use photosynthetic reactions to generate hydrogen from biomass [34]. Several methods can be used in this process, such as photosynthesis, biophotolysis, photofermentation, dark fermentation, or the use of a hybrid reactor system that combines dark and photofermentation.

iii. Several alternative solutions for producing hydrogen through electrolysis are available, by selecting energy sources such as using public electricity (U-E), photovoltaic electricity (PV-E), and wind energy (Wind-E).

Owing to the abundance of renewable energy sources, options in this study were selected so as to include technologies with which hydrogen is produced through various processes or through the use of various energy sources. Since this study places emphasis on the perspective of hydrogen production, the technologies that are still under development or far from commercialization have been excluded, such as hydrogen production from solar/nuclear energy, thermochemical hydrogen production, and hydrogen production via the water-splitting reaction in a photo-electrolytic cell.
Following evaluation, seven hydrogen production technologies were selected for further assessment:

1. Natural-gas reforming (SMR) technology
2. Natural-gas reforming with CO₂ capture and storage (SMR-CC)
3. Hydrogen production via electrolysis by using public electricity (U-E)
4. Hydrogen production via electrolysis by photovoltaic electricity (PV-E)
5. Hydrogen production via electrolysis by wind power (Wind-E)
6. Hydrogen production technology via biomass gasification (Bio-G)
7. Hydrogen production technology via fermentation (Bio-F)

3.3. Criteria and options of hydrogen production technologies

To summarize the above criteria and options for hydrogen production technologies, 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 the seven selected hydrogen production technologies with the greatest potential for development in Taiwan (see Fig. 1).

4. Evaluation of hydrogen production technologies

Because of the complexity involved in selecting the best option among various hydrogen production technologies, this study considered 14 criteria in 4 aspects to assess 7 hydrogen production technologies. According to Adler and Ziglio [35], the suitable number of participating experts in the Delphi method is about 10–15, if there is a higher degree of homogeneity among the experts. The number of experts recommended by Jones and Twiss is 10–50 [36]. In this study, we selected 20 experts: the top 13 academic experts in the field of hydrogen energy research in Taiwan according to the budgets of their research projects and 7 experts from industry. Finally, 17 experts agreed to participate in this study. The evaluation procedures are described as follows.

Experts’ information was collected by survey questionnaires. In all, 17 questionnaires were successfully returned and validated. The weights for the 14 criteria and ratings of seven hydrogen production technologies were converted into fuzzy sets based on the experts’ responses on a 7-point Likert scale (Table 3). The scales for six criteria—CO₂ emission, fossil fuel consumption, capital cost, feedstock cost, hydrogen production cost, and land use—were reversed based on actual responses. This is because the values of these six criteria are required to be as small as possible.

The value of 0.1119 is less than the threshold value of 0.2 set by this research and is thus acceptable for the group consensus estimation. The distance between two fuzzy numbers was calculated by measuring the deviation between the average fuzzy evaluation data and the experts’ evaluation data. For instance, for expert 1 under the criterion of energy efficiency (c₁), the average fuzzy weight is (0.75, 0.89, 0.96) and the original evaluation data is (0.9, 1.0, 1.0). Hence, the distance between these two fuzzy numbers is given by

\[ \sqrt{\frac{1}{3}[0.75 - 0.9]^2 + (0.89 - 1)^2 + (0.96 - 1)^2]} = 0.1119 \]

The value of 0.1119 is less than the threshold value of 0.2 set by this research and is thus acceptable for the group consensus estimation.

