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Measuring the relative efficiency of hydrogen energy technologies for implementing the hydrogen economy: An integrated fuzzy AHP/DEA approach

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ABSTRACT

To provide and improve national energy security and low-carbon green energy economy, as a government-supported research institute related to developing new and renewable energy technologies, including energy efficiency, Korea Institute of Energy Research (KIER) needs to establish a long-term strategic energy technology roadmap (ETRM) in the hydrogen economy sector for sustainable economic development. In this paper, we establish a strategic ETRM for hydrogen energy technologies in the hydrogen economy considering five criteria: economic impact (EI), commercial potential (CP), inner capacity (IC), technical spin-off (TS), and development cost (DC). As an extended research, we apply the integrated two-stage multi-criteria decision-making approach, including the hybrid fuzzy analytic hierarchy process (AHP) and data envelopment analysis (DEA) model, to assess the relative efficiency of hydrogen energy technologies in order to scientifically implement the hydrogen economy. Fuzzy AHP reflects the vagueness of human thought with interval values, and allocates the relative importance and weights of four criteria: EI, CP, IC, and TS. The DEA approach measures the relative efficiency of hydrogen energy technologies for the hydrogen economy with a ratio of outputs over inputs.

The result of measuring the relative efficiency of hydrogen energy technologies focuses on 4 hydrogen technologies out of 13 hydrogen energy technologies. KIER has to focus on developing 4 strategic hydrogen energy technologies from economic view point in the first phase with limited resources. In addition, if energy policy makers consider as some candidates for strategic hydrogen technologies of the other 9 hydrogen energy technology, the performance and productivity of 9 hydrogen energy technologies should be increased and the input values of them have to be decreased.

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With a scientific decision-making approach, we can assess the relative efficiency of hydrogen energy technologies efficiently and allocate limited research and development (R&D) resources effectively for well-focused R&D.

1. Introduction

Due to its economic development, especially with its steel and petrochemical industries, Korea is the 10th largest energy consumer in the world. However, because of its lack of natural resources, Korea imports nearly 96% of its energy resources from foreign countries. Thus, Korea is easily affected by the frequent fluctuation of crude oil prices. Korea needs to change its industrial structure to a low-carbon green energy society and lower its energy consumption without losing sustainable development [1].

In the power generation sector, oil, coal, nuclear, natural gas, hydro power, and renewable energy sources accounted for 9.6%, 32.9%, 24.1%, 24.3%, 7.5%, and 1.5% of consumption in 2009, respectively. Fossil fuel dependence on oil, coal, and natural gas is higher than other resources in the power generation sector [2]. The 2012 target, established in 2003, is to supply 5% of total energy consumption through new and renewable energy. Korea has to invest strategically and increase the ratio of new and renewable energy in the power generation sector in order to transform into a low-carbon green society and to meet the new and renewable energy target. From 1988 to 2003, Korean government invested about 80 million UDS for the promotion of developing alternative energy. From 2004 to 2008, Korean government has increased the investment of developing new and renewable energy with 360 million USD strategically. Over 31% of R&D budget of new and renewable energy is accounted [3].

Addressing the climate change problems is crucial issue because it seems to be irreconcilable agenda. Korea faces the challenge of reducing its greenhouse gas emission to a level that meets the standards laid out in the United Nations Framework Convention on Climate Change (UNFCCC). It also has to cope with minimizing the effect of its economy. In addition, interest in energy technology development has increased because the Low-Carbon Green Growth policy has been incorporated into the national agenda for sustainable economic development.

A strategic hydrogen energy technology development plan can be one of the best alternatives to cope with Korea's national energy security and environment. Developing hydrogen energy technologies that are environment-friendly, abundant, and affordable will be the cornerstone for implementing the hydrogen economy. In 2005, we analyzed the world energy outlook to create a hydrogen energy technology roadmap (ETRM) providing the Korean energy policy directions [4,5]. This roadmap underlined developing hydrogen energy technologies considering Korea's energy circumstance for focused research and development (R&D) outcomes and outputs. The hydrogen ETRM supplies primary energy technology milestones to be developed with a 10-year long-term view point, from 2006 to 2015. We shortlisted criteria to assess the hydrogen energy technologies with finite R&D budgets. The criteria included economic impact (EI), commercial potential (CP), inner capacity (IC), technical spin-off (TS), and development cost (DC). We established strategic hydrogen ETRM for the hydrogen economy to cope with the next 10 years as an aspect of energy technology development. We suggested Korea's long-term direction and approach for developing strategic hydrogen energy technologies for the hydrogen economy sector.

