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Econometric analysis of the R&D performance in the national hydrogen energy technology development for measuring relative efficiency: The fuzzy AHP/DEA integrated model approach

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ABSTRACT

Hydrogen energy technology can be one of the best key players related to the sector of the United Nations Framework Convention on Climate Change (UNFCCC) and the hydrogen economy. Comparing to other technologies, hydrogen energy technology is more environmentally sound and friendly energy technology and has great potential as a future dominant energy carrier. Advanced nations including Korea have been focusing on the development of hydrogen energy technology R&D for the sustainable development and low carbon green society. In this paper, we applied the integrated fuzzy analytic hierarchy process (Fuzzy AHP) and the data envelopment analysis (DEA) for measuring the relative efficiency of the R&D performance in the national hydrogen energy technology development. On the first stage, the fuzzy AHP effectively reflects the vagueness of human thought. On the second stage, the DEA approach measures the relative efficiency of the national R&D performance in the sector of hydrogen energy technology development with economic viewpoints. The efficiency score can be the fundamental data for policymakers for the well focused R&D planning.

1. Introduction

U.S., Japan, and the EU have invested significant funds and R&D resources into the development of hydrogen energy technologies which include the production and storage of fuel cell vehicles, the use of fuel cells for power generation and residential purposes, and the development of hydrogen infrastructure. Hydrogen energy technology is one of the most important alternatives preparing for the United Nations Framework Convention on Climate Change (UNFCCC). Hydrogen will be used in portable power generation systems, micro-power systems, transportation applications, residential applications, and industrial and distributed generation systems after 2020 timeframe. Hydrogen would be produced and delivered using the existing infrastructure and would eventually change to renewable sources of energy after 2020. The

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global economy will depend on hydrogen in the future for environmentally sustainable development and the low carbon green growth. As part of its efforts to develop future energy technologies, the Korean government has identified hydrogen energy technologies such as hydrogen and fuel cells as one of the green energy industrializations and sustainable developments for implementing the low carbon green growth of Korea. To this end, Korean government established the Hydrogen Energy R&D Center (HERC) and the National R&D Organization for Hydrogen & Fuel Cells (H2FC) in 2003 and 2004. Korea has focused on strategic investment in the sector of hydrogen and fuel cells development.

In reality, inputs and outputs of real world problems are often imprecise, and it is hard to tackle them with crisp numbers as reflecting human's appraisals related to pairwise comparisons. The AHP, which was developed by Saaty in the early 1970s, is a subjective tool with which to analyze the qualitative criteria needed to generate alternative priorities with 9-point scales [1]. The AHP enables decision makers to structure complex problems in a simple hierarchical form, and to assess a large number of quantitative and qualitative factors in a systematic manner. However, the AHP method is unable to provide the crisp values needed to properly reflect the fuzziness associated with decision-making problems in the real world. Nevertheless, the AHP method has proven to be a powerful decision analysis technique in the area of multi-criteria decision making (MCDM), and has been successfully applied to the tackling of MCDM problems generally. It's utilization area is as follows: R&D planning, the best policy selection, the assessment of alternatives, the allocation of resources, the determination of requirements, the prediction of outcomes, design systems, performance measurement, and the optimization and resolution of decision conflicts. Lee et al. applied the AHP approach to assess national competitiveness in the hydrogen energy technology sector [2,3] and establish national long-term improvements in energy efficiency and GHG control plans related to the Korea's energy policy [4].

To successfully produce well focused R&D outcomes in the hydrogen energy technology R&D sector, it is very meaningful to economically measure national hydrogen energy technology competitiveness. This study is the extension of our previous works [2,3], which aims to analyze Korea's national competitiveness in the hydrogen energy technology R&D sector based on the quantitative data accrued using the integrated fuzzy analytic hierarchy process (fuzzy AHP) and data envelopment analysis (DEA) approaches from an economic viewpoint. On the first stage, we applied the Fuzzy AHP approach to effectively reflect the fuzziness of human thoughts and alternatives. On the second stage, we applied the DEA approach to economically evaluate the relative efficiency and ranking of national R&D performance related to the hydrogen energy technology development sector.

In this study, we employed 4 criteria, namely technological status, R&D human resources, R&D budget, and the hydrogen technology infrastructure, to assess national competitiveness in the hydrogen technology sector. In addition, a peer-review, consisting of 33 experts in the area of hydrogen economy, was conducted, and the weights of pairwise comparisons of the criteria were synthesized. We compared the results of national competitiveness in the hydrogen energy technology sector. The results of this study will provide policy and decision makers with the strategic approach needed to effectuate well focused R&D and to produce an econometrical efficiency outcomes in the hydrogen energy technology R&D sector, as well as the fundamental data required to forge energy policy.

This paper is organized as follows: Section 2 introduces the general knowledge of the fuzzy set and fuzzy numbers. Section 3 describes the fuzzy AHP and the DEA approach. Section 4 deals with the hierarchy of the criteria used to evaluate national competitiveness in the hydrogen energy technology R&D performance sector. Section 5 displays the quantitative data obtained in relation to hydrogen energy technology R&D. Section 6 gives an illustrative example of the integrated fuzzy AHP and DEA approaches. Finally, Section 7 concludes this study.

2. Fuzzy set and fuzzy numbers

In the real world, it is very hard to extract precise data, pertaining to measurement indicators, from human judgments. It is because human preferences encompass a degree of uncertainty, and decision makers may very well be reluctant or unable to assign crisp numerical values to pairwise comparison. Decision makers prefer natural language expressions comparing with the crisp numbers when evaluating criteria and alternatives.

