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A fuzzy analytic hierarchy process (AHP)/data envelopment analysis (DEA) hybrid model for efficiently allocating energy R&D resources: In the case of energy technologies against high oil prices

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ABSTRACT

"The Low Carbon, Green Growth" was declared as Korean national agenda in 2008. Korea has been enhancing the green growth for the sustainable economic development and fostering energy. To improve Korean national energy security and promote the "Low Carbon, Green Growth", we established a long term strategic energy technology roadmap. In this paper, five criteria, such as economical impact, commercial potential, inner capacity, technical spin-off, and development cost, were used to assess the strategic energy technologies against high oil prices. We developed the integrated two-stage multi-criteria decision making (MCDM) approach which was used to evaluate the relative weights of criteria and measures the relative efficiency of energy technologies against high oil prices. On the first stage, the fuzzy analytic hierarchy process, reflecting the vagueness of human thought with interval values instead of crisp numbers, allocated the relative weights of criteria effectively instead of the AHP approach. On the second stage, the data envelopment analysis approach measured the relative efficiency of energy technologies against high oil prices with economic viewpoints. The relative efficiency score of energy technologies against high oil prices can be the fundamental decision making data which help decision markers to effectively allocate the limited R&D resources.

Contents

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Nomenclature

AHP	Analytic hierarchy process
CCR	Charnes, Cooper and Rhodes
CP	commercial potential
DC	development cost
DEA	data envelopment analysis
DMU	decision making unit
EI	economical impact
ETRM	energy technology roadmaps
IC	inner capacity
MCDM	multi-criteria decision making
TFN	triangular fuzzy number
TS	technical spin-off

1. Introduction

Korean economy has been easily affected by the change in oil prices as Korea has poor natural resources. In addition, Korea is the 10th largest energy consuming nation in the world and imports more than 98% of its total energy consumption. Korea has been facing the challenge of reducing the emission of greenhouse gases to the level that meets the standards laid out in the United Nations Framework Convention on Climate Change (UNFCCC). The Korean Government declared the ''Low Carbon, Green Growth'' as the national agenda in 2008, which emphasizes an environmentally sustainable economic development and progress to foster low-carbon socially. The interests of developing strategic energy technologies have increased due to Korea's poor natural resources and energy environments.

We established the strategic energy technology roadmap (ETRM) in the sector of energy technologies against high oil prices, coping with the forthcoming 10-year period from 2006 to 2015. A strategic energy technology development is one of the best alternatives considering the current status of Korean energy environments. We analyzed the world energy outlook to establish ETRM against high oil prices and provided energy policy directions in 2005 with a long-term viewpoint [1,2].

ETRM focuses on the strategic development of energy technologies considering Korean energy circumstance. Korea is the 10th largest energy consumer in the world and more than 95% of consumed energy in Korea relies on imports according to IEA in 2008. To cope with the fluctuation of oil prices change, Korea has to focus on developing energy efficiency technologies against high oil prices case because she has very poor natural resources nation and one of the biggest energy consumers in the world.

We made a list of criteria for assessing energy technologies against high oil prices. Five criteria, which were established by the brainstorming of experts related to develop energy technologies, are composed of economical impact (EI), commercial potential (CP), inner capacity (IC), technical spin-off (TS), and development cost (DC). ETRM supplies primary energy technologies which will be developed with a long-term viewpoint.

In the real world, it is very hard to extract precise data of input and output and tackle them with crisp numbers which reflect human's appraisals related to pairwise comparisons. Saaty has proposed the AHP approach as a decision-making method to solve unstructured problems [3]. The AHP approach is a subjective tool with which to analyze the qualitative criteria needed to generate alternative priorities with 9-point scales. The AHP approach empowers 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. However, the AHP method is unable to provide the crisp values such as 9-point scales needed to properly reflect the fuzziness associated with decision-making problems in the real world. Nevertheless, the AHP method has proven to be a much more powerful decision analysis technique in the sector of multi-criteria decision making (MCDM), and has been successfully applied to the tackling of MCDM problems generally. Its utilization area involves tasks such as R&D planning [4], the best policy selection [5,6], 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.

In the sector of energy policy and energy technology development, AHP approach is widely applied for assessment of policy options and strategic energy technologies for well focused R&D such as competitiveness analysis of hydrogen energy technology portfolio [5], Climate change mitigation evaluation [7], alternative fuel-bus selection [8], sustainability assessment of flooring system [9], renewable energy selection in the case of Pakistan [10], and wind observation station location selection [11].