As an extended research [6], the main purpose of the current research is to assess the relative efficiency of hydrogen energy technologies and prioritize the relative preference of these technologies in the hydrogen economy sector as we strategically allocate finite R&D budgets. We use the fuzzy analytic hierarchy process (AHP) to evaluate the relative weights of low levels of hydrogen energy technologies, and use data envelopment analysis (DEA) measure the relative efficiency of these technologies in the hydrogen economy sector.

The paper is arranged as follows. Section 2 shows the execution flowchart to address and assess the relative efficiency of hydrogen energy technologies. Section 3 presents the concept of fuzzy sets and numbers. Section 4 discusses the fuzzy AHP process and DEA approach, including the hierarchy of criteria and alternatives. Section 5 describes the classification of hydrogen energy technologies for the hydrogen economy. Section 6 shows the numerical examples of hydrogen energy technologies. Finally, Section 7 presents the conclusion.

2. Execution flowchart

The execution flowchart is composed of six phases. Fig. 1 shows the schematic of the execution flowchart. In the first phase, we analyze the energy policy and energy environment, and provide a shortlist of hydrogen energy technologies for the hydrogen economy. The second phase formulates the criteria used to weigh the relative importance of criteria and alternatives. In the third phase, the hierarchy structure is built, and the criteria are sorted. In the fourth phase, criteria weights of hydrogen energy technologies are calculated using the fuzzy AHP process. During the fifth phase, the efficiency of hydrogen energy technologies is measured using the DEA approach. Finally, the efficiency values produced in the fifth phase are evaluated and aggregated in the sixth phase. In this research, the coupled fuzzy AHP/DEA model is used to measure the relative efficiency of hydrogen energy technologies with two multi-criteria decision-making (MCDM) methods.

3. Fuzzy sets and numbers

In the real world, precise data concerning measurement indicators are hard to extract. Decision makers also prefer

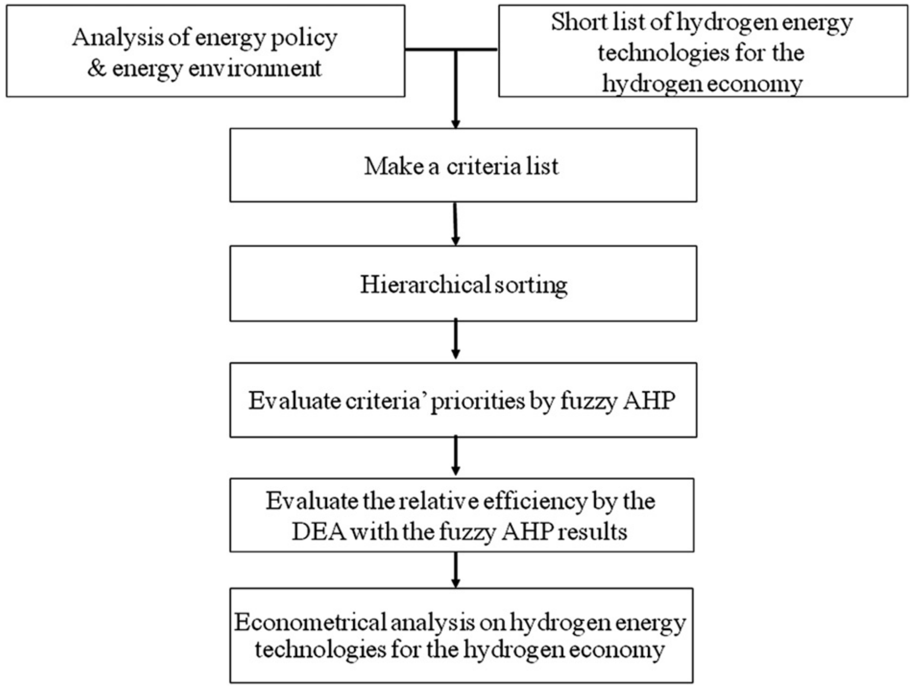

Fig. 1 – Execution flowchart.

natural language expression rather than crisp numbers in making assessments. The fuzzy set theory deals with ambiguous situations or situations that are not well defined. The data is presented to show human thoughts and perceptions using approximate information and uncertainty in order to generate reasonable alternatives in decision-making problems.