The concept of fuzzy theory was first introduced by Zadeh in 1965 [5]. Fuzzy theory includes elements such as fuzzy set, membership function, and the fuzzy numbers used to efficiently change vague information into useful data. Fuzzy set theory deals with the ambiguous situations well. By approximating information and uncertainty where the generation of reasonable alternatives to problems needing decisions is concerned, it effectively resembles human's fuzziness and perceptions. Fuzzy set theory uses groups of data with boundaries that feature lower, median, and upper values that are not sharply defined. Because most of the decision-making problems in the real world take place amidst situations where pertinent data and the sequences of possible actions are not precisely known, the merit of using the fuzzy approach is that it expresses the relative importance of the alternatives and the criteria with fuzzy numbers rather than crisp ones. A fuzzy set is characterized by a membership function, which assigns a membership range value between 0 and 1 to each criterion and alternative.

Triangular fuzzy numbers (TFN) and trapezoidal fuzzy numbers are usually employed to capture the vagueness of the parameters related to the selection of the alternatives. In order to reflect the fuzziness which surrounds the decision makers when they select alternatives or conduct a pairwise comparison judgment matrix, TFN is expressed with boundaries instead of crisp numbers. In this study, we use TFN to prioritize national competitiveness in the fuzzy hydrogen energy sector. TFN is designated as $M_{ij} = (l_{ij}, m_{ij}, u_{ij})$. m_{ij} is the median value of fuzzy number M_{ij}, l_{ij} and u_{ij} is the left and right side of fuzzy number M_{ij} respectively.

Consider two TFN M_1 and M_2, $M_1 = (l_1, m_1, u_1)$ and $M_2 = (l_2, m_2, u_2)$. Their operations laws are as follows:

$$(l_1, m_1, u_1) \oplus (l_2, m_2, u_2) = (l_1 + l_2, m_1 + m_2, u_1 + u_2) \quad (1)$$

$$(l_1, m_1, u_1) \otimes (l_2, m_2, u_2) = (l_1 \times l_2,\ m_1 \times m_2,\ u_1 \times u_2) \quad (2)$$

$$(l_1, m_1, u_1)^{-1} = (1/u_1, 1/m_1, 1/l_1) \quad (3)$$

3. Fuzzy analytic hierarchy process and data envelopment analysis

3.1. Fuzzy analytic hierarchy process

In the AHP, the decision-making process is modified into a hierarchical structure. At each level of the hierarchy, the AHP uses pairwise comparison judgments and matrix algebra to identify and estimate the relative priorities of criteria and alternatives. This in turn is carried out by breaking down a problem into its smaller constituent parts. The AHP thus leads from simple pairwise comparison judgments to priorities arranged within a hierarchy [6]. However, the AHP cannot effectively take into account uncertainty when assessing and tackling a problem. For example, when the AHP is employed to capture experts' knowledge acquired through perceptions or preferences, the AHP still cannot effectively reflect human thoughts with its crisp numbers.

In contrast, the fuzzy AHP, an extension of the AHP model, has been applied to resolve hierarchical fuzzy decision-making problems. Lee et al. applied the fuzzy AHP method to strategically assess the development of energy technologies for sustainable development [7] and to establish the R&D portfolios of energy technologies [8]. The fuzzy AHP can tackle fuzziness or the problem of vague decision making more efficiently by using fuzzy scales with lower, median, and upper values. The fuzzy AHP can be contrasted with the AHP's crisp 9-points scale and synthesis of the relative weights using fuzzy sets, membership functions, and fuzzy numbers. Although the fuzzy AHP approach needs cumbersome computation process as tackling a real world problem, it is much more systematic than other MCDM methods. The fuzzy AHP captures human's appraisal of fuzziness and ambiguity as making pairwise comparisons of criteria and alternatives.

The fuzzy scale used for pairwise comparisons of one attribute over another is shown in Table 1 [9]. We used the fuzzy scale when decision makers conduct pairwise comparison judgments with regards to criteria and alternatives. Let $A = (a_{ij})_{nxm}$ be a fuzzy pairwise comparison judgment matrix. Let $M_{ij} = (l_{ij}, m_{ij}, u_{ij})$ be a TFN.

The steps used for the fuzzy AHP are as follows:

Step 1: Pairwise comparison judgments of attributes are made using fuzzy numbers situated on the same level of the hierarchy structure.

Step 2: The value of the fuzzy synthetic extent with respect to the ith object is defined as

$$S_i = \sum_{j=1}^{m} M_{ij} \otimes \left[\sum_{i=1}^{n} \sum_{j=1}^{m} M_{ij} \right]^{-1} \quad (4)$$

$$\text{s.t.} \quad \sum_{j=1}^{m} M_{ij} = \left(\sum_{j=1}^{m} l_{ij}, \sum_{j=1}^{m} m_{ij}, \sum_{j=1}^{m} u_{ij} \right), \quad i = 1, 2, 3, \ \ldots, \ n \quad (5)$$

Table 1 – Fuzzy scale.

