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This document appeared in

Detlef Stolten, Thomas Grube (Eds.):

18th World Hydrogen Energy Conference 2010 - WHEC 2010

Parallel Sessions Book 5: Strategic Analyses / Safety Issues / Existing and Emerging Markets

Proceedings of the WHEC, May 16.-21. 2010, Essen

Schriften des Forschungszentrums Jülich / Energy & Environment, Vol. 78-5

Institute of Energy Research - Fuel Cells (IEF-3)

Forschungszentrum Jülich GmbH, Zentralbibliothek, Verlag, 2010

ISBN: 978-3-89336-655-2

Fuzzy AHP/ DEA Approach with Scale Efficiency for Measuring the Relative Efficiency of Hydrogen R&D Programs in the Sector of Developing Hydrogen Energy Technologies

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1 Introduction

Korea takes 10th place of largest energy consuming nations in the world since she spends 222 million ton of oil equivalent per year and depends on the most amount of consumed energy resources, which account for 96% import in 2008 with the 5.6% self-sufficiency ratio of energy resources. The interest of energy technology development has increased due to her poor energy environments. Specifically, the fluctuation of oil prices has been easily affecting Korean energy environments and economy. Considering her energy environments, energy technology development can be one of the optimal solution and breakthrough to solve Korea's energy circumstances, energy security, and the low carbon green growth with Korea's sustainable development. Moreover, energy and environment issues are the key factors for leading the future sustainable competitive advantage and green growth of one nation over the others nations. Lots of advanced nations have been trying to develop the energy technologies with the establishment of the strategic energy technology R&D programs for creating and maintain a competitive advantage and leading the global energy market.

In 2005, we established strategic hydrogen energy technology roadmap in the sector of developing hydrogen energy technologies for coping with next 10 years from 2006 to 2015 as an aspect of hydrogen energy technology development. Hydrogen energy technologies are environmentally sound and friendly comparing with conventional energy technologies. Hydrogen energy technologies can play a key role and is the one of the best alternatives getting much attentions coping with UNFCCC and the hydrogen economy. Hydrogen energy technology roadmap shows meaningful guidelines for implementing the low carbon green growth society.

We analyzed the world energy outlook to make hydrogen ETRM and provide energy policy directions in 2005. It focuses on developing hydrogen energy technology considering Korea's energy circumstance. We make a list of evaluation criteria for assessing and prioritize hydrogen energy technologies in the sector of hydrogen ETRM with finite resources and R&D funds. The criteria are composed of economic impact, commercial potential, inner

capacity, and technical spin-off. Hydrogen ETRM supplies primary energy technologies to be developed with a long-term view for the low carbon green growth. We suggest Korea's long-term direction and strategy for developing hydrogen energy technologies in the sector of hydrogen ETRM with the hydrogen economy. The main purpose of this research is to assess the priority of hydrogen energy technologies in the sector of hydrogen ETRM since we allocate and invest R&D budgets strategically as an extended research [1]. In this paper, we focus on the assessment of hydrogen energy technologies econometrically by using an integrated 2-stage approach, which is fuzzy analytic hierarchy (Fuzzy AHP) process and the data envelopment analysis (DEA) in the sector of hydrogen energy technologies. The research results suggest the most efficient hydrogen energy technology is selected by the multi-criteria decision making approach. In addition it also provides Korean hydrogen energy technology policymakers and decision makers with the right hydrogen energy technologies econometrically as they implement a strategic R&D plan.

2 Fuzzy Sets and Numbers

In the real world, it is not easy to extract precise data concerning measurement indicators. And decision makers prefer natural language expression rather than crisp numbers in assessment of decision making problems. Fuzzy set theory deals with ambiguous situations effectively with the interval values instead of crisp numbers. It looks like human thoughts and perceptions of using approximate information and uncertainty to generate the reasonable alternative of decision making problem. The concept of fuzzy theory was introduced by Zadeh in 1965 [2]. Fuzzy theory includes fuzzy set, membership function, and fuzzy number 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 fuzzy approach is to express the relative importance of the alternatives and the criteria with fuzzy numbers instead of using crisp numbers because most of the decision making in the real world takes place in a situation where the pertinent data and the sequences of possible actions are not precisely known. Triangular and trapezoidal fuzzy numbers are usually used to capture the vagueness of the parameters related to select the alternatives. TFN is expressed with boundaries instead of crisp numbers for reflecting the fuzziness as decision makers select the alternatives or pair-wise comparisons matrix. In this research, we use triangular fuzzy numbers (TFN) to prioritize hydrogen energy technology in the sector of hydrogen 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} . 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 AHP