The concept of fuzzy theory was introduced by Zadeh in 1965 [7]. Fuzzy theory includes fuzzy sets, membership functions, and fuzzy numbers to change vague data into useful data efficiently.

Fuzzy set theory implements groups of data with boundaries that are not sharply defined. The merit of using the fuzzy approach is that it expresses the relative importance of alternatives and criteria with fuzzy numbers instead of crisp numbers because most decision making in the real world takes place in situations where pertinent data and the sequences of possible actions are not precisely known.

Triangular and trapezoidal fuzzy numbers are generally used to capture the vagueness of the parameters related to select the alternatives. TFN is expressed with boundaries instead of crisp numbers to reflect the fuzziness as decision

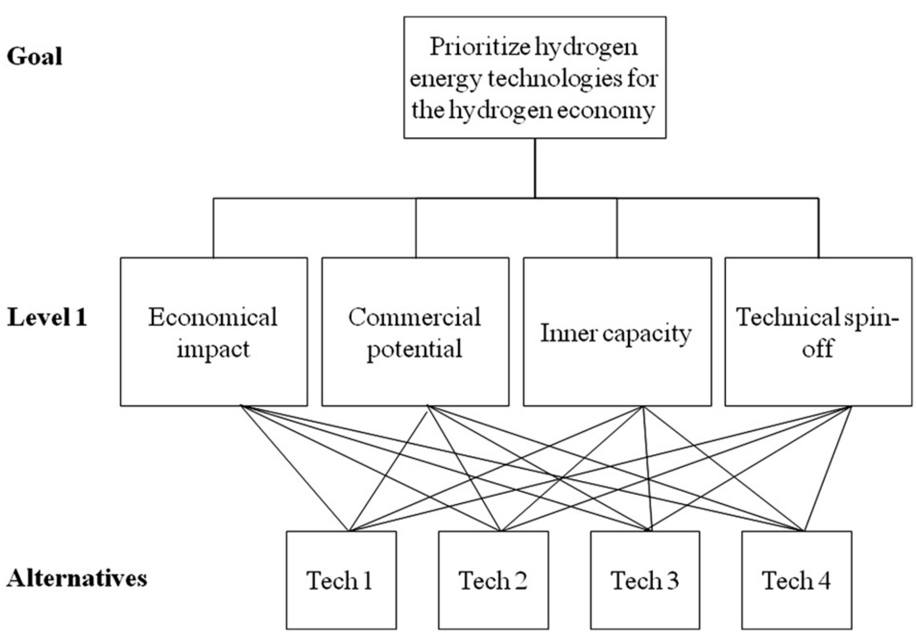

Fig. 2 – Hierarchy of the fuzzy AHP.

makers select alternatives or pairwise comparison matrices. In this research, we applied triangular fuzzy numbers (TFN) to prioritize energy technology in ETRM with fuzziness. TFN is designated as $M_{ij} = (l_{ij}, m_{ij}, u_{ij})$; m_{ij} is the median value of fuzzy number M_{ij}; and l_{ij} and u_{ij} are the left and right sides of fuzzy number M_{ij}, respectively.

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

$$(l_1, m_1, u_1) \oplus (l_2, m_2, u_2) = (l_1 + l_2, m_1 + m_2, u_1 + u_2) \tag{1}$$

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

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

4. Fuzzy AHP and DEA approach

4.1. Fuzzy AHP

AHP is a subjective method for analyzing qualitative criteria to weight the alternatives. Saaty first suggested AHP as a decision-making tool to resolve unstructured problems in 1977 [8]. Generally, decision making involves various tasks such as planning [9], selecting the best policy after evaluating a set of alternatives [10], allocating resources efficiently, determining requirements, measuring performance, and optimizing and resolving conflict. In the AHP method, the decision-making process is modeled as a hierarchical structure.

In this research, although the AHP captures the expert's knowledge by perception or preference, it still cannot entirely reflect human thoughts with crisp numbers. Therefore, fuzzy AHP, a fuzzy extension of AHP, is applied to solve the hierarchical fuzzy decision-making problems. Fig. 2 shows the hierarchy of criteria.

To evaluate and prioritize the weights of low-level hydrogen energy technologies, we provide four criteria in the first stage: EI, CP, IC, and TS. Hydrogen energy technologies of hydrogen ETRM are evaluated by the tier-one criteria.

Fuzzy scale for pairwise comparisons of one attribute over another is shown in Table 1 [11]. We use the fuzzy scale when decision makers make pairwise comparisons.