Important scale	Definition	Explanation
(1, 1, 1)	Equal importance	Two elements contribute equally
(2/3, 1, 3/2)	Moderate importance	One element is slightly favored over another
(3/2, 2, 5/2)	Strong importance	One element is strongly favored over another
(5/2, 3, 7/2)	Very strong importance	An element is very strongly favored over another
(7/2, 4, 9/2)	Extreme importance	One element is the highest favored over another

$$\sum_{i=1}^{n} \sum_{j=1}^{m} M_{ij} = \left(\sum_{i=1}^{n} \sum_{j=1}^{m} l_{ij}, \sum_{i=1}^{n} \sum_{j=1}^{m} m_{ij}, \sum_{i=1}^{n} \sum_{j=1}^{m} u_{ij} \right) \quad (6)$$

$$\left[\sum_{i=1}^{n} \sum_{j=1}^{m} M_{ij} \right]^{-1} = \left(\frac{1}{\sum_{i=1}^{n} \sum_{j=1}^{m} u_{ij}}, \frac{1}{\sum_{i=1}^{n} \sum_{j=1}^{m} m_{ij}}, \frac{1}{\sum_{i=1}^{n} \sum_{j=1}^{m} l_{ij}} \right) \quad (7)$$

The TFN value of $S_i = (l_i, m_i, u_i)$ is calculated using formulas (4)–(7).

Step 3: The values of S_i are compared and the degree of possibility of $S_j = (l_j, m_j, u_j) \geq S_i = (l_i, m_i, u_i)$ is calculated. That can be equivalently expressed as follows:

$$V(S_j \geq S_i) = \text{height}(S_i \cap S_j) = u_{S_j}(d) = \begin{cases} 1, & \text{if } m_j \geq m_i \\ 0, & \text{if } l_i \geq u_j \\ \frac{l_i - u_j}{(m_j - u_j) - (m_i - l_i)}, & \text{otherwise} \end{cases} \quad (8)$$

where d is the ordinate of the highest intersection point between u_{Si} and u_{Sj}. We need both the values of $V(S_j \geq S_i)$ and $V(S_i \geq S_j)$ to compare S_i and S_j.

Step 4: The minimum degree possibility $d(i)$ of $V(S_j \geq S_i)$ for i, $j = 1, 2,\ldots, k$ is calculated.

$$\begin{aligned} & V(S \geq S_1, S_2, S_3, \ldots, S_k), \quad \text{for } i = 1, 2, 3, \ldots, k \\ & = V[(S \geq S_1) \text{ and } (S \geq S_2) \text{ and} \ldots (S \geq S_k)] \\ & = \min\ V(S \geq S_i) \quad \text{for } i = 1, 2, 3, \ldots, k \end{aligned} \quad (9)$$

Assume that

$$d'(A_i) = \min\ V(S \geq S_i), \quad \text{for } i = 1, 2, 3, \ldots, k$$

Then the weight vector is defined as

$$W' = \left(d'(A_1), d'(A_2), \ldots, d'(A_n) \right)^T \quad (10)$$

where A_i ($i = 1, 2,\ldots, n$) are the n elements.

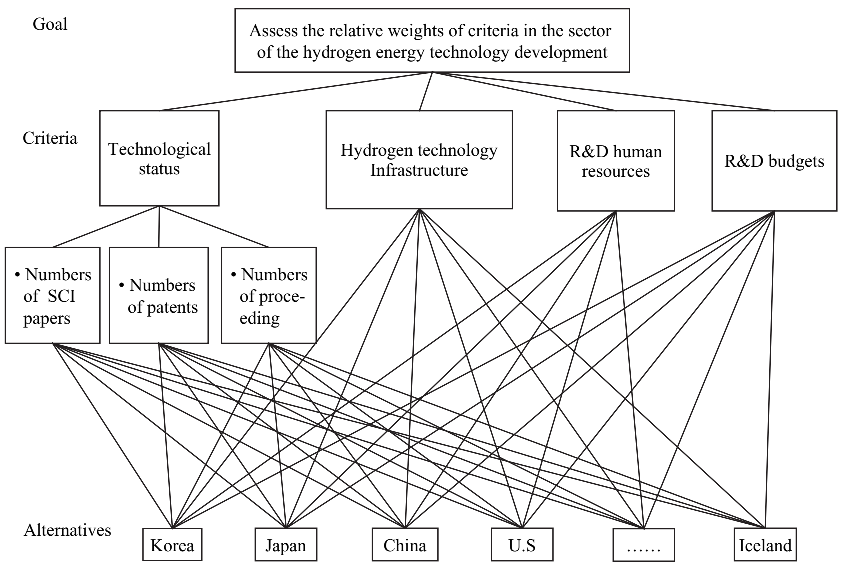

Fig. 1 – Hierarchy model for assessing criteria and alternatives.

Step 5: The weight vectors are then normalized as follows.

$$W = (d(A_1), d(A_2), \ldots, d(A_n))^T \tag{11}$$

where W is a non-fuzzy number.

3.2. Data envelopment analysis

The Data Envelopment Analysis (DEA) is an evaluation tool used in conjunction with decision making units (DMUs) that effectively solves many decision-making problems by simultaneously integrating multiple inputs and outputs using a ratio of the limited weight sum of outputs to the limited weight sum of inputs. This mathematical method has been applied to a wide range of applications since 1978. The DEA is generally applied not only to assess the service productivity of banks [10], insurance companies [11], hospitals [12], universities [13] and restaurants, but also to evaluate the project efficiency [14]. In addition, it was applied to make a strategic R&D portfolio in the sector of energy technology R&D with economic viewpoints [15–17].

The DEA ration form, proposed by Charnes, Cooper and Rhodes [18], is designed to measure the relative efficiency or productivity of a specific DMU_k. The DEA formulation is given as follows. Suppose that there is a set of n DMUs which is to be analyzed. Each set of the DMUs uses m common inputs and s common outputs. Let k ($k = 1, \ldots, n$) denotes the DMU whose relative efficiency or productivity is to be maximized.

