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Measuring the Relative Efficiency of Greenhouse Gas Technologies: An AHP/DEA Hybrid Model Approach

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***Abstract*— The 10-year National Plan for Energy Technology Development established in 1997 has now expired. To this end, the Korean government must now establish a new strategic ten-year plan that will cover the period from 2006 through 2015. In this paper, we prioritize the relative weights of energy technologies in terms of the national greenhouse gas plan using the AHP/DEA hybrid model. This model, which is composed of the analytic hierarchy process and data envelopment analysis, represents one of the multi-criteria decision making (MCDM) methods. In order to facilitate decision-makers and energy policy makers tasks in conjunction with the formulation of national decisions and energy policies, this study introduces a scientific procedure which can be used to measure the relative efficiency and priorities of various greenhouse gas technologies.**

***Index Terms*—AHP, DEA, Energy Policy, Greenhouse gas technology**

I. Introduction

In 1997, the Korean Government established the '10-year National Plan for Energy Technology Development'. The impending expiration of this plan has meant that the Korea government must now focus on the formulation of a new long-term strategic plan. The steady increase in the energy technology R&D budget has meant that the time has also come to establish an efficient energy and resource technology R&D strategy.

The new national plan aims to improve energy intensity, reduce the emission of greenhouse gases to levels that meets the standards laid out in the United Nations Framework Convention on Climate Change, and contribute to the economic development of Korea. This new plan must also take into consideration an energy environment that features high oil prices, the United Nations Framework Convention on Climate Change, and the advent of a hydrogen economy.

In this paper, we use the Analytic Hierarchy Process (AHP) and Data Envelopment Analysis (DEA) hybrid model to weigh the relative preferences of greenhouse gas technologies. The Analytic Hierarchy Process (AHP) is a subjective method used to analyze qualitative criteria in order to generate a weighing of the operating units. Saaty first proposed AHP as a decision-making method which could be used to solve unstructured problems in 1977 [1]. In general, Saaty indicated that decision making involves tasks such as planning [2], the generation of a set of alternatives, the setting of priorities [3], the selection of the best policy once a set of alternatives has been established, allocation of resources, determination of requirements, prediction of outcomes, designing of systems, measurement of performance, ensuring of system stability, and the optimization and resolution of conflicts [4].

Saaty introduced four principles in relation to the AHP: decomposition, prioritization, synthesis and sensitivity analysis. Under the AHP, a decision making process is modeled after a hierarchical structure. At each level of the hierarchy, the decision maker is required to make pairwise comparisons between decision alternatives and criteria using a scaling ratio for the weighing of attributes. The AHP determines the relative ranks or priorities of the decision alternatives.

The DEA is an analytical procedure based on mathematical programming that was developed by Charnes et al. (1978) as a means of measuring the relative efficiency of decision making units (DMUs) in a set. It is used to assess the relative efficiency of DMUs. Once the efficiency of energy technology development has been evaluated, a DMU is then classified as efficient or inefficient.

We employed a long-term perspective when establishing the criteria employed to evaluate energy technology priorities for the greenhouse gas plan. We used the AHP to generate the relative weights of the criteria and alternatives in the greenhouse gas plan. Thereafter, the relative weights were applied to the data used to measure the efficiency of the DEA method. This study represents the first ever instance in which the AHP/DEA hybrid model has been used to determine the energy technology priorities for the greenhouse gas plan. The results obtained using this AHP/DEA hybrid model not only provide the government with an effective decision-making tool, given that the government is the body responsible for the forging of strategic energy and resource R&D policy, but also represent a consensus of experts in the greenhouse gas planning sector.

The remainder of this paper is structured as follows. In section II, the methodology used herein, which consists of

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both the AHP and DEA methods and includes an execution flow chart, is introduced. The results of the discussion are then presented in Sections III and IV. Section V consists of the concluding remarks.

II. Methodology

A. Execution flow chart

The execution flow chart is composed of 6 phases. Fig. 1 shows the schematic of the execution flow chart. In the first phase, we analyzed the energy policy, energy environment, and a short list of greenhouse gas technologies. The 2nd phase consists of the formulation of a list of criteria used to weigh the relative importance of criteria and alternatives.