Let $A = (a_{ij})_{n \times m}$ be a fuzzy pairwise comparison judgments matrix. Let $M_{ji} = (l_{ij}, m_{ij}, u_{ij})$ be a TFN.

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

The steps of fuzzy AHP are as follows.

Step 1: Make pairwise comparisons of attributes by using fuzzy numbers in 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

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

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

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

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

Calculate the TFN value of $S_i = (l_i, m_i, u_i)$ by Formulae (4), (5), (6), and (7).

Step 3: Compare the values of S_i and calculate the degree of possibility of $S_j = (l_j, m_j, u_j) \geq S_i = (l_i, m_i, u_i)$. The equivalent expression is as follows:

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

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

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

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

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

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

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

Step 5: We normalize the weight vectors as follows:

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

where W is a non-fuzzy number.

4.2. DEA

The DEA approach is a nonparametric MCDM assessment tool used in conjunction with decision-making units (DMUs) to effectively solve many decision-making problems by simultaneously integrating multiple inputs and outputs. This mathematical method has been used to solve a wide range of applications since 1978. The DEA is generally applied not only to assess the service productivity of banks [12], insurance companies [13], hospitals [14], universities [15] and restaurants, but also to evaluate the efficiency of R&D programs [16–18].

Fig. 3 shows the hierarchy structure of the DEA process, which consists of a single input factor and multiple output factors. The input factor consists of the DC associated with the development of hydrogen economy technologies. The four output factors are EI, CP, IC, and TS. The relative weights calculated using the fuzzy AHP approach are applied in conjunction with the output factors employed as part of the DEA approach.

The DEA ration form was first proposed by Charnes, Cooper, and Rhodes (CCR) [19], and was designed to measure the relative efficiency or productivity of a specific DMU_k. The DEA formulation is given as follows:

Suppose there is a set of n DMUs to be analyzed, each of which uses m common inputs and s common outputs.

Let k ($k = 1,\ldots, n$) denote the DMU whose relative efficiency or productivity is to be maximized, as represented by

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

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

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

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

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. The value 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.

The two types of CCR models are the input-oriented model, in which the inputs are maximized, and the output-oriented model, in which the outputs are maximized. Given that the focus is on maximizing multiple outputs, this paper used the following output-oriented CCR model:

$$\min \ px_0 \tag{16}$$

$$\text{s.t} \quad qy_0 = 1 \tag{17}$$

$$-pX + qY \le 0 \tag{18}$$

$$p \ge 0, q \ge 0, \tag{19}$$

where x_0 and y_0 are the input and output vectors of DMU_o, respectively. In Equation 18, X and Y variables refer to matrices of inputs and outputs, respectively. Let an optimal solution of LP_0 be (v^*, u^*). Then, an optimal solution of the output-oriented model is obtained from

$$p^* = v^*/\theta^*, q^* = u^*/\theta^*. \tag{20}$$

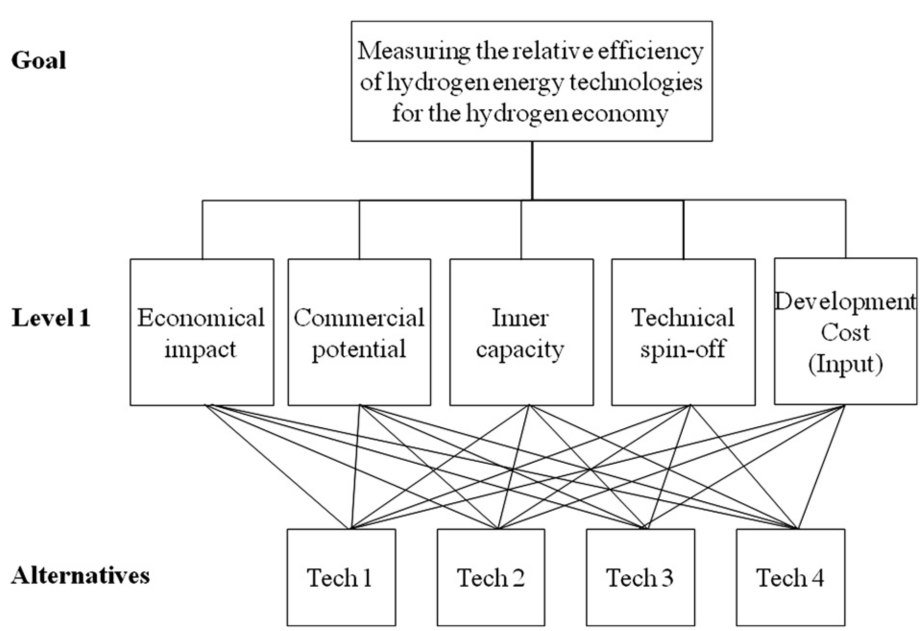

Fig. 3 – Hierarchy of the DEA approach.