To successfully assess the energy technologies against high oil prices, it is very meaningful to economically measure energy technologies against high oil prices. This study is the extension of our previous work [12], which aims to assess the energy technologies against high oil prices based on the quantitative data accrued using the fuzzy analytic hierarchy process (Fuzzy AHP) and data envelopment analysis (DEA) approaches from an economic viewpoint. Because it is crucial to select the strategic energy technologies for considering the economic aspects with the ratio of outputs over inputs in the case of poor natural resources nations such as Korea and well focused R&D in the sector of energy technology development is equal to the second natural resources acquisition.

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 evaluate the relative efficiency econometrically and priorities of energy technologies against high oil prices.

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 outcome in the sector of energy technologies against high oil prices.

This paper unfolds in the following fashion: Section 2 presents the execution flow chart of this research. Section 3 introduces the concept of fuzzy sets and numbers. Section 4 describes the fuzzy AHP and DEA approach. Section 5 displays the classification of energy technologies against high oil prices. In Section 6, the numerical examples of energy technologies against high oil prices are presented including two-stage approaches and single fuzzy AHP approach. Finally, Section 7 concludes this study.

2. Execution flow chart

The execution flow chart is composed of six phases for assessing and prioritizing the relative weights of energy technologies against high oil prices. Fig. 1 shows the schematic of the execution flow chart. The 1st phase analyzes the energy policy, energy environment, and a short list of energy technologies against high oil prices. The 2nd phase consists of the formulation of a list of criteria used to weigh the relative importance of criteria and alternatives. The 3rd phase structures the hierarchy of

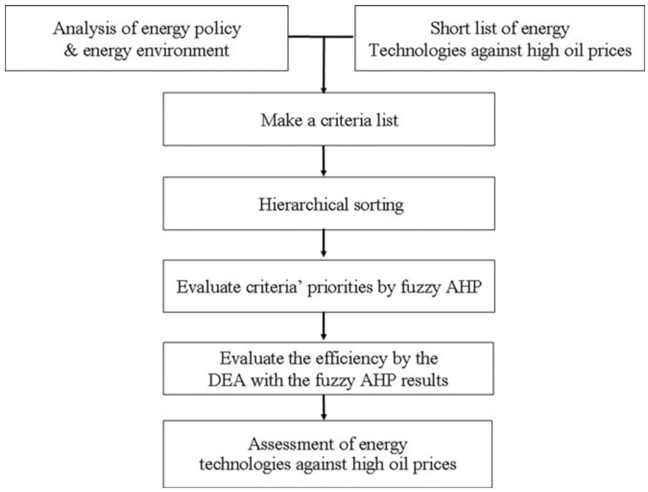

Fig. 1. Execution flow chart.

criteria. In the 4th phase, criteria weights of energy technologies against high oil prices are calculated by the fuzzy AHP. The 5th phase measures the efficiency score of energy technologies against high oil prices by using the DEA approach. Finally, the efficiency values produced in the 5th phase are evaluated and aggregated in the 6th phase. In this study, the fuzzy AHP/DEA hybrid model was used to measure the relative efficiency of energy technologies against high oil prices with two MCDM methods.

3. Fuzzy sets and numbers

In reality, it is very hard to extract precise data related to measurement indicators by human judgements. Decision makers and policymakers also prefer natural language expression rather than crisp numbers. Fuzzy set theory applied in this research deals with ambiguous or not well defined situations. It looks like human thoughts and perceptions of using approximate information and uncertainty to generate the reasonable alternatives of decision making problems.

The concept of fuzzy theory is introduced and addressed by Zadeh in 1965 for the first time [13]. Fuzzy theory is composed of three key factors, which are 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 and strength of using fuzzy approach is to express the relative importance of the alternatives and the criteria with fuzzy numbers instead of using simple crisp numbers as most of the decision making problems 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 which are related to select the alternatives. Triangular fuzzy numbers (TFN) are expressed with boundaries instead of crisp numbers for reflecting the fuzziness as decision makers select the alternatives or pairwise comparisons matrix. In this research, we used TFN to prioritize energy technologies against high oil prices 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:

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

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

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

4. Fuzzy AHP and DEA

4.1. Fuzzy AHP

The analytic hierarchy process (AHP) is a subjective method for analyzing qualitative criteria to weigh the alternatives. It is the powerful and useful MCDM approach tool. Saaty suggested the AHP as a decision making tool to resolve unstructured problems [3]. Decision making process is formulated as a hierarchical structure in the AHP method. At each level of the hierarchy, the AHP uses pairwise comparisons to estimate the relative priorities of criteria and alternatives. Although the AHP method is to capture the expert's knowledge by perception or preference, AHP still cannot reflect the human thoughts totally with crisp numbers comparing with the fuzzy AHP method due to its interval values instead of simple crisp numbers.

