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A fuzzy analytic hierarchy process approach for assessing national competitiveness in the hydrogen technology sector

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ABSTRACT

As it is more environmentally sound and friendly than conventional energy technologies that emit carbon dioxide, hydrogen technology can play a key role in solving the problems caused by the greenhouse gas effect and in coping with the hydrogen economy. Numerous countries around the world, including Korea, have increasingly focused on R&D where hydrogen technology development is concerned. This paper focuses on the use of the fuzzy analytic hierarchy process (fuzzy AHP), which is an extension of the AHP method and uses interval values to reflect the vagueness of human thought, to assess national competitiveness in the hydrogen technology sector. This analysis based on the AHP and fuzzy AHP methods revealed that Korea ranked 6th in terms of national competitiveness in the hydrogen technology sector.

1. Introduction

Developed nations such as the U.S., Japan, and the EU have invested significant funds and R&D resources into the development of hydrogen technologies. These have included 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. As part of its efforts to develop future energy technologies, the Korean government has identified hydrogen technologies such as hydrogen and fuel cells as one of the next-generation growth engines. To this end, Korea's Ministry of Education, Science and Technology (MEST) and Ministry of Knowledge Economy (MKE) inaugurated, in 2003 and 2004 respectively, the Hydrogen Energy R&D Center (HERC) and the National R&D Organization for Hydrogen and Fuel Cells (H2FC). Moreover, the Korean government has also concentrated its efforts on strategic investment in hydrogen and fuel cells, and attempted to analyze Korea's national competitiveness in the hydrogen technology sector based on the quantitative data accrued using the fuzzy analytic hierarchy process (fuzzy AHP) approach. This paper deals with the extended research of AHP approach of Korea's national competitiveness in the hydrogen technology sector [1].

The Fuzzy AHP approach effectively reflects the fuzziness of human linguistic values and alternatives when it comes to making pairwise comparison judgments in the real world. Because the Fuzzy AHP use the interval values of lower, median, and upper values instead of the crisp number when the peer-reviewers execute the pairwise comparisons of the criteria and alternatives efficiently. The Fuzzy AHP, which was applied to the triangular membership funtions, was presented

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Nomenclature

AHP	analytic hierarchy process
DEA	data envelopment analysis
GHG	greenhouse gas
H2FC	national RD&D organization for hydrogen and fuel cell
HERC	hydrogen energy R&D center
MCDM	multi-criteria decision-making
MKE	ministry of knowledge economy
MEST	ministry of education, science and technology
NA	not available
SCI	science citation index

in the early 1980 by Van Laarhoven and Pedrycz [2]. Mikhailove suggested fuzzy preference programming method to calculate the weights with α-cuts decomposition approach [3]. Chang introduced a new extent analysis approach for the synthetic extent values, which is applied to the interval values of pairwise comparisons in this research [4]. On the other hand, the AHP method is limited to provide the relative weights of peer-reviewer' thought and intuition since it is unable to properly reflect the fuzziness associated with the real world decision-making problems by using crisp numbers. The AHP, which was developed by Professor Saaty in the early 1970s, is a subjective tool with which to analyze, based on a crisp 9-point scale, the qualitative criteria needed to generate alternative priorities and preferences [5].

The AHP enables decision makers to structure complex problems in a simple hierarchical form, and to evaluate a large number of quantitative and qualitative factors in a systematic manner despite the presence of multiple conflicting criteria. The AHP 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. In general, the AHP has been utilized in various areas such as R&D planning, the selection of the best policy alternatives once a set of alternatives has been identified, the allocation of resources, the determination of requirements, prediction of outcomes, design systems, measurement of performance, and the optimization and resolution of decision conflicts [6]. To this end, Lee was the first to apply the AHP approach to the forging of long-term improvements in national energy efficiency and GHG control plans as part of the formulation of Korea's national energy policy [7].

This paper assesses national competitiveness in the hydrogen technology sector using the fuzzy AHP approach, in which the decision maker's pairwise comparison judgments are represented as fuzzy triangular numbers. Moreover, this study employs 4 criteria, namely technological status, R&D human resources, R&D budget, and the hydrogen technology infrastructure, as the factors with which to assess national competitiveness in the hydrogen technology sector. This study also effectuates a comparison of the results of national competitiveness in the hydrogen technology sector obtained using the fuzzy AHP process and those achieved when using the AHP method. In addition, a peer-review consisting of 33 experts in the area of hydrogen economy was also effectuated, and the weights of pairwise comparisons of criteria were also synthesized. The results of this paper will provide policy and decision makers with the strategic approach needed to effectuate focused R&D in the hydrogen technology sector, as well as the fundamental data required to forge energy policy.