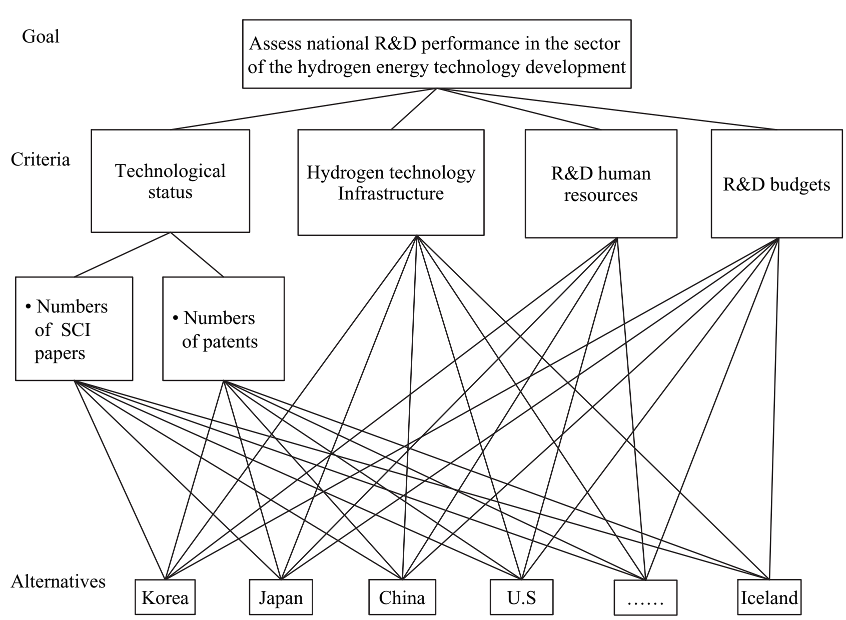

Fig. 2 – DEA model for measuring the efficiency of national R&D performance in the hydrogen energy technology development sector.

Table 2 – Quantitative data related to hydrogen energy technology R&D sector.

Nation	Technological status			R&D human resources	R&D budget (million dolar)	Infrastructure of hydrogen technology
	SCI paper	Patents	Paper proceedings			
Korea	199	69	23	590	22	6
Japan	577	645	92	2663	191	24
China	378	10	13	934	NA	3
Taiwan	51	28	5	167	NA	1
India	73	6	6	161	NA	1
Israel	19	9	2	67	NA	0
Singapore	23	3	3	54	NA	2
Turkey	35	0	0	67	4.6	0
Australia	17	8	2	62	NA	1
U.S	571	1023	578	3813	340	86
Canada	127	94	19	429	26	10
Mexico	22	1	0	75	NA	0
Brazil	42	0	1	100	NA	1
Germany	161	201	26	885	76	29
England	77	31	44	405	32	3
France	84	47	2	361	48	5
Italy	95	11	4	327	52	5
Holland	45	15	1	168	36	1
Norway	40	6	1	102	11	2
Swiss	47	7	3	134	16	1
Sweden	41	3	3	97	NA	2
Russia	37	5	4	157	NA	0
Denmark	28	10	5	94	22	6
Spain	48	1	3	182	12	2
Austria	5	3	3	37	9.1	1
Poland	33	0	0	78	NA	0
Belgium	0	1	0	3	9.2	3
Portugal	12	0	0	36	NA	1
Greece	28	2	0	81	6.1	1
Iceland	0	0	2	4	NA	1

Table 3 – Fuzzy evaluation of the goal.

	Technological status (TS)	R&D human resources (HR)	R&D budget (B)	Infrastructure of hydrogen Technology (I)
TS	(1, 1, 1)	(3/2, 2, 5/2)	(3/2, 2, 5/2)	(5/2, 3, 7/2)
	(1, 1, 1)	(2/7, 1/3, 2/5)	(3/2, 2, 5/2)	(1, 1, 1)
	(1, 1, 1)	(2/3, 1, 3/2)	(2/5, 1/2, 2/3)	(1, 1, 1)
	▪	▪	▪	▪
	▪	▪	▪	▪
	(2/5, 1/2, 2/3)	(1, 1, 1)	(1, 1, 1)	(2/3, 1, 3/2)
	(5/2, 3, 7/2)	(1, 1, 1)	(2/7, 1/3, 2/5)	(3/2, 2, 5/2)
HR	(2/3, 1, 3/2)	(1, 1, 1)	(2/7, 1/3, 2/5)	(1, 1, 1)
	▪	▪	▪	▪
	▪	▪	▪	▪
	(2/5, 1/2, 2/3)	(1, 1, 1)	(1, 1, 1)	(2/3, 1, 3/2)
	(2/5, 1/2, 2/3)	(2/5, 1/2, 2/3)	(1, 1, 1)	(1, 1, 1)
B	(3/2, 2, 5/2)	(5/2, 3, 7/2)	(1, 1, 1)	(5/2, 3, 7/2)
	▪	▪	▪	▪
	▪	▪	▪	▪
	(2/7, 1/3, 2/5)	(2/3, 1, 3/2)	(2/3, 1, 3/2)	(1, 1, 1)
	(1, 1, 1)	(2/5, 1/2, 2/3)	(1, 1, 1)	(1, 1, 1)
I	(1, 1, 1)	(1, 1, 1)	(2/7, 1/3, 2/5)	(1, 1, 1)
	▪	▪	▪	▪

Table 4 – Mean values of Fuzzy evaluation in the level of criteria.