Therefore, the fuzzy AHP, which is a fuzzy extension of AHP, is applied to solve the hierarchical fuzzy MCDM problems. There are numerous cases for employing fuzzy AHP in the sector of energy policy and technology development plan, including evaluation of solid waste management system [14], power generation project [15], ranking suitable sites for irrigation in the case of Tunisia [16], and selection of the best solar thermal collection technology for electricity generation in India [17].

Fig. 2 shows the hierarchy of criteria. To evaluate and prioritize the weights of low level of energy technologies, we compose four criteria in the first stage, which are economical impact, commercial potential, inner capacity, and technical spin-off. Energy technologies against high oil prices are evaluated by the one-tier criteria from the modification of the previous Korea's first national energy technology development plan with expert's brainstorming [4].

Table 1 shows the scale for pairwise comparisons of one attribute over another in Fuzzy AHP approach [18]. The numbers 2/3, 1, 3/2, 2, 5/2, 3, 7/2, 4 and 9/2 were used as fuzzy scaling ratios, corresponding to the strength of preference for one element over another with interval values instead of crisp numbers.

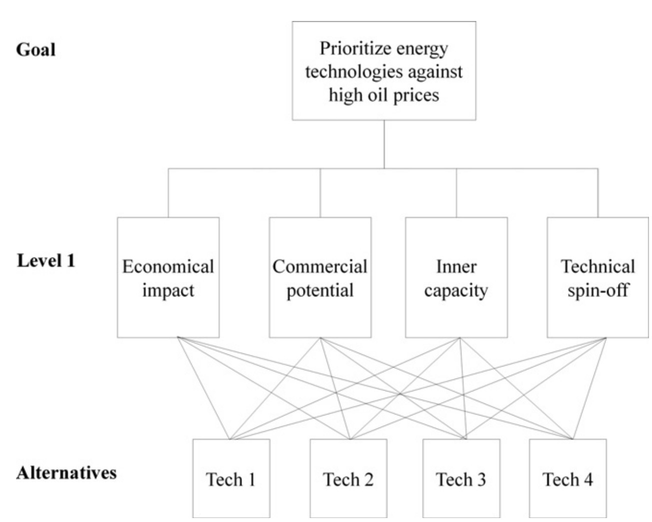

Fig. 2. Hierarchy of criteria.

Table 1
Fuzzy scale.

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

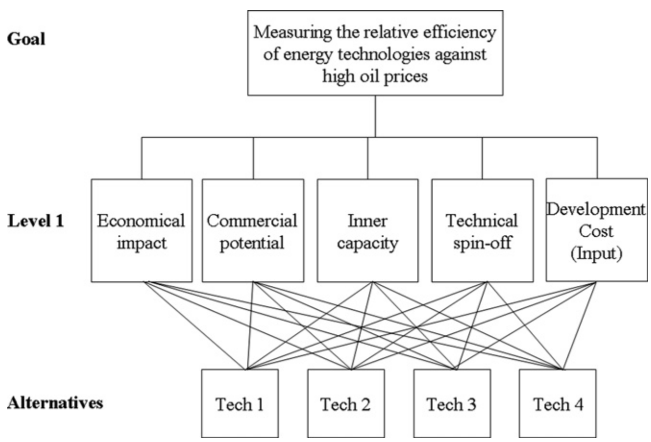

Fig. 3. DEA model for measuring the relative efficiency of energy technologies against high oil prices.