The paper unfolds in the following fashion: Section 2 introduces the fuzzy set and fuzzy numbers. Section 3 describes the fuzzy AHP approach. Section 4 deals with the hierarchy of the criteria used to evaluate national competitiveness in the hydrogen technology sector. Section 5 displays the quantitative data obtained in relation to hydrogen energy. In Section 6, an illustrative example of the comparison of the fuzzy AHP and AHP approaches is presented. The conclusion is then carried out in Section 7.

2. Fuzzy set and fuzzy numbers

In the real world, precise data pertaining to measurement indicators is very hard to extract from human judgments. This 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 comparison judgments. Decision makers also prefer natural language expressions over exact numbers when assessing criteria and alternatives. Fuzzy set theory deals with ambiguous or not well-defined situations. By approximating information and uncertainty where the generation of reasonable alternatives to problems needing decisions is concerned, it effectively resembles human thoughts and perceptions.

The concept of fuzzy theory was first introduced by Zadeh in 1965 [8]. 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 uses groups of data with boundaries that feature lower, median, and upper values that are not sharply defined. Because most of the decision-making in the real world takes 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 research, 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:

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

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

$$(l_1, m_1, u_1) \otimes (l_2, m_2, u_2) = (l_1 \times l_2, m_1 \times m_2, u_1 \times u_2) \tag{2}$$

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

3. Fuzzy analytic hierarchy process

Under the AHP, the decision-making process is modified into a hierarchical structure. At each level of the hierarchy, 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 [9]. However, the AHP cannot take into account uncertainty when assessing and tackling a problem effectively. However, 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. This can be contrasted with the AHP's crisp 9-point scale and synthesis of the relative weights using fuzzy sets, membership functions, and fuzzy numbers.

Although the AHP is employed herein to capture experts' knowledge acquired through perceptions or preferences, the AHP still cannot effectively reflect human thoughts with its crisp numbers. Therefore, fuzzy AHP, an extension of the AHP model, is applied to resolve hierarchical fuzzy decision-making problems.

The fuzzy scale used for pairwise comparisons of one attribute over another by Chang [4] is shown in Table 1. We use 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

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

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

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

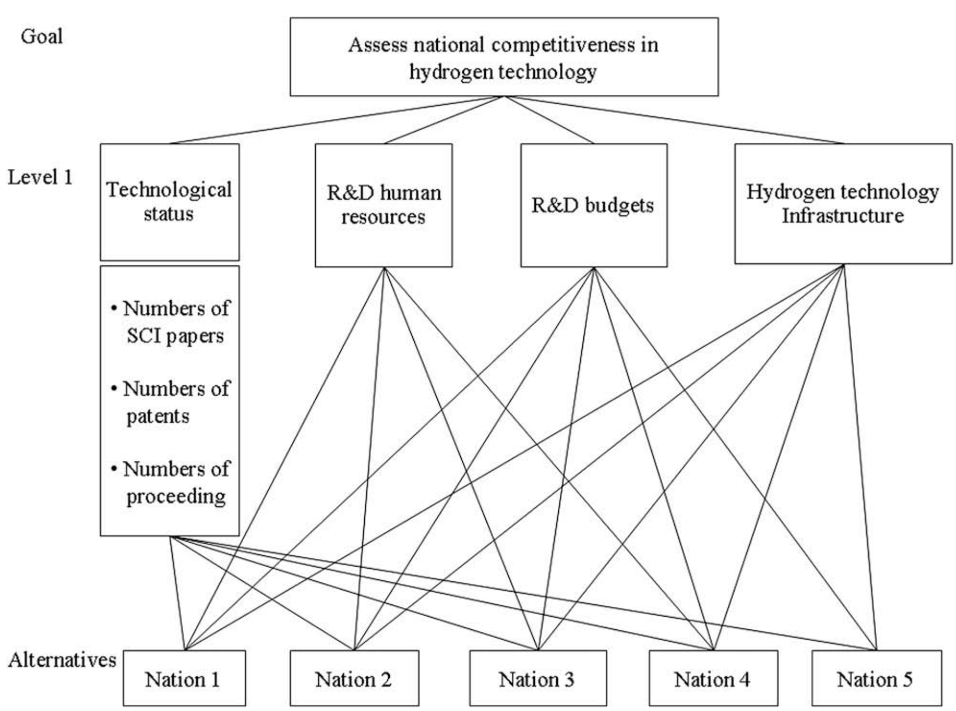

Fig. 1 – Hierarchy model for assessing criteria and alternatives.