	Technological status (TS)	R&D human resources (HR)	R&D budget (B)	Infrastructure of hydrogen Technology (I)
TS	(1.000, 1.0000, 1.000)	(0.697, 1.029, 1.407)	(0.604, 0.827, 1.108)	(0.958, 1.230, 1.511)
HR	(0.735, 0.976, 1.314)	(1.000, 1.000, 1.000)	(0.681, 0.876, 1.136)	(1.023, 1.288, 1.605)
B	(0.732, 0.933, 1.200)	(0.930, 1.195, 1.520)	(1.000, 1.000, 1.000)	(0.874, 1.142, 1.491)
I	(0.640, 0.780, 0.967)	(0.623, 0.777, 0.977)	(0.671, 0.876, 1.144)	(1.000, 1.000, 1.000)

$$\text{Max } h_k = \frac{\sum_{r=1}^{s} u_{rk} Y_{rk}}{\sum_{i=1}^{m} v_{ik} X_{ik}} \tag{12}$$

$$\text{s.t.} \quad \frac{\sum_{r=1}^{s} u_{rk} Y_{rk}}{\sum_{i=1}^{m} v_{ik} X_{ik}} \le 1, \quad \text{for } j = 1, \ldots, n \tag{13}$$

$$u_{rk} > 0 \quad \text{for } r = 1, \ldots, s \tag{14}$$

$$v_{ik} > 0 \quad \text{for } i = 1, \ldots, m \tag{15}$$

where u_{rk} is the variable weight given to the rth output of the kth DMU, v_{ik} is the variable weight given to the ith input of the kth DMU, u_{rk} and v_{ik} are decision variables determining the relative efficiency of DMU_k, Y_{rj} is the rth output of the jth DMU, and X_{ij} is the ith input of the jth DMU. This also assumes that all Y_{rj} and X_{ij} are positive. h_k is the efficiency score which is less than and equal to 1. When the efficiency score of h_k is 1, DMU_k is regarded as an efficient frontier.

There are two types of CCR models. One version is the input oriented model in which the inputs are maximized. The other is the output-oriented model in which the outputs are maximized. As the focus is on maximizing multiple outputs, this paper employs the output-oriented CCR model.

4. Hierarchy of the criteria

The assessment of national hydrogen energy technology R&D performance consists of one-tier criteria. The hierarchy structure of the criteria is shown in Fig. 1. At the top of the control hierarchy, there exists the goal which calculates the relative weights of criteria on the first phase. As a result of the Fuzzy AHP approach, number of proceeding, one of the sub-criteria, has no important values with zero and is excluded. On the second phase, we employ number of SCI and patents as sub-criteria with the application of measuring the relative efficiency of national R&D performance related to develop hydrogen energy technologies. Fig. 2 illustrates the hierarchy of DEA approach for the econometric analysis. The final goal is to assess national R&D performance in the sector of hydrogen energy technology development in a relative fashion. At Level 1, there exist four criteria: technological status, R&D human resources, R&D budgets, and hydrogen technology infrastructure. Technological status in turn consists of 2 sub-criteria, namely quantity of SCI papers and patents. The hierarchy is structured of multiple input and output factors. The input factors composed of R&D human resources and budgets associated with the development of hydrogen economy technology R&D sector. There are three output factors, namely numbers of SCI papers, patents, and infrastructure of hydrogen technology. The relative weights, calculated using the fuzzy AHP approach, are applied in conjunction with the output factors employed as part of the DEA approach.

5. Quantitative data related to hydrogen energy technologies

In this paper, we collected quantitative data related to hydrogen energy based on such factors as technological status, which is in turn composed of such elements as SCI papers, patents, and paper proceedings; R&D human resources; R&D budget; and hydrogen technology infrastructure. Table 2 exhibits the quantitative data related to hydrogen energy technologies.

The quantity of SCI papers was calculated based on the number of relevant articles found in the chemical abstracts

Table 5 – Values of $V(S_i \ge S_j)$.

$V(S_1 \ge S_j)$	Value	$V(S_2 \ge S_j)$	Value	$V(S_3 \ge S_j)$	Value	$V(S_4 \ge S_j)$	Value
$V(S_1 \ge S_2)$	0.984	$V(S_2 \ge S_1)$	1.000	$V(S_3 \ge S_1)$	1.000	$V(S_4 \ge S_1)$	0.776
$V(S_1 \ge S_3)$	0.945	$V(S_2 \ge S_3)$	0.961	$V(S_3 \ge S_2)$	1.000	$V(S_4 \ge S_2)$	0.750
$V(S_1 \ge S_4)$	1.000	$V(S_2 \ge S_4)$	1.000	$V(S_3 \ge S_4)$	1.000	$V(S_4 \ge S_3)$	0.709

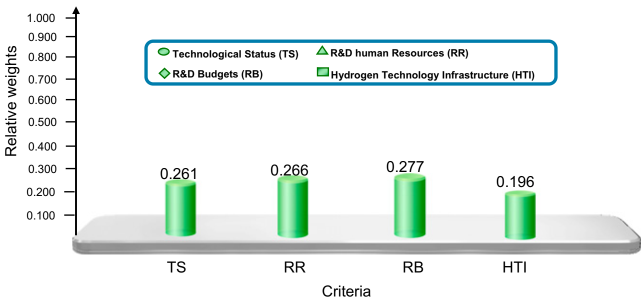

Fig. 3 – Criteria relative weights.

of the top 30 listed journals. Representative journals include the International journal of Hydrogen Energy, Journal of Alloys and Compounds, Journal of Power Sources, Applied Catalysis, Journal of the American Chemical Society, and Fuel Cells.