We used the fuzzy scale when decision makers make pairwise comparisons. Let $A=(a_{ij})_{nxm}$ be a fuzzy pairwise comparison judgements matrix. Let $M_{ij}=(l_{ij}, m_{ij}, u_{ij})$ be a TFN. The step of calculating the relative weights of criteria using the 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 ith object is defined as

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

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

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

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

We calculate TFN value of $S_i=(l_i, m_i, u_i)$ by the formula (4)–(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:

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

where d is the ordinate of the highest intersection point between uS_i and uS_j. We need to compare both the values of $V(S_j \geq S_i)$ and $V(S_i \geq S_j)$ with S_i and S_j.
Step 4: We calculate the minimum degree possibility $d(i)$ of $V(S_j \geq S_i)$ for $i,j=1,2, \ldots,k$.

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

Assume that

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

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. That is 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. *Data envelopment analysis*

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 been applied to solve a wide range of applications since 1978. The DEA is generally applied not only to assess the service productivity of banks [19], insurance companies [20], hospitals [21], universities [22] and restaurants, but also to evaluate the efficiency of R&D programs [23,25], to implement energy policy [26], assessment of sustainable energy consumption [27], China's regional energy and environmental efficiency [28], future scenario optimality of renewable energy [29], and to evaluation of potential reduction in carbon emissions [30].

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 development cost associated with the development of energy technologies against high oil prices. There are four output factors, namely economical 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 ration form, proposed by Charnes et al. [31], 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 ($k=1, 2, \ldots, n$) denotes the DMU whose relative efficiency or productivity is to be maximized:

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

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

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

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

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 (Charnes, Cooper and Rhodes) 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 model.

5. Classification of energy technologies against high oil prices

The classified energy technologies against high oil prices are shown in Table 2. In the case of Korea for developing well focused energy technologies against high oil prices, we make a short-list of energy efficiency improvement technologies to cope with high oil prices in this research because other researches are focused on developing new and renewable energy technologies for copying with the UNFCCC and the implementation of hydrogen economy [24].

It is divided into six categories and 14 energy technologies. Low-level is composed of six sectors of building technology, industry technology, transportation technology, coal technology, and non-conventional technology. Core energy technologies are composed of energy technologies against high oil prices in each low-level group. In this research, we focus on the sector of energy technologies against high oil prices as an extended research.

6. Numerical examples

6.1. Priority of criteria

We made pairwise comparisons of four criteria to assess energy technologies against high oil prices. Table 3 shows the fuzzy evaluation matrix with response to the goal. Economical impact, commercial potential, inner capacity, and technical spin-off stand for EI, CP, IC, and TS, respectively.

Table 2
Classification of energy technologies against high oil prices.

High-level	Low-level	Core technologies
Technologies for high oil prices	Building tech	Lighting tech
		Airconditioning tech
		Building envelope tech
		Building system tech
	Industry tech	Common tech
		Waste heat tech
		Petroleum refinery and fine chemical tech
	Transportation tech	Automobile tech
	Coal tech	Direct utilization tech
		Conversion utilization tech
	Non-conventional fuel tech	Oil shale/Oil sand tech
		Pyrolysis/Gasification tech of waste
	Biomass tech	Direct utilization tech
		Conversion tech

As a result of 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. TFN values of criteria are as follow:

$$S_1(\text{EI}) = (3.97,4.60,5.40) \otimes \left(\frac{1}{20.20},\frac{1}{16.60},\frac{1}{14.01}\right)$$
$$= \left(3.971 \times \frac{1}{20.2},4.601 \times \frac{1}{16.60},5.401 \times \frac{1}{14.01}\right) = (0.20,0.28,0.39)$$

$$S_2(\text{CP}) = (3.97,4.60,5.40) \otimes \left(\frac{1}{20.20},\frac{1}{16.60},\frac{1}{14.01}\right) = (0.20,0.28,0.39)$$

$$S_3(\text{IC}) = (3.23,3.80,4.67) \otimes \left(\frac{1}{20.20},\frac{1}{16.60},\frac{1}{14.01}\right) = (0.16,0.23,0.33)$$

$$S_4(\text{TS}) = (2.85,3.60,4.73) \otimes \left(\frac{1}{20.20},\frac{1}{16.60},\frac{1}{14.01}\right) = (0.14,0.22,0.34)$$

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

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

$$D'(1) = \min V(S_1 \ge S_2, S_3, S_4) = \min(1.00,1.00,1.00) = 1.00$$
$$D'(2) = \min V(S_2 \ge S_1, S_3, S_4) = \min(1.00,1.00,1.00) = 1.00$$
$$D'(3) = \min V(S_3 \ge S_1, S_2, S_4) = \min(0.72,0.74,1.00) = 0.72$$
$$D'(4) = \min V(S_4 \ge S_1, S_2, S_3) = \min(0.70,0.70,0.94) = 0.70$$

Then the weight vector is like that.