Table 2 – Quantitative data related to hydrogen technology.

Nation	Technological status			R&D human resources	R&D budget (million dollar)	Infrastructure of hydrogen technology
	SCI Paper	Patents	Paper proceedings			
Korea	199	69	23	590	22	4
Japan	577	645	92	2663	191	18
China	378	10	13	934	NA	2
Taiwan	51	28	5	167	NA	0
India	73	6	6	161	NA	0
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	2
U.S.	571	1023	578	3813	340	43
Canada	127	94	19	429	26	9
Mexico	22	1	0	75	NA	0
Brazil	42	0	1	100	NA	0
Germany	161	201	26	885	76	19
England	77	31	44	405	32	1
France	84	47	2	361	48	1
Italy	95	11	4	327	52	2
Holland	45	15	1	168	36	1
Norway	40	6	1	102	11	0
Swiss	47	7	3	134	16	1
Sweden	41	3	3	97	NA	1
Russia	37	5	4	157	NA	0
Denmark	28	10	5	94	22	1
Spain	48	1	3	182	12	2
Austria	5	3	3	37	9.1	0
Poland	33	0	0	78	NA	0
Belgium	0	1	0	3	9.2	2
Portugal	12	0	0	36	NA	2
Greece	28	2	0	81	6.1	1
Iceland	0	0	2	4	NA	1

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

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:

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

where d is the ordinate of the highest intersection point between u_{S_i} and u_{S_j}. 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 $i, j = 1, 2, \ldots\ldots, k$ is calculated.

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

Assume that

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

Then the weight vector is defined as

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

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

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

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

where W is a non-fuzzy number.

4. Hierarchy of the criteria

The assessment of national hydrogen technology competitiveness 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 of this problem. The goal is to assess national hydrogen technology competitiveness 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 3 sub-criteria, namely quantity of SCI papers, patents, and paper proceedings.

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)
	–	–	–	–
	–	–	–	–
HR				
	(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)
	(2/3, 1, 3/2)	(1, 1, 1)	(2/7, 1/3, 2/5)	(1, 1, 1)
	–	–	–	–
	–	–	–	–
B				
	(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)
	(3/2, 2, 5/2)	(5/2, 3, 7/2)	(1, 1, 1)	(5/2, 3, 7/2)
	–	–	–	–
	–	–	–	–
I				
	(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)
	(1, 1, 1)	(1, 1, 1)	(2/7, 1/3, 2/5)	(1, 1, 1)
	–	–	–	–
	–	–	–	–

5. Quantitative data related to hydrogen energy

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.

The quantity of SCI papers was calculated based on the number of relevant articles found in the chemical abstracts 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 such means as 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 31 nations.

R&D budget assigned to the development of hydrogen technology was taken from an IEA/OECD paper presented in 2004 entitled, 'Hydrogen & Fuel Cells-Review of national R&D budget' [10]. 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$/1150KRW. 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 [11].

6. Illustrative example

6.1. Scenario 1

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 which took part in the peer-reviews 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, the results of which are shown in Table 4.

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

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

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)

Table 5 – Values of $V(S_i \geq S_j)$.

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

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

S_3(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(Infrastructure 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 $i, j = 1, 2, 3, \ldots\ldots, k$ 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 determined to be the following 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.

The final weights of the 4 criteria (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. When the AHP method was employed, the criteria weights became 0.2743, 0.2745, 0.2775, and 0.1737 respectively. Although the relative weights were somewhat different when the fuzzy AHP and AHP methods were employed, the ranking order resulting from these two MCDM methodologies was the same. In both cases, R&D budget was most preferred factor at the criteria level. This was in turn

Table 6 – Normalized quantitative data related to hydrogen technology.