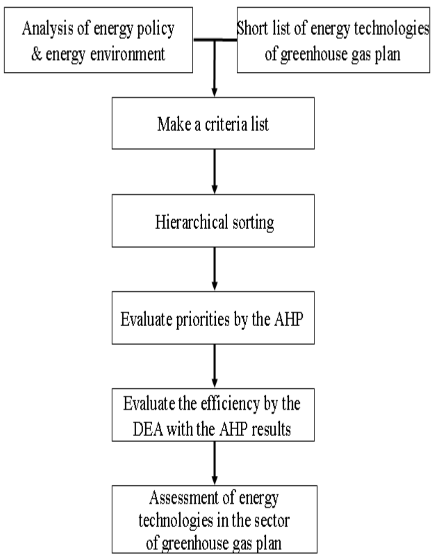

Fig. 1 Execution flow chart

In the 3rd phase, the hierarchy structure was established, and the criteria sorted. In the 4th phase, energy technology priorities were identified using the AHP process. During the 5th phase, the efficiency of greenhouse gas technologies was ascertained using the DEA approach. Finally, the efficiency values produced in the 5th phase were evaluated and aggregated in the 6th phase. In essence, this study uses the AHP/DEA hybrid model to prioritize greenhouse gas technologies for the national greenhouse gas technology plan, and weigh greenhouse gas technology priorities.

B. AHP method

The AHP enables decision makers to structure a complex problem in the form of a simple hierarchy and to evaluate a large number of quantitative and qualitative factors in a systematic manner under multiple conflicting criteria. The AHP makes use of pairwise comparison matrices, hierarchical structures, and ratio scaling to apply weights to attributes. As shown in Fig. 2, problems are decomposed into the hierarchy of a goal, attributes, and alternatives using the AHP process. The criteria, alternatives, and the hierarchy are structured in the 3rd phase, and then used to break down the complex problem into a number of small constituent elements and structures these elements

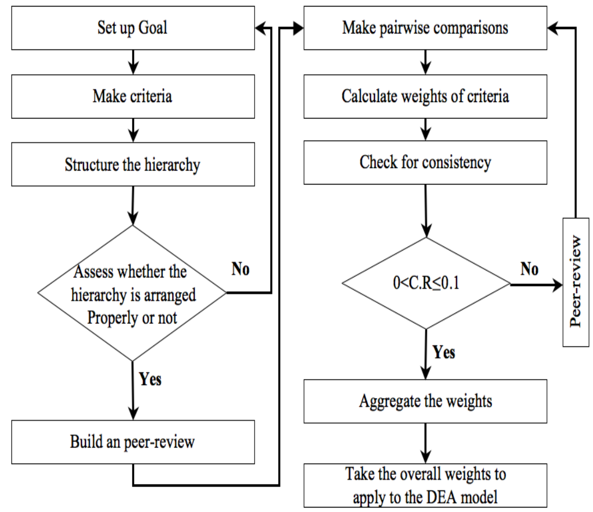

Fig. 2 The AHP process

TABLE I
SCALE FOR PAIRWISE COMPARISIONS

Importance scale	Definition	Explanation
1	Equal importance	Two elements contribute equally
3	Moderate importance	One element is slightly favored over another
5	Strong importance	One element is strongly favored over another
7	Very strong importance	An element is very strongly favored over another
9	Extreme importance	One element is the most favored over another

in a hierarchical form. The 4th stage revolves around the evaluation of whether the hierarchy, based on the target, has been properly arranged. Once the hierarchy has been assessed, a peer-review is executed in the 5th stage, with the weights of experts then aggregated. While pairwise comparisons are conducted in the 6th stage, the weights of the criteria are calculated and checked for consistency in the 7th and 8th stages. Then, in the 9th stage, a review of the consistency ratio (CR) is conducted in order to ensure that it falls between 0 and 0.1. If the CR is determined to be greater than 0 but less than 0.1, we then move to the 10th stage, at which the weights are aggregated. Finally, the overall weights of greenhouse gas technologies are then used in conjunction with the DEA model.

Table I shows the scale for pairwise comparisons. The numbers 1, 3, 5, 7 and 9 are used as scaling ratios, and correspond to the strength of preference for one element over another. For example, the number 9 indicates a case of extreme importance over another element. Generally, the 9-point scale is used because the qualitative distinctions are meaningful in practice, and also because these have proven to have an element of precision in cases where items are being compared to one another. The ability to make qualitative distinctions is well represented by the 5 possible choices of equal, moderate, strong, very strong, and extreme.

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Caution should be exercised when using the AHP process to ascertain the weights of criteria and alternatives that the decision maker is consistent in terms of preference ratings. Formula 1 describes the process used to ascertain the overall weights of alternatives.

$$\begin{pmatrix} \frac{w_1}{w_1} & \frac{w_1}{w_2} & \cdots & \frac{w_1}{w_n} \\ \frac{w_2}{w_1} & \frac{w_2}{w_2} & \cdots & \frac{w_2}{w_n} \\ \vdots & \vdots & \cdots & \vdots \\ \frac{w_n}{w_1} & \frac{w_n}{w_2} & \cdots & \frac{w_n}{w_n} \end{pmatrix} \begin{pmatrix} w_1 \\ w_2 \\ \vdots \\ w_n \end{pmatrix} = \begin{pmatrix} nw_1 \\ nw_2 \\ \vdots \\ nw_n \end{pmatrix} \Rightarrow AX = nX$$

(1)

If a_{ij} represents the importance of alternative i over alternative j and a_{ik} represents the importance of alternative i over alternative k, then $a_{ij} \cdot a_{jk}$ must be equal to a_{ik}, which is an estimate of the ratio W_i / W_k used to make judgments.