Table 2 – Classification of hydrogen energy technologies.			
High-level	Mid-level	Low-Level	Core technologies
Technologies for the hydrogen economy	Hydrogen Tech	Hydrogen production	Natural gas hydrogen production tech
			Thermochemical hydrogen production tech
			Water electrolyzer hydrogen production tech
		Hydrogen separation & Storage	Chemical storage tech of solid
			High purity hydrogen production tech
	Fuel cell Tech	PEMFC	Portable fuel cell tech
			Fuel cell vehicle tech
			Hoem/Industry system tech
			Micro fuel cell
		DMFC	Laptop's fuel cell tech
			Portable fuel cell tech
		SOFC	Fuel cell for power generation
			Fuel cell for home & APU

Clearly, (p^*, q^*) is feasible for LP_0. The optimal solution comes from Equation 21, presented as

$$p^* x_0 = \upsilon^* x_0 / \theta^* = \eta^* \tag{21}$$

$$\hat{x}_0 = x_0 - t^{-*} \tag{22}$$

$$\hat{y}_0 = \eta^* y_0 + t^{+*} \tag{23}$$

where t^{-*} and t^{+*} are the slack variables of inputs and outputs related to DMU_0, respectively.

5. Classification of hydrogen energy technologies for the hydrogen economy

Hydrogen energy technologies are composed of five low levels of hydrogen energy technologies considered under Korea's energy environment. The classified hydrogen energy technologies of the hydrogen economy are shown in Table 2.

Table 3 – Fuzzy evaluation of the goal.				
	EI	CP	IC	TS
EI	(1, 1, 1)	(1, 1, 1)	(1, 1, 1)	(2/3, 1, 3/2)
	(1, 1, 1)	(2/3, 1, 3/2)	(1, 1, 1)	(2/3, 1, 3/2)
	(1, 1, 1)	(1, 1, 1)	(2/3, 1, 3/2)	(3/2, 2, 5/2)
	■	■	■	■
	■	■	■	■
CP	(1, 1, 1)	(1, 1, 1)	(1, 1, 1)	(2/3, 1, 3/2)
	(2/3, 1, 3/2)	(1, 1, 1)	(2/3, 1, 3/2)	(1, 1, 1)
	(1, 1, 1)	(1, 1, 1)	(2/3, 1, 3/2)	(3/2, 2, 5/2)
	■	■	■	■
	■	■	■	■
IC	(1, 1, 1)	(1, 1, 1)	(1, 1, 1)	(2/3, 1, 3/2)
	(1, 1, 1)	(2/3, 1, 3/2)	(1, 1, 1)	(2/3, 1, 3/2)
	(2/3, 1, 3/2)	(2/3, 1, 3/2)	(1, 1, 1)	(2/3, 1, 3/2)
	■	■	■	■
	■	■	■	■
TS	(2/3, 1, 3/2)	(2/3, 1, 3/2)	(2/3, 1, 3/2)	(1, 1, 1)
	(2/3, 1, 3/2)	(1, 1, 1)	(2/3, 1, 3/2)	(1, 1, 1)
	(2/5, 1/2, 2/3)	(2/5, 1/2, 2/3)	(2/3, 1, 3/2)	(1, 1, 1)
	■	■	■	■
	■	■	■	■

■ denotes that there is another value for another expert's fuzzy evaluation of criteria.

In the first stage, we weigh the relative priority of low levels of hydrogen energy technologies using the fuzzy AHP approach. We then measure the relative efficiency of 13 shortlisted hydrogen energy technologies on the second stage by using the DEA approach.

6. Numerical examples

6.1. *Priority of criteria*

We made pairwise comparisons of four criteria to assess the hydrogen energy technologies in the sector of the hydrogen economy. Table 3 shows the fuzzy evaluation matrix with response to the goal.

The result of the fuzzy evaluation of criteria, which is the mean value, is shown in Table 4.