Nation	Technological status			R&D human resources	R&D budget (million dollar)	Infrastructure of hydrogen technology
	SCI Paper	Patents	Paper proceedings			
Korea	0.0683	0.0308	0.0272	0.0478	0.0241	0.0342
Japan	0.1979	0.2881	0.1089	0.2159	0.2092	0.1579
China	0.1297	0.0045	0.0154	0.0757	NA	0.0175
Taiwan	0.0175	0.0125	0.0059	0.0135	NA	0.0000
India	0.0250	0.0027	0.0071	0.0131	NA	0.0088
Israel	0.0065	0.0040	0.0024	0.0054	NA	0.0000
Singapore	0.0079	0.0013	0.0036	0.0044	NA	0.0175
Turkey	0.0120	0.0000	0.0000	0.0054	0.0050	0.0000
Australia	0.0058	0.0036	0.0024	0.0050	NA	0.0000
U.S.	0.1959	0.4569	0.6840	0.3092	0.3724	0.3772
Canada	0.0436	0.0420	0.0225	0.0348	0.0285	0.0789
Mexico	0.0075	0.0004	0.0000	0.0061	NA	0.0000
Brazil	0.0144	0.0000	0.0012	0.0081	NA	0.0000
Germany	0.0552	0.0898	0.0308	0.0718	0.0832	0.1667
England	0.0264	0.0138	0.0521	0.0328	0.0350	0.0088
France	0.0288	0.0210	0.0024	0.0293	0.0526	0.0088
Italy	0.0326	0.0049	0.0047	0.0265	0.0570	0.0175
Holland	0.0154	0.0067	0.0012	0.0136	0.0394	0.0088
Norway	0.0137	0.0027	0.0012	0.0083	0.0120	0.0000
Swiss	0.0161	0.0031	0.0036	0.0109	0.0175	0.0088
Sweden	0.0141	0.0013	0.0036	0.0079	NA	0.0088
Russia	0.0127	0.0022	0.0047	0.0127	NA	0.0000
Denmark	0.0096	0.0045	0.0059	0.0076	0.0241	0.0088
Spain	0.0165	0.0004	0.0036	0.0148	0.0131	0.0175
Austria	0.0017	0.0013	0.0036	0.0030	0.0100	0.0000
Poland	0.0113	0.0000	0.0000	0.0063	NA	0.0000
Belgium	0.0000	0.0004	0.0000	0.0002	0.0101	0.0175
Portugal	0.0041	0.0000	0.0000	0.0029	NA	0.0175
Greece	0.0096	0.0009	0.0000	0.0066	0.0067	0.0088
Iceland	0.0000	0.0000	0.0024	0.0003	NA	0.0088

Table 7 – The overall weights and ranks in scenario 1 resulted from the fuzzy AHP approach.

Nation	Technological status			R&D human resources	R&D budget (million dollar)	Infrastructure of hydrogen technology	Weight	Rank
	SCI paper	Patents	Paper proceedings					
Korea	0.0079	0.0045	0.0000	0.0127	0.0067	0.0067	0.0385	6
Japan	0.0229	0.0421	0.0000	0.0574	0.0579	0.0310	0.2111	2
China	0.0150	0.0007	0.0000	0.0201	0.0000	0.0034	0.0392	5
Taiwan	0.0020	0.0018	0.0000	0.0036	0.0000	0.0000	0.0074	16
India	0.0029	0.0004	0.0000	0.0037	0.0000	0.0017	0.0085	14
Israel	0.0008	0.0006	0.0000	0.0014	0.0000	0.0000	0.0028	28
Singapore	0.0009	0.0002	0.0000	0.0012	0.0000	0.0034	0.0057	20
Turkey	0.0014	0.0000	0.0000	0.0014	0.0014	0.0000	0.0042	24
Australia	0.0007	0.0005	0.0000	0.0013	0.0000	0.0034	0.0060	19
U.S.	0.0226	0.0667	0.0000	0.0822	0.1030	0.0740	0.3485	1
Canada	0.0050	0.0061	0.0000	0.0092	0.0079	0.0155	0.0438	4
Mexico	0.0009	0.0001	0.0000	0.0016	0.0000	0.0000	0.0026	29
Brazil	0.0017	0.0000	0.0000	0.0022	0.0000	0.0000	0.0038	26
Germany	0.0064	0.0131	0.0000	0.0191	0.0230	0.0327	0.0943	3
England	0.0030	0.0020	0.0000	0.0087	0.0097	0.0017	0.0252	9
France	0.0033	0.0031	0.0000	0.0078	0.0145	0.0017	0.0304	8
Italy	0.0038	0.0007	0.0000	0.0070	0.0158	0.0034	0.0307	7
Holland	0.0018	0.0010	0.0000	0.0036	0.0109	0.0017	0.0190	10
Norway	0.0016	0.0004	0.0000	0.0022	0.0033	0.0000	0.0075	15
Swiss	0.0019	0.0005	0.0000	0.0029	0.0048	0.0017	0.0118	13
Sweden	0.0016	0.0002	0.0000	0.0021	0.0000	0.0017	0.0056	21
Russia	0.0015	0.0003	0.0000	0.0034	0.0000	0.0000	0.0052	22
Denmark	0.0011	0.0003	0.0000	0.0020	0.0067	0.0017	0.0122	12
Spain	0.0019	0.0001	0.0000	0.0039	0.0036	0.0034	0.0130	11
Austria	0.0002	0.0002	0.0000	0.0008	0.0028	0.0000	0.0039	25
Poland	0.0013	0.0000	0.0000	0.0017	0.0000	0.0000	0.0030	27
Belgium	0.0000	0.0001	0.0000	0.0001	0.0028	0.0034	0.0064	18
Portugal	0.0005	0.0000	0.0000	0.0008	0.0000	0.0034	0.0047	23
Greece	0.0010	0.0001	0.0000	0.0017	0.0018	0.0017	0.0066	17
Iceland	0.0000	0.0000	0.0000	0.0001	0.0000	0.0017	0.0018	30