TABLE II
RANDOM INDEX

Matrix index	RI value	Matrix index	RI value
1	0	6	1.24
2	0	7	1.32
3	0.58	8	1.41
4	0.9	9	1.45
5	1.12	10	1.49

If Matrix A is not a non-zero vector, there is a $\lambda_{\max}$ of $Ax = \lambda_{\max}$, which is the largest eigenvector of Matrix A. If the pairwise comparisons matrix is perfectly consistent, then λ=n and CR is 0. For each alternative, the Consistency Ratio is determined to be the ratio of Consistency Index (CI) to Random Index (RI). Formula 2 provides the process of calculating the CI values. The values of RI are also described in Table II.

$$CI = \frac{\lambda_{\max} - n}{n-1} \tag{2}$$

$$CR = \frac{CI}{RI} \tag{3}$$

CR$\leq$0.10 implies a satisfactory degree of consistency in the pairwise comparisons matrix, but if C.R.>0.10, then serious insistencies might exist and AHP might not yield meaningful results.

The AHP criteria are composed of a 2-tier hierarchy. The hierarchy structure of criteria is exposed in Fig. 3. At the top of the control hierarchy, the goal is to weigh the importance of various energy technologies in terms of the national greenhouse gas plan.

There are 5 criteria at Level 1, namely UNFCCC, economical spin-off, technical spin-off, urgency of technology development, and quantity of energy use.

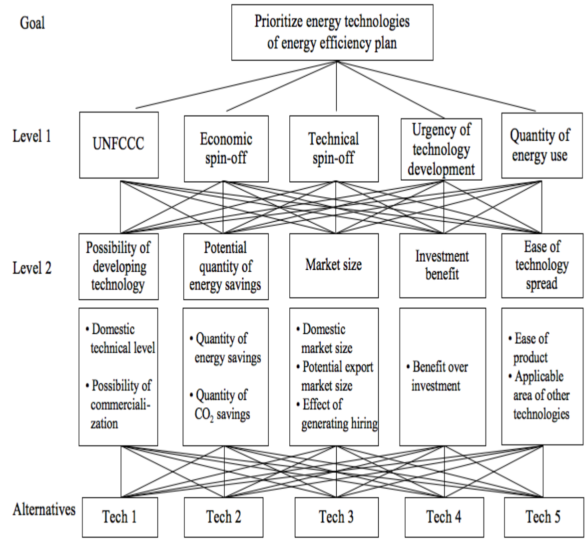

Fig. 3 AHP hierarchy structure

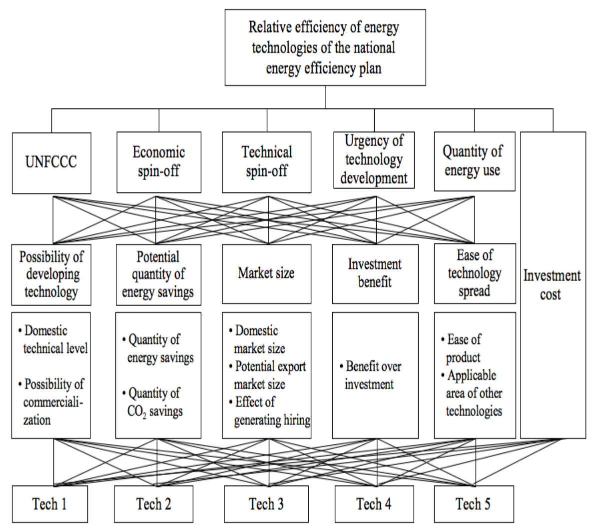

Fig. 4 Hierarchy structure using the DEA process

Meanwhile, Level 2 is composed of 5 sub-criteria: possibility of developing technologies, potential quantity of energy savings, market size, investment benefit, and ease of energy use.

C. DEA method

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 [5], insurance companies (Mahajan et al, 1991), hospitals [6], universities [7] and restaurants, but also to evaluate the efficiency of R&D programs [8].

Fig. 4 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 investment cost associated with the development of greenhouse gas technologies. There are five output factors, namely possibility of developing technology, potential quantity of energy savings, market size, investment benefit, and ease of technology spread; all of which are multiplied by the weights of the above-mentioned UNFCCC, economic spin-off, technical spin-off, urgency of technology development, and quantity of energy use. The relative weights calculated using the AHP approach, are thus applied in conjunction with the output factors employed as part of the DEA approach.

