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Relative efficiency of energy technologies in the Korean mid-term strategic energy technology development plan

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ABSTRACT

Korea is vulnerable to oil price volatility due to its significant energy import dependence, which accounts for almost 97% of the primary energy consumption. Korea ranked eighth worldwide in terms of the volume of oil consumption in 2014 according to the BP statistical review 2015. Consequently, the best way to address the energy problem in Korea and enhance its national energy security is to implement a mid-term strategic energy technology development plan supported by the Korean Research Council for Public Science and Technology, along with well-focused research and development (R&D). We thus established a mid-term strategic energy technology development plan for the five years from 2007 to 2011, which serves as a guide for producing focused R&D outputs and outcomes, and provides a continuous energy technology development policy for coping with the significant government scientific and technology policy shift toward a world class research institute. This paper applies data envelopment analysis (DEA), a multi-criteria decision-making approach, to measure the relative efficiency of nine selected energy technologies included in the mid-term strategic energy technology development plan, from an economic viewpoint, from 2007 to 2008. As policymakers, we need to analyze and determine whether nine energy technologies have to be carried out continuously or not by considering the R&D performance of the nine selected energy technologies is competitive under limited R&D investment and resources. Using the DEA approach, energy technology R&D programs can be thus effectively assessed in relation to the relative efficiency of the nine selected energy technologies. Two core technologies, namely redox flow battery (RFB) and combined heat and power plant (CHP), need to enhance their R&D outputs and outcomes to become relatively efficient technologies from an economic viewpoint. The government and energy policymakers can re-evaluate their status and enhance any weak points towards strategically shifting to a world-class research institute within five years.

1. Introduction

Korea is one of the largest oil consumers worldwide, ranking eighth in oil utilization in 2014, when it consumed 273.2 million tons [1]. Fig. 1 shows the world primary energy consumption in 2014: China is the world's largest primary energy consuming nation, as a result of its rapid economic growth and expansion, followed by the U.S., Russia, and India in this order. The BRICs (Brazil, Russia, India, and China) are included in the top seven primary energy consuming countries, as their economic development required the heavy consumption of their energy resources. Japan, the fifth largest energy consuming nation, consumed 456.1 million Tonnes of Oil Equivalent (TOE) in 2014. Regarding Korea's primary oil consumption, its primary energy consumption is slightly larger than that of France. Additionally, 98% of the energy resources consumed by Korea are imported, making it vulnerable to oil price volatility. As a result, interest in the strategic and well-focused development of energy technologies has increased in Korea due to its large dependence on imported energy resources and limited research and development (R&D) budget. Korea is also facing the challenge of reducing greenhouse gas (GHG) emissions in observance of the United Nations Framework Convention on Climate Change (UNFCCC). The importance of this task is underscored not only by the fact that Korea is the ninth largest emitter of carbon dioxide worldwide, but also by that it registers the fastest rate of carbon dioxide emission increase.

Over the past decades, the Korean economy has demonstrated rapid growth, along with high-tech industrialization. The Korean government has faced the challenge of moving from catch-up to lead-up strategies in the R&D sector. The government has also attempted to solidify the

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Nomenclature

AHP	Analytic hierarchy process
B	R&D budget
CHP	Combined heat and power plant
D	Domestic
DEA	Data envelopment analysis
DMU	Decision making unit
DOE	Department of Energy
DSSC	Dye-sensitized solar cell
ETRM	Energy technology roadmap
F	Technology dissemination fee
HERC	Hydrogen energy R&D center
HR	Human resources
J	DMU reference set
KORP	Korean Research Council for Public Science and Technology
KRW	Korean won
N	Number
O	Overseas
PEMFC	Polymer electrolyte membrane fuel cell
RFB	Redox flow battery
SWOT	Strengths, weaknesses, opportunities, and threats
TD	Technology dissemination
TOE	Ton of Oil Equivalent

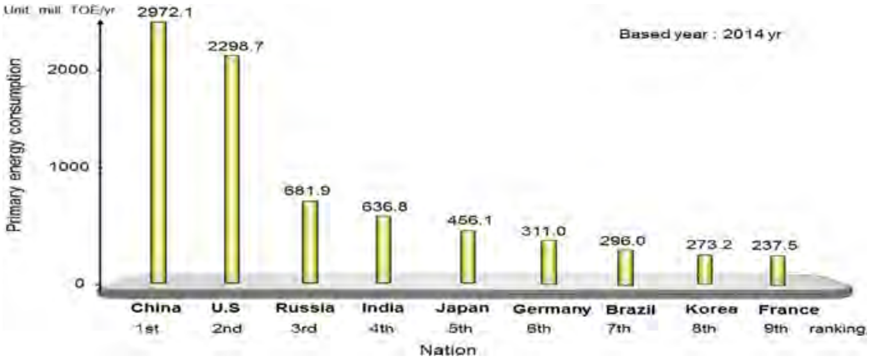

Fig. 1. World primary energy consumption according to BP 2015.

structure of sustainable development using strategic investment in the R&D sector. Specifically, the energy R&D sector is crucial to addressing national energy security, including global climate change issues and low-carbon green growth.