followed by R&D human resources. At the sub-criteria level, the relative weights of the quantity of SCI papers, patents, and paper proceedings when using the fuzzy AHP method were determined to be 0.1154, 0.1460, and 0.0000 respectively. Meanwhile, the relative weights uncovered when using the AHP method were 0.1007, 0.1487, and 0.0249 respectively. Here again, the ranking order of the sub-criteria was the same in the case of both methodologies.

The quantitative data pertaining to hydrogen technology shown in each column of Table 2 was then normalized in order to be able to synthesize the weights of the 4 criteria. The normalized data can be found in Table 6.

Table 8 – The relative weights of the AHP and fuzzy AHP based on scenario 1.

Nation	AHP		Fuzzy AHP		Nation	AHP		Fuzzy AHP	
	Weight	Rank	Weight	Rank		Weight	Rank	Weight	Rank
Korea	0.0335	6	0.0385	6	France	0.0302	8	0.0304	8
Japan	0.2102	2	0.2111	2	Italy	0.0303	7	0.0307	7
China	0.0375	5	0.0392	5	Holland	0.0188	10	0.0190	10
Taiwan	0.0075	15	0.0074	16	Norway	0.0074	16	0.0075	15
India	0.0082	14	0.0085	14	Swiss	0.0115	13	0.0118	13
Israel	0.0028	28	0.0028	28	Sweden	0.0054	20	0.0056	21
Singapore	0.0053	21	0.0057	20	Russia	0.0052	22	0.0052	22
Turkey	0.0041	24	0.0042	24	Denmark	0.0121	12	0.0122	12
Australia	0.0056	19	0.0060	19	Spain	0.0126	11	0.0130	11
U.S.	0.3584	1	0.3485	1	Austria	0.0040	25	0.0039	25
Canada	0.0424	4	0.0438	4	Poland	0.0029	27	0.0030	27
Mexico	0.0025	29	0.0026	29	Belgium	0.0060	18	0.0064	18
Brazil	0.0037	26	0.0038	26	Portugal	0.0043	23	0.0047	23
Germany	0.0914	3	0.0943	3	Greece	0.0063	17	0.0066	17
England	0.0263	9	0.0252	9	Iceland	0.0017	30	0.0018	30

We then applied the relative weights of the 4 criteria to the normalized data. Table 7 shows the overall weights and ranks in terms of national hydrogen technology sector competitiveness when calculated using the fuzzy AHP approach.