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

We normalized the weight vectors. That is as follows:

$$W' = (0.29,0.29,0.21,0.20)^T$$

The final weights of the four criteria, EI, CP, IC, and TS, are 0.29, 0.29, 0.21, and 0.20, respectively. In the four criteria, EI and CP are the most preferred criteria comparing with the other criteria.

6.2. Quantitative data of shortlisted energy technologies

Shortlisted energy technologies against high oil prices are classified based on a 10-point scale which was established by the brainstorming of experts in the field of energy technology development. Table 6 shows the 10-point scale for the inner capacity and the technical spin-off. The numbers 2, 4, 6, 8 and 10, which correspond to the extent of the preference for one element over the others, are used herein as scaling ratios.

Tables 7 and 8 display, respectively, the 10-point scale for the economical impact and the commercial potential. As shown in Table 9, a single input and multiple outputs data, which are shortlisted energy technologies against high oil prices, are described. Table 9 shows the data which were multiplied by the fuzzy AHP results for measuring the relative efficiency of energy technologies against high oil prices by using the DEA approach. Table 10 shows the preferred data, applied to the fuzzy AHP criteria' relative weights, in which the four multiple inputs data were changed.

6.3. Relative efficiency of energy technologies against high oil prices

We calculated the relative efficiency of energy technologies against high oil prices by using the DEA approach in the second stage. As shown in Table 11, it shows the relatvie efficiency scores and the ranks of energy technologies against high oil prices by the result of fuzzy AHP/DEA hybrid appraoch. In the sector of building

Table 3
Fuzzy evaluation of 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)

-: Fuzzy number of another expert's evaluation values.

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

Table 6
Ten-points 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.

technolgy, lighting technology is the most valuable to develop. In the industry sector, waste heat technology is preferred. Conversion utilization technology is much more valuable than direct utilization technology in the sector of coal technology. Direct utilization technology is preferred to develop in the sector of biomass technology. Conversion utilization technology and direct utilization technology are the most preferred energy technologies in the sector of energy technologies against high oil prices, followed by the lighting technology and waste heat technology from an econometric viewpoint.

Table 7
Ten-points 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 saving 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.

6.4. *Result comparisons of fuzzy AHP and DEA based on fuzzy AHP*

We analyzed the relative weigths and ranks of 14 energy efficiency technologies against high oil prices resulted from the cases of single fuzzy AHP and DEA based on fuzzy AHP results. In the case of fuzzy AHP result, we allocated the relative weights of four criteria, including economical impact, commercial potential, inner capacity, and technical spin-off, from the expert's peer-review with pairwise comparisons based on the interval values.

Table 12 describes the relative weights and ranks of 14 energy efficiency technologies by the fuzzy AHP. Pyrolysis/gasification technology of waste, conversion unility technology, common technology of industry, building envelope, and building system technology are preferred by the fuzzy AHP approach. On the other hand, comparison of fuzzy AHP and DEA based on fuzzy AHP approaches is shown in Table 13. When we compare the relative ranks of fuzzy AHP and DEA based on fuzzy AHP, energy conversion utilization technology and building envelope are taken the higher ranks simultaneously. Ranks of most of the energy technologies are reversed since DEA approach is considering the relative efficiency of outputs over inputs from an economic viewpoint. In the case of poor natural resources nation with

Table 8
Ten-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 judgements.

Table 9
Single input and multi outputs against high oil prices.

Low-level	Core technologies	Inputs	Outputs			
		Dc(mil.KRW)	EI	CP	IC	TS
Building tech	Lighting tech	550	7.0	7.0	7.0	7.0
	Airconditioning tech	2520	7.0	8.0	6.0	7.0
	Building envelope tech	700	8.0	7.0	8.0	8.0
	Building system tech	2150	8.0	7.0	8.0	8.0
Industry tech	Common tech	4500	8.0	8.0	8.0	9.0
	Waste heat tech	600	7.0	8.0	5.0	7.0
	Petroleum refinergy and fine chemical tech	805	6.0	7.0	7.0	7.0
Transportation tech	Aotomobile tech	1720	7.0	6.0	6.0	7.0
Coal tech	Direct utilization tech	3500	7.0	7.0	8.0	8.0
	Conversion utilization tech	700	9.0	8.0	8.0	9.0
Non-conventional fuel cell tech	Oil shale/oil sand tech	1500	8.0	5.0	4.0	7.0
	Pyrolysis/gasification tech of waste	1275	9.0	8.0	9.0	9.0
Biomass	Direct utilization tech	400	5.0	7.0	7.0	5.0
	Conversion tech	527	6.0	6.0	7.0	5.0

Table 10
Preferred data applied to the Fuzzy AHP criteria' relative weights.