We calculated TFN values of the four criteria by using the fuzzy evaluation values in Table 4. The TFN values of the criteria are as follows:

$$\begin{aligned} S_1(EI) &= (3.97, 4.60, 5.40) \otimes (1/20.20, 1/16.60, 1/14.01) \\ &= (3.97 \times 1/20.2, 4.60 \times 1/16.60, 5.40 \times 1/14.01) \\ &= (0.20, 0.28, 0.39) \end{aligned}$$

$$\begin{aligned} S_2(CP) &= (3.97, 4.60, 5.40)) \otimes (1/20.20, 1/16.60, 1/14.01) \\ &= (0.20, 0.28, 0.39) \end{aligned}$$

$$\begin{aligned} S_3(IC) &= (3.23, 3.80, 4.67)) \otimes (1/20.20, 1/16.60, 1/14.01) \\ &= (0.16, 0.23, 0.33) \end{aligned}$$

Table 4 – Fuzzy evaluation of criteria.				
	EI	CP	IC	TS
EI	(1.00, 1.00, 1.00)	(0.93, 1.00, 1.10)	(1.03, 1.20, 1.40)	(1.00, 1.40, 1.90)
CP	(0.93, 1.00, 1.10)	(1.00, 1.00, 1.00)	(0.97, 1.20, 1.50)	(1.07, 1.40, 1.80)
IC	(0.81, 0.90, 1.03)	(0.75, 0.90, 1.13)	(1.00, 1.00, 1.00)	(0.67, 1.00, 1.50)
TS	(0.56, 0.80, 1.17)	(0.63, 0.80, 1.07)	(0.67, 1.00, 1.50)	(1.00, 1.00, 1.00)

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

$V(S_1 \geq S_i)$	value	$V(S_2 \geq S_i)$	value
$V(S_1 \geq S_2)$	1.00	$V(S_2 \geq S_1)$	1.00
$V(S_1 \geq S_3)$	1.00	$V(S_2 \geq S_3)$	1.00
$V(S_1 \geq S_4)$	1.00	$V(S_2 \geq S_4)$	1.00
$V(S_3 \geq S_i)$	value	$V(S_4 \geq S_i)$	value
$V(S_3 \geq S_1)$	0.72	$V(S_4 \geq S_1)$	0.70
$V(S_3 \geq S_2)$	0.74	$V(S_4 \geq S_2)$	0.70
$V(S_3 \geq S_4)$	1.00	$V(S_4 \geq S_3)$	0.94

$$S_4(TS) = (2.85, 3.60, 4.73)) \otimes (1/20.20, 1/16.60, 1/14.01) = (0.14, 0.22, 0.34)$$

We compared the values of S_i and calculated the degree of possibility of $S_j = (l_j, m_j, u_j) \geq S_i = (l_i, m_i, u_i)$ using Equation (8). Table 5 shows the values of $V(S_j \geq S_i)$.

We calculated the minimum degree possibility $d'(i)$ of $V(S_j \geq S_i)$ for $i,j = 1,2,\ldots,k$.

$$D'(1) = \min\ V(S_1 \geq S_2, S_3, S_4) = \min\ (1.00, 1.00, 1.00) = 1.00$$

$$D'(2) = \min\ V(S_2 \geq S_1, S_3, S_4) = \min\ (1.00, 1.00, 1.00) = 1.00$$

$$D'(3) = \min\ V(S_3 \geq S_1, S_2, S_4) = \min\ (0.72, 0.74, 1.00) = 0.72$$

$$D'(4) = \min\ V(S_4 \geq S_1, S_2, S_3) = \min\ (0.70, 0.70, 0.94) = 0.70$$

The weight vector is as follows:

$$W' = (1.00, 1.00, 0.72, 0.70)^T$$

We normalized the weight vectors as follows:

$$W = (0.29, 0.29, 0.21, 0.20)^T$$

The final weights of EI, CP, IC, and TS, are 0.29, 0.29, 0.21, and 0.20, respectively. Among the four criteria, EI and CP are preferred over the other two.

6.2. *Quantitative data of shortlisted hydrogen energy technologies*

Shortlisted hydrogen energy technologies to foster the hydrogen economy are classified based on a 10-point scale. Table 6 shows the 10-point scale for IC and TS. The numbers 2, 4, 6, 8, and 10, which correspond to the extent of preference for one element over others, are used as scaling ratios. For example, a technology with a score of 10 can be regarded as exhibiting a degree of IC and TS much higher than that of the other technologies. Conversely, a score of 2 means that one energy technology ranks much lower than the others in terms of a particular criterion.