The quantity of patents was calculated based on the number of patents registered and opened in the United States and Europe since 2000. To this end, Korea and Japan own so many patents that we considered that this factor might skew the assessment of the national quantity of patents. As such we decided to eliminate them from the consideration of these two countries' patent cases. We established the database for hydrogen production, storage, and utilization through keyword filtering, international patent code filtering, and patentee and inventor filtering in order to collect the quantity data for patents.

The quantity of paper proceedings was determined based on the top 8 listed proceedings in the sector of hydrogen production, storage, and utilization found in chemical abstracts since 2000. The representative paper proceedings included the following: the proceedings of the symposium of the Material Research Society, AIP conference proceedings, the national meeting of the American Chemical Society, the proceedings of the SPIE, and the AIChE Annual meeting.

Information pertaining to R&D human resources was collected by the researchers using data related to the quantity of SCI papers, patents, and paper proceedings. We then formed a hydrogen technology database for 30 nations.

R&D budget assigned to the development of hydrogen energy technology was taken from the IEA/OECD paper entitled 'Hydrogen & Fuel Cells-Review of national R&D budget' [19]. Korean R&D budget, which was estimated based on the total budget of MEST and MKE in 2004, was determined to equate 21.74 million dollars at an exchange rate of 1$/1150 KRW. The hydrogen technology infrastructure takes into consideration the number of hydrogen fueling stations found in each nation according to the Fuel Cells website in 2006 [20] and Worldwide Hydrogen Fueling Stations [21].

6. Illustrative example

6.1. *Priority of criteria*

A peer-review process, consisting of 51 experts from the academic, government, industrial, and research sectors, was conducted. All in all, 33 responses were received. 24 of the experts responded that consistency should be maintained and the calculation of the weights of the 4 criteria should be synthesized. Table 3 shows the fuzzy assessment matrix created by making pairwise comparison judgments of the criteria. Thereafter, we identified the average values for each column in Table 3, which are shown in Table 4.

Using formulas (4) through (7), we were able to determine the triangular fuzzy number (TFN) values of the 4 criteria to be the following:

$$S_1(\text{Technological status}) = (3.259, 4.089, 5.027) \otimes (1/19.382, 1/15.928, 1/13.168) = (0.168, 0.257, 0.382)$$

$$S_2(\text{RD human resources}) = (3.440, 4.140, 5.055) \otimes (1/19.382, 1/15.928, 1/13.168) = (0.177, 0.260, 0.384)$$

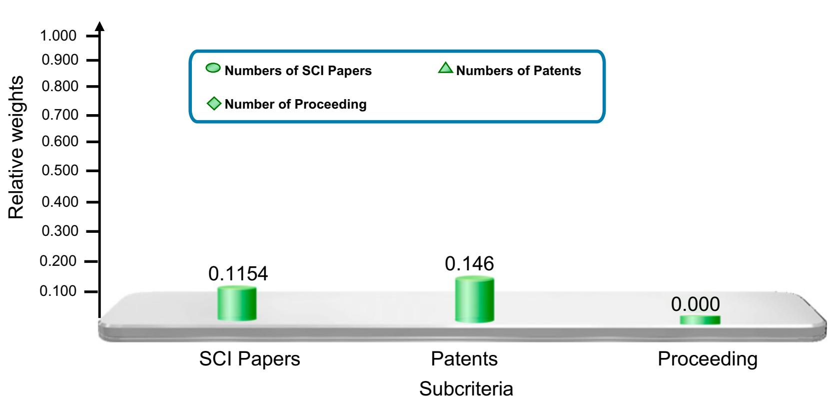

Fig. 4 – Sub-criteria relative weights.

Table 6 – Normalized quantitative data related to hydrogen energy technology R&D sector.

Nation	Technological status			R&D human resources	R&D budget (million dolar)	Infrastructure of hydrogen technology
	SCI paper	Patents	Paper proceedings			
Korea	0.0683	0.0308	0.0272	0.0478	0.0241	0.0302
Japan	0.1979	0.2881	0.1089	0.2159	0.2092	0.1206
China	0.1297	0.0045	0.0154	0.0757	NA	0.0151
Taiwan	0.0175	0.0125	0.0059	0.0135	NA	0.0050
India	0.0250	0.0027	0.0071	0.0131	NA	0.0050
Israel	0.0065	0.0040	0.0024	0.0054	NA	0.0000
Singapore	0.0079	0.0013	0.0036	0.0044	NA	0.0101
Turkey	0.0120	0.0000	0.0000	0.0054	0.0050	0.0000
Australia	0.0058	0.0036	0.0024	0.0050	NA	0.0050
U.S	0.1959	0.4569	0.6840	0.3092	0.3724	0.4322
Canada	0.0436	0.0420	0.0225	0.0348	0.0285	0.0503
Mexico	0.0075	0.0004	0.0000	0.0061	NA	0.0000
Brazil	0.0144	0.0000	0.0012	0.0081	NA	0.0050
Germany	0.0552	0.0898	0.0308	0.0718	0.0832	0.1457
England	0.0264	0.0138	0.0521	0.0328	0.0350	0.0151
France	0.0288	0.0210	0.0024	0.0293	0.0526	0.0251
Italy	0.0326	0.0049	0.0047	0.0265	0.0570	0.0251
Holland	0.0154	0.0067	0.0012	0.0136	0.0394	0.0050
Norway	0.0137	0.0027	0.0012	0.0083	0.0120	0.0101
Swiss	0.0161	0.0031	0.0036	0.0109	0.0175	0.0050
Sweden	0.0141	0.0013	0.0036	0.0079	NA	0.0101
Russia	0.0127	0.0022	0.0047	0.0127	NA	0.0000
Denmark	0.0096	0.0045	0.0059	0.0076	0.0241	0.0302
Spain	0.0165	0.0004	0.0036	0.0148	0.0131	0.0175
Austria	0.0017	0.0013	0.0036	0.0030	0.0100	0.0050
Poland	0.0113	0.0000	0.0000	0.0063	NA	0.0000
Belgium	0.0000	0.0004	0.0000	0.0002	0.0101	0.0151
Portugal	0.0041	0.0000	0.0000	0.0029	NA	0.0050
Greece	0.0096	0.0009	0.0000	0.0066	0.0067	0.0050
Iceland	0.0000	0.0000	0.0024	0.0003	NA	0.0050