Low-level	Core technologies	Inputs	Outputs			
		Dc(mil.KRW)	EI	CP	IC	TS
Building tech	Lighting tech	550	2.03	2.03	1.47	1.47
	Airconditioning tech	2520	2.03	2.32	1.26	1.47
	Building envelope tech	700	2.32	2.03	1.68	1.68
	Building system tech	2150	2.32	2.03	1.68	1.68
Industry tech	Common tech	4500	2.32	2.32	1.68	1.89
	Waste heat tech	600	2.03	2.32	1.05	1.47
	Petroleum refinergy and fine chemical tech	805	1.74	2.03	1.47	1.47
Transportation tech	Aotomobile tech	1720	2.03	1.74	1.26	1.47
Coal tech	Direct utilization tech	3500	2.03	2.03	1.68	1.68
	Conversion utilization tech	700	2.61	2.32	1.68	1.89
Non-Conventional fuel cell tech	Oil shale/oil sand tech	1500	2.32	1.45	0.84	1.47
	Pyrolysis/gasification tech of waste	1275	2.61	2.32	1.89	1.89
Biomass	Direct utilization tech	400	1.45	2.03	1.47	1.05
	Conversion tech	527	1.74	1.74	1.47	1.05

Table 11
Efficiency scores and ranks.

Low-level	Core technologies	Efficinecy score	Rank
Building tech	Lighting tech	0.996	3
	Airconditioning tech	0.219	12
	Building envelope tech	0.894	6
	Building system tech	0.291	11
Industry tech	Common tech	0.156	14
	Waste heat tech	0.920	4
	Petroleum refinergy and fine chemical tech	0.681	7
Transportation tech	Aotomobile tech	0.317	10
Coal tech	Direct utilization tech	0.179	13
	Conversion utilization tech	1.000	1
Non-Conventional fuel cell tech	Oil shale/oil sand tech	0.415	9
	Pyrolysis/gasification tech of waste	0.552	8
Biomass	Direct utilization tech	1.000	1
	Conversion tech	0.899	5

Table 12
Relative weights and ranks of fuzzy AHP approach.

Low-level	Core technologies	EI	CP	IC	TS	Weight	Normalized weight	Rank
Building tech	Lighting tech	0.069	0.069	0.050	0.050	0.237	0.070	8
	HVAC tech	0.069	0.078	0.043	0.050	0.239	0.070	7
	Building envelope	0.078	0.069	0.057	0.057	0.261	0.077	4
	Building system tech	0.078	0.069	0.057	0.057	0.261	0.077	4
Industry tech	Common tech	0.078	0.078	0.057	0.064	0.278	0.082	3
	Waste heat tech	0.069	0.078	0.035	0.050	0.232	0.068	9
	Refinery/petroleum/fine chemical tech	0.059	0.069	0.050	0.050	0.227	0.067	10
Transportation tech	Vehicle tech	0.069	0.059	0.043	0.050	0.220	0.065	11
Coal tech	Direct utilization tech	0.069	0.069	0.057	0.057	0.251	0.074	6
	Conversion util. tech	0.088	0.078	0.057	0.064	0.287	0.085	2
Non-conventional fuel cell tech	Oil shale/oil sand tech	0.078	0.049	0.028	0.050	0.206	0.060	12
	Pyrolysis/gasification tech of waste	0.088	0.078	0.064	0.064	0.294	0.087	1
Biomass	Direct utilization tech	0.049	0.069	0.050	0.035	0.203	0.060	13
	Conversion tech	0.059	0.059	0.050	0.035	0.203	0.060	13

Table 13
Relative results of fuzzy AHP and DEA based on fuzzy AHP.