Table 6 – 10-point scale for IC and TS.

Scale	Definition
2	Inner capacity and technical spin-off are at an extremely low level
4	Inner capacity and technical spin-off are at a low level
6	Inner capacity and technical spin-off are at a medium level
8	Inner capacity and technical spin-off are at a high level
10	Inner capacity and technical spin-off are at an extremely high level
1, 3, 5, 7, 9	Intermediate values are used to compromise between two judgments

Table 7 – 10-point scale for EI.

Scale	Definition
2	Potential energy saving is less than 10,000 TOE/year, CO_2 emission reduction is less than 10,000 tCO_2/year
4	Potential energy saving is between 10,000 and 500,000 TOE/year, CO_2 emission reduction is between 10,000 and 500,000 tCO_2/year
6	Potential energy saving is between 500,000 and 1,000,000 TOE/year, CO_2 emission reduction is between 500,000 and 1,000,000 Tco_2/year
8	Potential energy saving is between 1,000,000 and 2,000,000 TOE/year, CO_2 emission reduction is between 1,000,000 and 5,000,000 tCO_2/year
10	Potential energy savings is greater than 2,000,000 TOE/year, CO_2 emission reduction is greater than 5,000,000 tCO_2/year
1, 3, 5, 7, 9	Intermediate values are used to compromise between two judgments

Tables 7 and 8 display the 10-point scale for the EI and the CP, respectively. A score of 10 for EI implies potential energy savings of more than 2 million TOE/year, or a reduction in CO_2 emissions greater than 5 million tCO_2/year. Meanwhile, a score of 10 for the possibility of commercialization indicates that a particular energy technology is currently at the technology dissemination phase, and that core patents and the dissemination of the energy technology can be secured within three years.

Table 9 shows a single input and multiple outputs data, which are shortlisted energy technologies in the sector of the hydrogen economy. It describes the data multiplied by the fuzzy AHP results for measuring the relative efficiency of energy technologies in the hydrogen economy using the DEA approach.

Table 8 – 10-point scale for CP.

Scale	Definition
2	Phase of quickening technology development, need arises to research new technological concepts
4	Phase of technology development, component technologies need to be developed
6	Core patent acquirement phase
8	Commercialization phase, core patents can be obtained and technologies commercialized within 3–5 years
10	Technological dissemination phase, core patents can be acquired and technologies disseminated within 3 years
1, 3, 5, 7, 9	Intermediate values are used to compromise between two judgments

Table 9 – Single input and multi outputs data of shortlisted hydrogen energy technologies.

Low-level	Shortlisted energy tech	Inputs	Outputs			
		Development cost(mil.KRW)	EI	CP	IC	TC
Hydrogen Production tech	Hydrogen production tech from natural gas	500	8.0	7.0	9.0	8.0
	Thermalchemical hydrogen production tech	500	7.0	4.0	7.0	7.0
	Water electrolysis hydrogen production tech	500	6.0	5.0	6.0	7.0
Hydrogen separation & storage tech	Chemical storage tech of solid	500	7.0	5.0	7.0	7.0
	High purity hydrogen separation tech	500	7.0	4.0	7.0	7.0
PEMFC tech	Portable fuel cell tech	540	8.0	8.0	9.0	8.0
	Fuel cell vehicle tech	540	8.0	8.0	9.0	9.0
	Home/Industry system tech	500	8.0	7.0	8.0	8.0
DEFC tech	Micro fuel cell tech	500	6.0	6.0	8.0	7.0
	Laptop's fuel cell tech	500	6.0	7.0	8.0	7.0
	Portable power fuel cell tech	500	6.0	7.0	8.0	7.0
SOFC tech	Power generation fuel cell tech	540	6.0	7.0	4.0	4.0
	Home/APU fuel cell tech	540	6.0	7.0	4.0	4.0

Table 10 – Preferred data applied to the fuzzy AHP results.