The analytic hierarchy process (AHP) is a subjective method for analyzing qualitative criteria to weight the alternatives. Saaty suggested AHP as a decision making tool to resolve unstructured problems since 1977 [3]. Generally, decision making involves various areas such as planning, selecting a best policy, the competitiveness analysis [4], and allocating resources efficiently. In this research, though the AHP is able to capture the expert's knowledge by perception or preference, the AHP still cannot reflect the human thoughts totally with crisp numbers. Therefore, fuzzy AHP, which is a fuzzy extension of AHP, is applied to solve the hierarchical fuzzy decision making problems with fuzzy scales instead of crisp numbers. Fuzzy AHP is also applied to the real world decision making problem such as implementation of the optimal R&D policy, R&D plan and resource allocation widely [5].

We use the fuzzy scale when decision makers make pairwise comparisons.

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

The procedure of fuzzy AHP is as follows:

Step 1: We make pairwise comparisons of attributes by using the fuzzy numbers in the same level of hierarchy structure.

Step 2: The value of fuzzy synthetic extent with respect to the i^{th} object is defined as

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

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

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

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

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

Step 3: We compare the values of S_i respectively and calculate the degree of possibility of $S_j = (l_j, m_j, u_j) \geq S_i = (l_i, m_i, u_i)$. 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_{S_i} and u_{S_j} . We need to 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: We calculate the minimum degree possibility $d(i)$ of $V(S_j \geq S_i)$ for $i, j=1, 2, \dots, k$.

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

Assume that

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

Then the weight vector is defined as

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

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

Step 5: We normalize the weight vectors. That is as follows.

$$W = (d(A_1), d(A_2), \dots, d(A_n))^T \quad (11)$$

where W is a non-fuzzy number.

4 DEA

Data Envelopment Analysis 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. This mathematical method has enjoyed a wide range of applications since 1978. The DEA is generally applied not only to assess the service productivity of banks, insurance companies, hospitals, universities and restaurants, but also to evaluate the efficiency of R&D programs and to implement energy policy [6]. The hierarchy structure of the DEA process, which consists of a single input factor and multiple output factors. The input factor consists of the development cost associated with the development of

hydrogen energy technologies. There are four output factors, namely economic impact, commercial potential, inner capacity, and technical spin-off. 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 ratio form, proposed by Charnes, Cooper and Rhodes, 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 to be analyzed, each of which uses *m* common inputs and *s* common outputs. Let *k* (*k*=1, 2, ..., *n*) denote the DMU whose relative efficiency or productivity is to be maximized.

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

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

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

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

where *u_{rk}* is the variable weight given to the *r*th output of the *k*th DMU, *v_{ik}* is the variable weight given to the *i*th input of the *k*th DMU, *u_{rk}* and *v_{ik}* are decision variables determining the relative efficiency of DMU_k, *Y_{rj}* is the *r*th output of the *j*th DMU, and *X_{ij}* is the *i*th input of the *j*th DMU. This also assumes that all *Y_{rj}* and *X_{ij}* are positive. *h_k* is the efficiency score, and 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(Charne, Cooper, Rhodes) and BCC(Banker, Charnes, Cooper) models. One version is the input oriented model, in which inputs are maximized, and 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 and BCC model.

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

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

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

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

x₀ and *y₀* are the input and output vector of DMU₀. In formular 18, *X* and *Y* variables mean that the matrix of inputs and outputs respectively. Let an optimal solution of LP₀ be (*v*^{*}, *u*^{*}), then an optimal solution of the output-oriented model is obtained from

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

It is clear that (p^*, q^*) is feasible for LP_0 . The optimal solution comes from the equation (21)

$$p^* x_0 = v^* x_0 / \theta^* = \eta^* \quad (21)$$

$$\hat{x}_0 = x_0 - t^* \quad (22)$$

$$\hat{y}_0 = \eta^* y_0 + t^+ \quad (23)$$

t^* and t^+ are the slack variables of input and outputs related to DMU_0 .