### Table 3 – Ratings of seven hydrogen production technologies (one expert’s ratings are given as an example).

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<td>L</td>
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</table>

### Table 4 – Average fuzzy weights of 14 criteria.

<table>
<thead>
<tr>
<th>Label</th>
<th>Criterion</th>
<th>Fuzzy weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>C₁</td>
<td>Energy efficiency</td>
<td>(0.75, 0.89, 0.96)</td>
</tr>
<tr>
<td>C₂</td>
<td>CO₂ emission</td>
<td>(0.69, 0.86, 0.94)</td>
</tr>
<tr>
<td>C₃</td>
<td>Fossil fuel consumption</td>
<td>(0.65, 0.83, 0.94)</td>
</tr>
<tr>
<td>C₄</td>
<td>Technological maturity</td>
<td>(0.55, 0.75, 0.91)</td>
</tr>
<tr>
<td>C₅</td>
<td>Technology development potential</td>
<td>(0.56, 0.76, 0.91)</td>
</tr>
<tr>
<td>C₆</td>
<td>Technological/industrial support</td>
<td>(0.54, 0.74, 0.89)</td>
</tr>
<tr>
<td>C₇</td>
<td>Capital cost</td>
<td>(0.56, 0.76, 0.92)</td>
</tr>
<tr>
<td>C₈</td>
<td>Feedstock cost</td>
<td>(0.58, 0.78, 0.92)</td>
</tr>
<tr>
<td>C₉</td>
<td>Hydrogen production cost</td>
<td>(0.58, 0.78, 0.92)</td>
</tr>
<tr>
<td>C₁₀</td>
<td>Domestic market demand</td>
<td>(0.59, 0.79, 0.92)</td>
</tr>
<tr>
<td>C₁₁</td>
<td>Global market demand</td>
<td>(0.54, 0.73, 0.88)</td>
</tr>
<tr>
<td>C₁₂</td>
<td>Land use</td>
<td>(0.51, 0.71, 0.86)</td>
</tr>
<tr>
<td>C₁₃</td>
<td>Safeguard</td>
<td>(0.70, 0.88, 0.98)</td>
</tr>
<tr>
<td>C₁₄</td>
<td>Social acceptance</td>
<td>(0.54, 0.74, 0.91)</td>
</tr>
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</table>
consensus. The same rule is applied to the rating of hydrogen technology options. For evaluating the option of natural-gas reforming under the criterion of energy efficiency, the average fuzzy rating is (0.48, 0.68, 0.85), and the original evaluation data is (0.5, 0.7, 0.9). Hence, the deviation is 0.0333, which means that the group consensus is achieved on this item.

In this study, the criterion that is used to evaluate group consensus was based on the condition that the group agreement is greater than 75% [22, 23]. In the first round, the average of criteria weights and the rating average is 77.19%, which is acceptable. Hence, no further questioning was required after the second round of the survey.

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

Seven technologies (t1, t2, t3, ..., t7) were rated by the same experts by taking into account the 14 criteria (c1, c2, ..., c14). The average fuzzy ratings are illustrated in Table 5.

The experts’ preferences for hydrogen production technologies were assessed by combining the fuzzy ratings and the fuzzy weights. The assessment of various hydrogen production technologies was conducted by defuzzifying the fuzzy evaluation. Hydrogen production technologies are thus listed by the order of priority (t1, t2, ..., t7) via their score rankings (Table 6).

Hydrogen production via wind power (Wind-E) is shown to be the best option for future development, followed by hydrogen production via electrolysis by photovoltaic electricity (PV-E) and hydrogen production technology via fermentation (Bio-F).

5. Discussion and conclusion

The results indicate that hydrogen production via wind power (Wind-E) ranks the highest among the seven selected technologies. This is because Wind-E does not use fossil fuels and has low CO2 emissions; fossil fuel consumption and CO2 emissions are both perceived important by experts. In addition, Wind-E, in evaluating safety (safeguard criterion) and social acceptance, also performs higher than the other hydrogen production technologies. For other criteria, Wind-E’s score shows a medium–high level of performance, except for the criterion of land use. Hence, referring to the proposed assessment model, Wind-E is the most appropriate hydrogen production technology in Taiwan.

The results of this study suggest that the capital cost (c9) of hydrogen production by wind power is high, but the feedstock cost (c3) and hydrogen production cost (c8) are very low. The main benefits of hydrogen production by wind power are very low CO2 emission (c10) and fossil fuel consumption (c16). The strengths of this technology are safeguard (c13) and social acceptance (c14). The weakness of using this technology is higher land use (c12) and lower energy efficiency (c13).