$$S_3(\text{RD budget}) = (3.536, 4.269, 5.0211) \otimes (1/19.382, 1/15.928, 1/13.168) = (0.182, 0.268, 0.396)$$

$$S_4(\text{Inftrasturcture of hydrogen technology}) = (2.933, 3.433, 4.088) \otimes (1/19.382, 1/15.928, 1/13.168) = (0.151, 0.216, 0.310)$$

We compared the values of S_i individually and identified the degree of possibility of $S_j = (l_j, m_j, u_j) \geq S_i = (l_i, m_i, u_i)$ using formula (8).

Table 5 shows the values of $V(S_i \geq S_j)$. Thereafter, we determined the minimum degree of possibility $d'(i)$ of $V(S_i \geq S_j)$ for $i, j = 1, 2, 3, \ldots, k$ using formula (9).

$$D'(1) = \min\ V(S_1 \geq S_2, S_3, S_4) = 0.945$$

$$D'(2) = \min\ V(S_2 \geq S_1, S_3, S_4) = 0.961$$

$$D'(3) = \min\ V(S_3 \geq S_1, S_2, S_4) = 1.000$$

$$D'(4) = \min\ V(S_4 \geq S_1, S_2, S_3) = 0.709$$

Therefore, the weight vector was found to be as below using formula (10):

$$W' = (0.945, 0.961, 1.000, 0.709)^T$$

We then normalized the weight vectors using formula (11) and obtained the relative weights of the 4 criteria.

$W = (0.261, 0.266, 0.277, 0.196)$ where W is a non-fuzzy number.

Fig. 3 describes the relative weights of the 4 criteria as a result of the fuzzy AHP process. The final weights for technological status, R&D human resources, R&D budget, and hydrogen technology infrastructure were found to be 0.261, 0.266, 0.277 and 0.196, respectively. R&D budget was the most preferred factor at the criteria level. This was in turn followed by R&D human resources. Fig. 4 shows the final relative weights of the sub-criteria. At the sub-criteria level, it is composed of the quantities of SCI papers, patents, and paper proceedings. The sub-criteria relative weights for SCI papers, patents, and proceeding are 0.442, 0.558 and 0.000, respectively. The final relative weights of the sub-criteria are calculated by multiplying the weight of technological status with the sub-criteria original weights, which account for (0.442, 0.558, 0.000) by the fuzzy AHP approach. At the sub-criteria level, the final relative weights of the quantity of SCI papers, patents, and paper proceedings were determined to be 0.1154, 0.1460 and 0.0000, respectively.

6.2. *Relative efficiency of hydrogen energy technology R&D performance*

The quantitative data, as shown in each column of Table 2, was then normalized in order to synthesize the weights of

Table 7 – Multi-inputs and multi-outputs multiplied by the fuzzy AHP approach.

Nation	Output			Input	
	Technological status		Infrastructure of hydrogen technology	R&D human resources	R&D budget (million dolar)
	SCI paper	Patents			
Korea	0.0079	0.0045	0.0059	0.0127	0.0067
Japan	0.0229	0.0421	0.0237	0.0574	0.0579
China	0.0150	0.0007	0.0030	0.0201	0.0000
Taiwan	0.0020	0.0018	0.0010	0.0036	0.0000
India	0.0029	0.0004	0.0010	0.0037	0.0000
Israel	0.0008	0.0006	0.0000	0.0014	0.0000
Singapore	0.0009	0.0002	0.0020	0.0012	0.0000
Turkey	0.0014	0.0000	0.0000	0.0014	0.0014
Australia	0.0007	0.0005	0.0010	0.0013	0.0000
U.S.	0.0226	0.0667	0.0848	0.0822	0.1030
Canada	0.0050	0.0061	0.0099	0.0092	0.0079
Mexico	0.0009	0.0001	0.0000	0.0016	0.0000
Brazil	0.0017	0.0000	0.0010	0.0022	0.0000
Germany	0.0064	0.0131	0.0286	0.0191	0.0230
England	0.0030	0.0020	0.0030	0.0087	0.0097
France	0.0033	0.0031	0.0049	0.0078	0.0145
Italy	0.0038	0.0007	0.0049	0.0070	0.0158
Holland	0.0018	0.0010	0.0010	0.0036	0.0109
Norway	0.0016	0.0004	0.0020	0.0022	0.0033
Swiss	0.0019	0.0005	0.0010	0.0029	0.0048
Sweden	0.0016	0.0002	0.0020	0.0021	0.0000
Russia	0.0015	0.0003	0.0000	0.0034	0.0000
Denmark	0.0011	0.0003	0.0059	0.0020	0.0067
Spain	0.0019	0.0001	0.0020	0.0039	0.0036
Austria	0.0002	0.0002	0.0010	0.0008	0.0028
Poland	0.0013	0.0000	0.0000	0.0017	0.0000
Belgium	0.0000	0.0001	0.0030	0.0001	0.0028
Portugal	0.0005	0.0000	0.0010	0.0008	0.0000
Greece	0.0010	0.0001	0.0010	0.0017	0.0018
Iceland	0.0000	0.0000	0.0010	0.0001	0.0000