There are various extension models of the CCR approach, among which the BCC model is representative. The BCC approach calculates the efficient frontier group spanned by the convex hull of the existing DMUs. In hence, the condition, which is $e\lambda=1$, is added in the CCR model considering the variable return to scale characterization, which accounts for increased return to scale(IRS), decreased return to scale(DRS), and constant return to scale(CRS).

The BCC output oriented model is expressed as from formular (24) to (27)

$$\min z = vx_0 \quad (24)$$

$$\text{s.t } uy_0 = 1 \quad (25)$$

$$-uX - uY - v_0 e \geq 0 \quad (26)$$

$$v \geq 0, u \geq 0, v_0 \text{ free in sign} \quad (27)$$

In this research we applied the scale efficiency(SE) approach, which is based on the CCR and BCC scores, to measure the relative efficiency of 9 energy technologies in the sector of mid-term strategic energy technology development plan from a view point of the econometrics. Let the CCR and BCC scores of a DMU be θ^*_{CCR} and θ^*_{BCC} respectively. the SE is defined by the formular (28). SE is not greater than the maximum efficiency score one.

$$SE = \theta^*_{CCR} / \theta^*_{BCC} \quad (28)$$

For a BCC efficient DMU with CRS characteristics, its scale efficiency is one in the maximum scale size. The CCR efficiency score is called the global technical efficiency (TE), since it takes no account of scale effect as distinguished from pure technical efficiency(PTE). On the other hand, BCC expresses the local PTE under variable return to scale circumstances.

5 Numerical Example

We make pairwise comparisons of 4 criteria, which are economic impact, commercial potential, inner capacity, and technical spin-off, to evaluate hydrogen energy technologies in hydrogen ETRM. Table 1 shows the fuzzy evaluation matrix with response to the goal.

Table 1: Fuzzy evaluation of the goal.

	EI	CP	IC	TS
EI	(1, 1, 1)	(1, 1, 1) (2/3, 1, 3/2) (1, 1, 1) ⋮ ⋮	(1, 1, 1) (1, 1, 1) (2/3, 1, 3/2) ⋮ ⋮	(2/3, 1, 3/2) (2/3, 1, 3/2) (3/2, 2, 5/2) ⋮ ⋮
CP	(1, 1, 1) (2/3, 1, 3/2) (1, 1, 1) ⋮ ⋮	(1, 1, 1)	(1, 1, 1) (2/3, 1, 3/2) (2/3, 1, 3/2) ⋮ ⋮	(2/3, 1, 3/2) (1, 1, 1) (3/2, 2, 5/2) ⋮ ⋮
IC	(1, 1, 1) (1, 1, 1) (2/3, 1, 3/2) ⋮ ⋮	(1, 1, 1) (2/3, 1, 3/2) (2/3, 1, 3/2) ⋮ ⋮	(1, 1, 1)	(2/3, 1, 3/2) (2/3, 1, 3/2) (2/3, 1, 3/2) ⋮ ⋮
TS	(2/3, 1, 3/2) (2/3, 1, 3/2) (2/5, 1/2, 2/3) ⋮ ⋮	(2/3, 1, 3/2) (1, 1, 1) (2/5, 1/2, 2/3) ⋮ ⋮	(2/3, 1, 3/2) (2/3, 1, 3/2) (2/3, 1, 3/2) ⋮ ⋮	(1, 1, 1)

Table 2: 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)

As a result of fuzzy evaluation of criteria, which is the mean value, is shown in Table 2. We calculate TFN values of 4 criteria by using the fuzzy evaluation values in Table 2. TFN values of criteria are as follow as an example:

$$S_1(\text{Economic impact}) = (3.97, 4.60, 5.40) \otimes (1/20.20, 1/16.60, 1/14.01) = (0.20, 0.28, 0.39)$$

We compare the values of S_i respectively and calculate the degree of possibility of $S_j = (l_j, m_j, u_j) \geq S_i = (l_i, m_i, u_i)$ by the formula (8). Table 3 shows the values of $V(S_j \geq S_i)$.

Table 3: Values of $(S_j \geq S_i)$.