<table>
<thead>
<tr>
<th>Table 5 – Average fuzzy ratings.</th>
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<tbody>
<tr>
<td>C1</td>
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<td>t1</td>
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<th>Table 6 – Assessment of hydrogen production technologies.</th>
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<td>Technology option</td>
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<td>SMR</td>
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<td>SMR-CC</td>
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5. Discussion and conclusion

The results indicate that hydrogen production via wind power (Wind-E) ranks the highest among the seven selected technologies. This is because Wind-E does not use fossil fuels and has low CO2 emissions; fossil fuel consumption and CO2 emissions are both perceived important by experts. In addition, Wind-E, in evaluating safety (safeguard criterion) and social acceptance, also performs higher than the other hydrogen production technologies. For other criteria, Wind-E’s score shows a medium–high level of performance, except for the criterion of land use. Hence, referring to the proposed assessment model, Wind-E is the most appropriate hydrogen production technology in Taiwan.

The results of this study suggest that the capital cost (c9) of hydrogen production by wind power is high, but the feedstock cost (c3) and hydrogen production cost (c8) are very low. The main benefits of hydrogen production by wind power are very low CO2 emission (c10) and fossil fuel consumption (c16). The strengths of this technology are safeguard (c13) and social acceptance (c14). The weakness of using this technology is higher land use (c12) and lower energy efficiency (c13).
Wind power generation is stochastic, and a substantial amount of power is settled in the balancing market, resulting in lower revenue for the wind power operator. Furthermore, electricity by its nature is hard to store. Hydrogen can form a buffer between electricity production and demand from the wind power plant. Therefore, electrolytic hydrogen production can prove beneficial in dealing with stochastic generators such as wind power plants. The operational flexibility of modern electrolysis plants and low-cost hydrogen storage make hydrogen an interesting option for power balancing [37]. Some field systems that use a combination of wind power and hydrogen/fuel cell technologies have been studied [38,39].

The main power supply in Taiwan is from a thermal power plant that has a high volume of CO_2 emission (0.623 kg CO_2/ kWh on an average). Hydrogen production via electrolysis by using public electricity (U-E) not only consumes a large amount of electricity but also produces high levels of CO_2. It is therefore unsuitable for use in Taiwan from the perspectives of energy conservation and carbon reduction. Although the performance of SMR-CC is better than that of SMR in terms of CO_2 emission, SMR-CC displays poor performance in energy efficiency, technological maturity, investment cost, and land use. Hence, SMR-CC is ranked last under this evaluation.

The evaluation revealed that the seven hydrogen production technologies show different performance under different criteria. Through the assessment of these criteria, it should be possible to analyze in greater detail the advantages and disadvantages of these technologies when evaluating their commercialization in the future. Wind-E, Bio-F, and SMR represent three types of technologies in the production of hydrogen, e.g., hydrogen production via renewable energy, via biomass, and via fossil fuels, respectively. Hence, it is essential to conduct strategic planning based on the strengths and weaknesses of relevant technologies under development. Three strategies are presented as follows:

i. In addition to hydrogen production via large wind-electricity generators, it is also recommended that relevant technologies and products related to medium-sized or small wind-electricity generators be developed. Hence, the cost of system implementation and land use are expected to decrease in this case.

ii. In the application of hydrogen production through Bio-F, it is important to implement more R&D on relevant technology and facilities in order to promote energy efficiency in production and to lower the cost of production equipment.

iii. In the application of hydrogen production via SMR, it is critical to complement this with CO_2 capture and storage to decrease the volume of CO_2 emissions. It is also important to emphasize the safety of systems operation and increase the level of social acceptance.

This is a preliminary study that uses FDM for the assessment of hydrogen production technologies. In this study, a model was constructed, for evaluating hydrogen production technologies based on an analysis of the FDM and experts’ opinions regarding hydrogen technology. The 17 experts invited to participate in this study have in-depth knowledge and practical experiences in the field of hydrogen energy. This study provides valuable suggestions for policy making through a systematic analysis and group consensus. The study can also be used to assess other hydrogen-related technologies in future research, such as hydrogen storage, hydrogen transportation and logistics, and the use of fuel cells.

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References