The DEA ration form, proposed by Charnes, Cooper and Rhodes (1978) [9], 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, …, n) denote the DMU whose relative efficiency or productivity is to be maximized.

$$Max\ \ h_k = \frac{\sum_{r=1}^{s} u_{rk} Y_{rk}}{\sum_{i=1}^{m} v_{ik} X_{ik}} \tag{4}$$

$$\text{s.t}\quad \frac{\sum_{r=1}^{s} u_{rk} Y_{rk}}{\sum_{i=1}^{m} v_{ik} X_{ik}} \le 1,\ for\ \ \mathrm{j} = 1,\dots,\mathrm{n} \tag{5}$$

$$u_{rk} > 0,\ \text{for } r = 1,\dots,s \tag{6}$$

$$v_{ik} > 0,\ \text{for } i = 1,\dots,m \tag{7}$$

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 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.

III. RESULTS

The AHP approach was employed herein to ascertain the relative weights of the criteria and alternatives that serve as the input and output values used to measure the efficiency of greenhouse gas technologies slated to be included in the national greenhouse gas plan using the DEA approach.

As shown in Table III, the use of the AHP approach resulted in multiple outputs and a single input. While possibility of developing technology, potential quantity of energy savings, market size, investment benefit, and ease of technology spread were the multiple outputs, investment cost was the single input used as part of the DEA approach. The unit of investment cost was million US dollars in 2006.

The results of the DEA approach are shown in Table IV.

TABLE IV
DEA EFFICIENCY SCORE

Technology	Efficiency score	Rank
CO2 capture storage and conversion tech	0.7534	2
Non-CO2 gas tech	1.0000	1
Advanced combustion tech	0.4411	7
Next-generation clean coal tech	0.2152	9
Clean petroleum and conversion tech	0.4264	8
DME tech	0.5692	4
GTL tech	0.6061	3
Gas hydrate	0.4724	6
GHG mitigation policy	0.4995	5

An efficiency score of 1.000 means that the pertinent DMU exhibits the highest efficiency, and that should be included in a more efficient frontier group than the other DMUs.

Non-CO2 gas technology thus constitutes the efficient frontier group with relative efficiency score one. This followed by CO2 capture storage and conversion technology, GTL technology, and DME technology.

TABLE III
INPUT AND OUTPUT DATA

Technology	Possibility of developing technology	Potential quantity of energy savings	Market size	Investment benefit	Ease of energy use	Investment cost
CO2 capture storage and conversion tech	0.212	0.213	0.207	0.166	0.185	157
Non-CO2 gas tech	0.105	0.104	0.110	0.151	0.132	58
Advanced combustion tech	0.068	0.049	0.080	0.093	0.083	94
Next-generation clean coal tech	0.101	0.106	0.109	0.107	0.102	272
Clean petroleum and conversion tech	0.073	0.069	0.061	0.059	0.064	94
DME [a] tech	0.087	0.084	0.074	0.075	0.084	84
GTL [b] tech	0.079	0.092	0.081	0.077	0.074	84
Gas hydrate	0.062	0.071	0.065	0.060	0.065	84
GHG [c] mitigation policy	0.042	0.042	0.042	0.042	0.042	47

[a] di-methyl ether
[b] gas to liquid
[c] greenhouse gas

The other 8 greenhouse technologies including policy were found to be inefficient.

IV. Discussion

This paper attempted to prioritize relative efficiency, or productivity, using the AHP and DEA hybrid model. This technique was used to apply overall efficiency scores to the greenhouse gas technologies included in the national greenhouse gas plan. The AHP is a powerful tool with which to decompose a complex problem into a simple hierarchical structure. Meanwhile, the DEA addresses many MCDM problems without being limited by multiple input and output units. While there are various DEA methods, we applied the output-oriented CCR model in order to measure the relative efficiency scores of greenhouse gas technologies.

V. Conclusion

This paper describes how to prioritize energy technologies within the national greenhouse gas plan using the AHP and DEA hybrid approach. This empirical illustration suggests that the greenhouse gas technologies can be efficiently weighted using MCDM methods. As a result of the application of the AHP/DEA approach, one greenhouse gas technology, namely Non-CO2 gas technology, was found to be more efficient than the other 8 greenhouse gas technologies. The merits of DEA, which is a non-parametric method, makes it such that this hybrid model can be used to efficiently compute the relative efficiency scores of greenhouse gas technologies.

This paper thus concludes that decision makers and policy makers in the energy sector can surmise that MCDM problems can be addressed using scientific procedures such as the AHP and the DEA hybrid model applied herein.

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