Low-level	Core technologies	Weight of fuzzy AHP	Rank of fuzzy AHP	Relative score of DEA-fuzzy AHP	Rank of DEA-fuzzy AHP
Building tech	Lighting tech	0.070	8	0.996	3
	HVAC tech	0.070	7	0.219	12
	Building envelope	0.077	4	0.894	6
	Building system tech	0.077	4	0.291	11
Industry tech	Common tech	0.082	3	0.156	14
	Waste heat tech	0.068	9	0.920	4
	Refinery/petrol/fine chemical tech	0.067	10	0.681	7
Transportation tech	Vehicle tech	0.065	11	0.317	10
Coal tech	Direct utilization tech	0.074	6	0.179	13
	Conversion utilization tech	0.085	2	1.000	1
Non-conventional fuel cell tech	Oil shale/oil sand tech	0.060	12	0.415	9
	Pyrolysis/gasification tech of waste	0.087	1	0.552	8
Biomass	Direct utilization tech	0.060	13	1.000	1
	Conversion tech	0.060	13	0.899	5

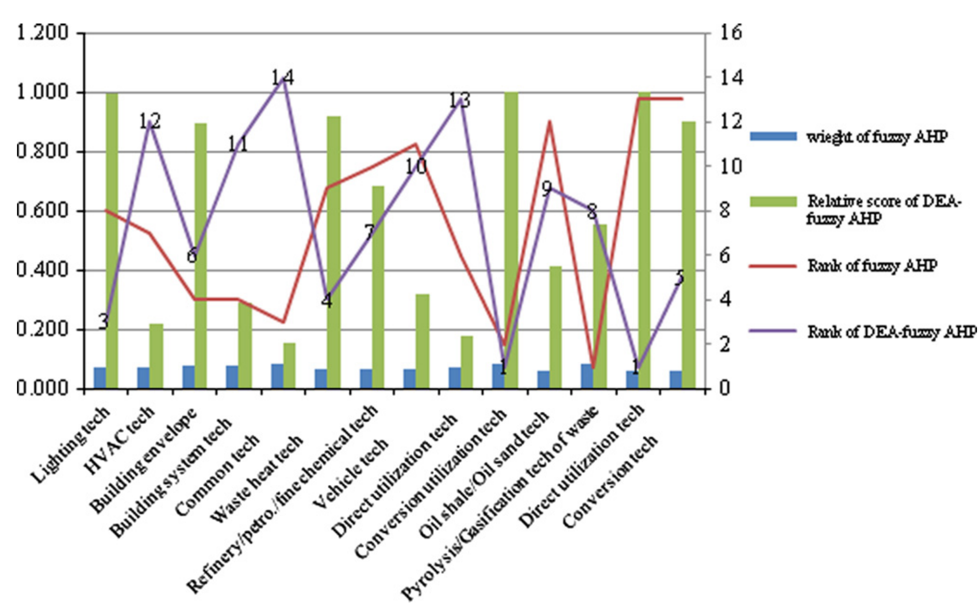

Fig. 4. Result comparisons of the fuzzy AHP and DEA based on the fuzzy AHP.

limited R&D budgets such as Korea, we have to consider the relative efficiency of outputs over inputs as we develop strategic energy technologies against high oil prices for well focused R&D by two-stage approach. The relative weights and efficiency scores of fuzzy AHP and DEA based on the fuzzy AHP are shown in Fig. 4.

7. Conclusions

We established the strategic energy technology roadmap (ETRM) in the sector of energy technologies against high oil prices, coping with the forthcoming 10-year period from 2006 to 2015. We focused on measuring the relative efficiency and prioritization of energy technologies against high oil prices from a econometric viewpoint. We also expounded how energy technologies against high oil prices can be measured in terms of the relative efficiency scores by using 2-stage multi-criteria decision making approch which uses the integrated Fuzzy AHP and DEA model approach. We allocated the relative weights of low levels of energy technologies against high oil prices using the fuzzy AHP approach. Fuzzy AHP effectively reflects the human thoughts with vagueness of real world decision making problems comparing with AHP which just evaluates the relative weights with crisp numbers. We measured the relative efficiency scores by the DEA approach.

The results of this research can provide energy policymakers and decision makers with the optimal alternatives for resource allocation and for effectuating well focused R&D outcomes as they establish and evaluate the priority and efficiency of energy technologies against high oil prices. In addition, we are planning to carry out the further study with the econometric viewpoint of energy technology development by using the integrated fuzzy AHP/DEA scale efficiency and slack based measurement.

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