Low-level	Shortlisted energy tech	Inputs	Outputs			
		Development cost(mil.KRW)	EI	CP	IC	TS
Hydrogen Production tech	Hydrogen production tech from natural gas	500	2.32	2.04	1.90	1.64
	Thermalchemical hydrogen production tech	500	2.04	1.17	1.48	1.44
	Water electrolysis hydrogen production tech	500	1.75	1.46	1.27	1.44
Hydrogen separation & storage tech	Chemical storage tech of solid	500	2.04	1.46	1.48	1.44
	High purity hydrogen separation tech	500	2.03	1.17	1.48	1.44
PEMFC tech	Portable fuel cell tech	540	2.34	2.34	1.90	1.64
	Fuel cell vehicle tech	540	2.34	2.34	1.90	1.85
	Home/Industry system tech	500	2.34	2.04	1.69	1.64
DEFC tech	Micro fuel cell tech	500	1.75	1.75	1.69	1.44
	Laptop's fuel cell tech	500	1.75	2.04	1.69	1.44
	Portable power fuel cell tech	500	1.75	2.04	1.69	1.44
SOFC tech	Power generation fuel cell tech	540	1.75	2.04	0.84	0.82
	Home/APU fuel cell tech	540	1.75	2.04	0.84	0.82

Table 10 shows the preferred data applied to the fuzzy AHP criteria' relative weights, wherein four multiple inputs data are changed.

6.3. *Relative efficiency of hydrogen energy technologies*

We calculated the relative efficiency of hydrogen energy technologies by using the DEA approach in the second stage. Table 11 shows the relative efficiency scores and the ranks of hydrogen energy technologies.

An efficiency score of 1.000 means an energy technology has been determined to belong to the efficient frontier group using the DEA model. In addition, an efficiency score of 1.000 is the optimal status considering the ratio of output variables over input variables from benefit cost analysis concept. If an efficiency score of portable fuel cell technology of PEMFC is

Table 11 – Relative efficiency scores and ranks.

Low-level	Shortlisted energy tech	Efficiency score	Rank
Hydrogen Production Tech	Hydrogen production tech from natural gas	1.000	1
	Thermalchemical hydrogen production tech	0.875	8
	Water electrolysis hydrogen production tech	0.840	13
Hydrogen separation & storage tech	Chemical storage tech of solid	0.875	8
	High purity hydrogen separation tech	0.875	8
PEMFC tech	Portable fuel cell tech	1.000	1
	Fuel cell vehicle tech	1.000	1
	Home/Industry system tech	1.000	1
DEFC tech	Micro fuel cell tech	0.889	7
	Laptop's fuel cell tech	0.951	5
	Portable power fuel cell tech	0.951	5
SOFC tech	Power generation fuel cell tech	0.875	8
	Home/APU fuel cell tech	0.875	8

1.000, there is no need for addition increase of output performance and input increase. If an efficiency score of micro fuel cell technology of DEFC is 0.889, in that case, there is needed to consider the quantity increase of outputs and the quantity decrease of inputs for having the efficiency score 1.000 as an efficient frontier group.

The efficient frontier group, consisting of hydrogen energy technologies, includes four technologies achieving relative efficiency scores of 1.000: hydrogen production technology from natural gas, portable fuel cell technology, fuel cell vehicle technology, and home/industry system. The other nine hydrogen energy technologies have been found to be relatively inefficient DMUs, following a comparison with the relative efficiency scores.

7. Conclusions

In this research, have expounded on how hydrogen energy technologies measure relative efficiency using the DEA approach based on performance and productivity. In the first stage, we allocated the relative weights of low levels of hydrogen energy technologies using the fuzzy AHP approach. In the second stage, we measured the efficiency scores using the DEA approach. Fuzzy AHP effectively reflects human thoughts with vagueness of real world decision-making problems compared with AHP, which only evaluates the relative weights with crisp numbers.

4 hydrogen energy technologies, hydrogen production technology from natural gas in the sector of hydrogen production and portable fuel cell technology, fuel cell vehicle technology, home/industry system technology in the sector of PEMC, are the most efficient technologies that should be focused on strategically with a view point of productivity and performance. The other 9 hydrogen technology have to be adjusted the quantity values of input and output variables for being the efficiency frontier group.

The results of this research can provide energy policy makers with optimal alternatives for resource allocation and for implementing well-focused R&D as they establish and evaluate the priority and efficiency of hydrogen energy technologies in the hydrogen economy sector. We plan to carry out further studies using the hybrid fuzzy AHP/DEA scale efficiency approach and slack-based measurement [20].

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Nomenclature

AHP	Analytic hierarchy process
CP	Commercial potential
DEA	Data envelopment analysis
DEFC	Direct ethanol fuel cell
DMU	Decision-making unit
EI	Economic impact
ETRM	Energy technology roadmap
IC	Inner capacity
MCDM	Multi-criteria decision-making
PEMFC	Polymer electrolyte membrane fuel cell
SOFC	Solid oxide fuel cell
TS	Technical spin-off

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