$V(S_1 \geq S_1)$	value	$V(S_2 \geq S_1)$	value
$V(S_2 \geq S_2)$	1.00	$V(S_2 \geq S_2)$	1.00
$V(S_3 \geq S_3)$	1.00	$V(S_3 \geq S_3)$	1.00
$V(S_4 \geq S_4)$	1.00	$V(S_4 \geq S_4)$	1.00
$V(S_2 \geq S_1)$	value	$V(S_4 \geq S_1)$	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
$V(S_4 \geq S_2)$	1.00	$V(S_4 \geq S_3)$	0.94

Table 4: 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 judgements

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

$$D'(1)=\min V(S_1 \geq S_2, S_3, S_4)=\min(1.00, 1.00, 1.00)=1.00, D'(2)= 1.00, D'(3)=0.72, D'(4)=0.70$$

Then the weight vector is like that:

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

We normalize the weight vectors. That is as follows:

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

The final relative weights of 4 criteria, which are economic impact, commercial potential, inner capacity, and technical spin-off, are 0.29, 0.29, 0.21, and 0.20 respectively. In 4 criteria, economic impact and commercial potential are the most preferred criteria comparing with the other criteria through the result of Fuzzy AHP approach with making pairwise comparisons of 4 criteria.

Table 5: 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 judgements

Table 6: 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, competent technologies need to be developed
6	Core patent acquirement phase
8	Commercialization phase, core patents can be obtained and technologies commercialized within 3 to 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 judgements

Shored listed hydrogen energy technologies are classified based on a 10-point scale. Table 4 shows the 10-point scale for inner capacity and technical spin-off. Table 5 and 6 display, respectively, the 10-point scale for economic impact and commercial potential. A single input and multiple outputs data, which is short listed hydrogen energy technologies, are described. The fuzzy AHP results multiples the 10 point scale and DEA approach is used to measure the relative efficiency of hydrogen energy technologies. We calculate the relative efficiency of hydrogen energy technologies by using the DEA approach in the second stage. Table 7 presents the relative efficiency scores and ranks of hydrogen energy technologies in the sector of hydrogen energy technology roadmap.

Table 7: Relative efficiency of hydrogen energy technologies.

Low-level	Core technologie	CCR	BCC	SE	Rank
Hydrogen Production Tech	Hydrogen production tech from natura gas	1.000	1.000	1.000	1
	Thermalchemical hydrogen production tech	0.875	0.875	1.000	1
	Water electrolysis hydrogen production tech	0.840	0.875	0.960	10
Hydrogen Separation & Storage Tech	Chemical storage tech of solid	0.875	0.875	1.000	1
	High purity hydrogen separation tech	0.875	0.875	1.000	1
PEMFC tech	Portable fuel cell tech	0.926	1.000	0.926	13
	Fuel cell vehicle tech	1.000	1.000	1.000	1
	Home/Industry system tech	1.000	1.000	1.000	1
DEFC tech	Micro fuel cell tech	0.889	0.889	1.000	1
	Laptop's fuel cell tech	0.889	0.889	1.000	1
	Portable power fuel cell tech	0.889	0.889	1.000	1
SOFC tech	Power generation fuel cell tech	0.810	0.875	0.926	11
	Home/APU fuel cell tech	0.810	0.875	0.926	11

6 Conclusions

Hydrogen ETRM is a long-term strategic plan, which is established by KIER, coping with next 10 years from 2006 to 2015. We focus on the strategic development of hydrogen energy technologies as the only government sponsored research institute related to develop energy technologies in Korea. When governors or policy makers make an allocation of finite R&D budgets related to develop energy technologies strategically, it needs to allocate R&D budgets reasonably and scientifically. Through this extended research results, finite R&D budgets can be allocated with strategic approach for Korea's well focused R&D. In this research, we focus on the prioritization of hydrogen energy technologies and expound up how hydrogen energy technologies are measured the relative efficiency scores using 2-stage multi-criteria decision making approach, which accounts of fuzzy AHP and DEA approach with scale efficiency. For further study, we are planning to apply the fuzzy AHP and TOPSIS approach as an extended research.

Acknowledgements

This research is funded by the R&D funds of hydrogen energy R&D center, MEST, Republic of Korea.

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