The U.S. (0.3485) was found to be the most competitive nation in terms of hydrogen technology, followed by Japan (0.2111), Germany (0.0943), Canada (0.0438), China (0.0392), and Korea (0.0385). The U.S. finished 1st in terms of the quantity of patents, R&D human resources, R&D budget, and hydrogen technology infrastructure. The only exception was in terms if the quantity of SCI papers (2nd place). Japan finished 2nd in terms of the quantity of patents, R&D human resources, and R&D budget and 1st where the quantity of SCI papers was concerned. Japan finished 3rd in terms of its hydrogen technology infrastructure. Meanwhile, Korea finished 6th overall. More specifically, Korea finished 5th in terms of the quantity of patents and R&D human resources, and 4th and 5th respectively where the quantity of SCI papers and hydrogen technology infrastructure were concerned. Korea did finish 9th in terms of its R&D budget, which was relatively lower than was the case with the other factors. Table 8 shows the relative weights and ranks calculated using the AHP and fuzzy AHP approaches.

The top 6 nations identified using the fuzzy AHP approach remained the same when the AHP method was employed. While 4 nations, namely Taiwan, Singapore, Norway, and Sweden, saw their rankings be reversed when the AHP method was employed, the other 26 nations maintained the same ranks in both the AHP and fuzzy AHP approaches.

6.2. *Scenario 2*

In scenario 2, the weight of R&D budget is not synthesized to the normalized data shown in Table 2. Table 9 shows the overall weights and ranks of scenario 2 resulted from the fuzzy AHP approach. The U.S. (0.2455) is also the most competitive nation related to the sector of hydrogen technology in scenario 2, followed by Japan (0.1553), Germany (0.0713), China (0.0392), Canada (0.0359), and Korea (0.0318). In top 6 rankings of Table 9, Chinese and Canadian ranking orders are reversed in scenario 2. The U.S. still takes 1st place in the quantity of patents, R&D human resources, and infrastructure of hydrogen technology excepting quantity of SCI papers (2nd place). Japan also takes 2nd place in the quantity of patents and R&D human resources excepting the quantity of SCI papers (1st place). Japanese infrastructure of hydrogen technology is placed in 3rd place. Korea still takes 6th place in the sector of national competitiveness of hydrogen technology. Korea takes 5th place in the quantity of patents and R&D human resources. Korean quantity of SCI papers and infrastructure of hydrogen technology are ranked 4th and 5th place respectively. Table 10 shows the relative weights and ranks of the AHP and fuzzy AHP approaches. The ranks of top 6 nations resulted from the fuzzy AHP approach are same

Table 9 – The overall weights and ranks in scenario 2 resulted from the fuzzy AHP approach.

Nation	Technological status			R&D human resources	Infrastructure of hydrogen technology	Weight	Rank
	SCI Paper	Patents	Paper proceedings				
Korea	0.0079	0.0045	0.0000	0.0127	0.0067	0.0318	6
Japan	0.0229	0.0421	0.0000	0.0574	0.0310	0.1553	2
China	0.0150	0.0007	0.0000	0.0201	0.0034	0.0392	4
Taiwan	0.0020	0.0018	0.0000	0.0036	0.0000	0.0074	13
India	0.0029	0.0004	0.0000	0.0037	0.0017	0.0085	11
Israel	0.0008	0.0006	0.0000	0.0014	0.0000	0.0028	27
Singapore	0.0009	0.0002	0.0000	0.0012	0.0034	0.0057	16
Turkey	0.0014	0.0000	0.0000	0.0014	0.0000	0.0028	26
Australia	0.0007	0.0005	0.0000	0.0013	0.0034	0.0060	15
U.S.	0.0226	0.0667	0.0000	0.0822	0.0740	0.2455	1
Canada	0.0050	0.0061	0.0000	0.0092	0.0155	0.0359	5
Mexico	0.0009	0.0001	0.0000	0.0016	0.0000	0.0026	28
Brazil	0.0017	0.0000	0.0000	0.0022	0.0000	0.0038	23
Germany	0.0064	0.0131	0.0000	0.0191	0.0327	0.0713	3
England	0.0030	0.0020	0.0000	0.0087	0.0017	0.0252	8
France	0.0033	0.0031	0.0000	0.0078	0.0017	0.0155	7
Italy	0.0038	0.0007	0.0000	0.0070	0.0034	0.0150	9
Holland	0.0018	0.0010	0.0000	0.0036	0.0017	0.0081	12
Norway	0.0016	0.0004	0.0000	0.0022	0.0000	0.0042	22
Swiss	0.0019	0.0005	0.0000	0.0029	0.0017	0.0069	14
Sweden	0.0016	0.0002	0.0000	0.0021	0.0017	0.0056	17
Russia	0.0015	0.0003	0.0000	0.0034	0.0000	0.0052	19
Denmark	0.0011	0.0003	0.0000	0.0020	0.0017	0.0055	18
Spain	0.0019	0.0001	0.0000	0.0039	0.0034	0.0093	10
Austria	0.0002	0.0002	0.0000	0.0008	0.0000	0.0012	30
Poland	0.0013	0.0000	0.0000	0.0017	0.0000	0.0030	25
Belgium	0.0000	0.0001	0.0000	0.0001	0.0034	0.0036	24
Portugal	0.0005	0.0000	0.0000	0.0008	0.0034	0.0047	21
Greece	0.0010	0.0001	0.0000	0.0017	0.0017	0.0047	20
Iceland	0.0000	0.0000	0.0000	0.0001	0.0017	0.0018	29