the 4 criteria. The normalized data are shown in Table 6. We then applied the relative weights of the 4 criteria to the normalized data. As shown in Table 7, it shows the multiple-input and multiple-output values, which are multiplied by the fuzzy AHP results, for measuring the relative efficiency scores from an econometric viewpoint. Multiple-input values account for R&D budget and R&D human resources. Multiple-output values are associated with technological status and infrastructure of hydrogen technology. Table 8 presents the relative efficiency scores in the sector of hydrogen energy technology R&D performance. Nine nations, including U.S., Japan, Canada and etc., were ranked 1. They are the most competitive nations and efficient frontier group. Meanwhile, Korea took the 14th place. Fig. 5 describes the multiple input and output data of some advanced nations in the sector of hydrogen energy technology R&D. In term of the quantities of paper and patent, Korea is at the comparative disadvantage comparing with U.S. and Japan. Korea is over 3 times less than U.S.'s SCI papers, almost 15 times less than U.S.'s patents and 9 times less than Japan's patents. In term of the infrastructure, Kore is about 14 times less than U.S. To be competitive with U.S. and Japan in the sector of hydrogen energy technology R&D, Korea needs to focus on producing much more quantitative outcomes such as SCI papers, Patents and infrastructure.

Table 8 – Efficiency scores and ranks by the DEA approach.

Nation	Efficiency score	Rank	Nation	Efficiency score	Rank
Korea	0.8976	14	France	0.7029	23
Japan	1.0000	1	Italy	0.6268	26
China	0.8926	15	Holland	0.6893	24
Taiwan	1.0000	1	Norway	0.8738	18
India	1.0000	1	Swiss	0.7754	21
Israel	0.8797	16	Sweden	0.9610	10
Singapore	1.0000	1	Russia	0.5483	27
Turkey	1.0000	1	Denmark	0.8093	19
Australia	0.8794	17	Spain	0.5441	28
U.S	1.0000	1	Austria	0.4255	30
Canada	1.0000	1	Poland	0.9331	13
Mexico	0.6469	25	Belgium	1.0000	1
Brazil	0.9346	12	Portugal	0.7803	20
Germany	0.9409	11	Greece	0.7236	22
England	0.5153	29	Iceland	1.0000	1

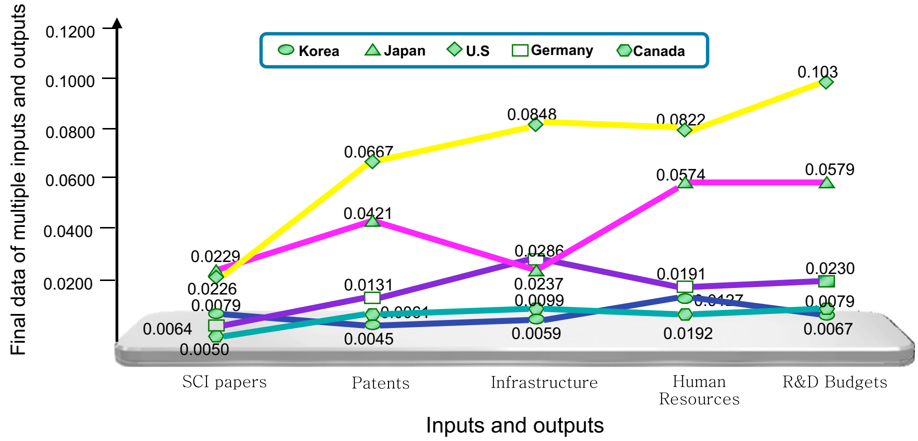

Fig. 5 – Final data comparison with advanced nations.

7. Conclusions

We applied the integrated fuzzy AHP/DEA approach to develop a framework for assessing the national R&D performance and competitiveness in the sector of hydrogen energy technology development. The results of this study are calculated by a scientific procedure of multi-criteria decision making approach. This study provides the optimal alternatives for establishing hydrogen energy policy for producing well focused R&D outcomes and evaluates the R&D performance of hydrogen energy technologies development from economic viewpoints. To be competitive with U.S. and Japan, Korea needs to focus on the outcomes such as SCI papers, patents, and infrastructure. Korea policymakers and decision makers have to strategically focus on strengthening those weak outcomes.

In our further study, we will investigate the scale efficiency approach of DEA for measuring the return scale of hydrogen energy technology R&D. Other integrated MCDM approaches such as fuzzy AHP/TOPSIS and fuzzy AHP/DEA Scale Efficiency method will be investigated and the results will be compared with the current work. Moreover, we will apply the current developed fuzzy AHP/DEA approach to design the energy technology roadmap in the energy policy sector [22].

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Nomenclature

AHP	Analytic hierarchy process
DEA	Data envelopment analysis
DMU	Decision making unit
GHG	Greenhouse gas
H2FC	National R&D organization for hydrogen & fuel cell
HERC	Hydrogen energy R&D center
MCDM	Multi-criteria decision making
MKE	Ministry of knowledge and economy
MEST	Ministry of education, science and technology
NA	Not available
SCI	Science citation index
TFN	Triangular fuzzy number
TOPSIS	Technique for order preference by similarity to the ideal solution

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