Table 10 – The relative weights of the AHP and fuzzy AHP based on scenario 2.

Nation	AHP		Fuzzy AHP		Nation	AHP		Fuzzy AHP	
	Weight	Rank	Weight	Rank		Weight	Rank	Weight	Rank
Korea	0.0268	6	0.0318	6	France	0.0156	8	0.0155	7
Japan	0.1522	2	0.1553	2	Italy	0.0145	9	0.0150	9
China	0.0379	4	0.0392	4	Holland	0.0078	12	0.0081	12
Taiwan	0.0075	13	0.0074	13	Norway	0.0041	22	0.0042	22
India	0.0082	11	0.0085	11	Swiss	0.0067	14	0.0069	14
Israel	0.0028	26	0.0028	27	Sweden	0.0054	17	0.0056	17
Singapore	0.0053	18	0.0057	16	Russia	0.0052	19	0.0052	19
Turkey	0.0027	27	0.0028	26	Denmark	0.0054	17	0.0055	18
Australia	0.0056	15	0.0060	15	Spain	0.0089	10	0.0093	10
U.S.	0.2551	1	0.2455	1	Austria	0.0013	30	0.0012	30
Canada	0.0345	1	0.0359	5	Poland	0.0029	25	0.0030	25
Mexico	0.0025	28	0.0026	28	Belgium	0.0032	24	0.0036	24
Brazil	0.0037	23	0.0038	23	Portugal	0.0043	21	0.0047	21
Germany	0.0683	3	0.0713	3	Greece	0.0044	20	0.0047	20
England	0.0166	7	0.0252	8	Iceland	0.0017	29	0.0018	29

comparing with the AHP results like scenario 1. The ranks of 6 nations, Israel, Singapore, Turkey, England, France, and Denmark, are reversed and the other 24 nations adhere the same ranks of both AHP and fuzzy AHP approaches.

7. Conclusions

A model for assessing national competitiveness in the hydrogen technology sector was established in this paper using the fuzzy AHP approach. We demonstrated herein the results compiled when two MCDM approaches, namely the fuzzy AHP and AHP methods, were employed. We created a one-tier hierarchy structure and assessed national competitiveness using 4 criteria, namely technological status, R&D human resources, R&D budget, and hydrogen technology infrastructure. Thereafter, we evaluated the hydrogen technology sectors of 30 nations using fuzzy AHP relative weights garnered using triangular fuzzy numbers. In scenario 1, which was based on the fuzzy AHP approach, the U.S. ranks first in terms of national competitiveness, followed by Japan, Germany, Canada, China, and Korea. In scenario 2, calculated using the AHP approach, the Chinese and Canadian rankings are reversed. The U.S., Germany, Japan, and Korea finished 1st, 2nd, 3rd, and 6th respectively. Korea's 6th place can be explained by its lower score in terms on the quantity of the patents and hydrogen technology infrastructure sections, which are the level of 6.7% and 9.1% comparing with U.S. Korea needs to upgrade those factors to strengthen the competitiveness related to the hydrogen technology sector.

Although the quantitative data presented in this paper is limited, we have efficiently demonstrated national competitiveness in the hydrogen technology sector based on 2 scenarios that included the use of the fuzzy AHP approach.

Finally, this study provides decision makers and policy makers within Korea's MEST and MKE, with the fundamental data needed to develop hydrogen technologies that are based on a well-focused R&D strategy. As a further study of this research, we are planning to analyze the data with the approached of the Fuzzy AHP/DEA hybrid model from the viewpoint of the econometric [12]. With those integrated hybrid models, we can assess the scale of efficiency of hydrogen energy technologies.

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