Moreover, Korea has been exerting significant efforts to ensure national energy security by diversifying its energy R&D programs and plans. As energy technology development is a crucial issue for energy security, Korea introduced various strategic national energy technology development plans for producing excellent outputs and outcomes through well-focused R&D.

In 1991, the Korean government established the five-year national energy conservation technology development plan for 1992–1996 with large energy saving potential [2,3]. It was included as part of the seventh five-year economic and social development plan.

In 1997, the 10-year energy technology development plan for 1997–2006 was launched with the scope of focusing on energy R&D projects of energy efficiency, alternative energy, and clean energy technology [4]. Specifically, 21 core energy programs were selected by their energy efficiency impact, improvement of energy supply and demand structure, technologies that lacked economic efficiency and were unlikely to expect voluntary participation by the private sector, and technologies that could minimize the environmental impact of energy use.

In 2005, the Korean government established the national energy technology development plan for 2006–2015 [5], which is significant because it is based on technological trees instead of R&D projects, giving rise to the establishment of the energy R&D technological trees with the consensus of experts in energy technology development and the policy sector. It is composed of five major sectors, namely energy efficiency, greenhouse gas, new and renewable energy, electrical power technology, and natural resource technology. This crucial plan also includes a technology roadmap for developing and acquiring core technologies in five major sectors until 2015.

In 2006, the Korea Institute of Energy Research (KIER), a government supported research institute for developing energy efficiency, greenhouse gas, new and renewable energies, and energy material technology, formulated an energy technology roadmap (ETRM) for the subsequent 10 years from the viewpoint of Korea's national energy technology and policy [6]. This program provides a direction for the national energy policy, beginning with the analysis of the world energy outlook. Moreover, the ETRM focuses on the development of energy technologies, while taking into account the aspects of the Korean energy environment, because the Korean government focused on producing excellent R&D outcomes and on government sponsored research institutes becoming world-class institutes within five years [7].

In 2008, President Lee's government introduced low-carbon and green growth as the national agenda within the transition towards becoming a global leader of green economic growth [8]. The Basic Energy Law was enacted for the implementation of the First National Basic Energy Plan, which is to provide future-oriented energy policy direction every five years until 2030 [9,10]. It mainly covers energy security, energy supply and management, supply and use of environmentally friendly energies, the reduction of greenhouse gas emissions, and safe management of energy.

Consequently, our study employs data envelopment analysis (DEA) to analyze the relative efficiency of nine strategic energy technologies for the mid-term strategic energy technology development plan because KIER, as a government sponsored research institute, requires to shift toward a world-class energy research institute in order to cope with the Korean government's science and technology policy direction through well-focused R&D programs. Additionally, energy policymakers need to recheck the portfolio of the mid-term strategic energy technology development plan by measuring the relative efficiency of R&D from an economic viewpoint. The plan comprises five major sectors, namely, energy efficiency, synfuel oil production, carbon capture and storage (CCS), renewable energy, and hydrogen infra-fuel cells.

In other words, the mid-term strategic energy technology development plan aims to produce world-class R&D outcomes within five years in terms of energy R&D technologies that manage the Korean energy environments flexibly and enhance national energy security. It focuses on the econometric viewpoint of the nine energy technologies from the mid-term strategic energy technology development plan. The results obtained using the DEA approach provide energy policymakers with an effective decision-making tool and key policy data. KIER is responsible for creating the strategic energy technology development plan and producing focused R&D outcomes, including a national energy policy. Therefore, the results will also present econometric efficiency for energy technology development from an economic viewpoint.

The remainder of this paper is structured as follows. Section 2 describes the execution flow of our research. Section 3 presents the methodology and introduces the DEA approach. Section 4 presents the discussions, including the classification of energy technologies, technological targets, and sensitivity analysis. Section 5 states concluding remarks.

2. Execution flow chart

2.1. Execution flow chart

The execution flow chart is composed of six phases for measuring the relative efficiency of the five-year mid-term strategic energy technology development plan for 2007–2011. Fig. 2 shows the flow chart of the execution scheme.

In the first phase, the Korean national agenda is analyzed based on a basic plan of science and technology and the 10-year energy and resource plan for 2006–2015 [5]. In the second phase, the core agenda of Korea Research Council of Public Science and Technology (KORP) is being reflected [7], with emphasis on the KIER management aims and ETRM [6]. The KORP core agenda is composed of five topics. The first aims to develop energy technologies for national energy security, enhance national competition, and upgrade the research outputs and quality towards a world-class research institute. The second develops energy technologies for securing national energy resources and their efficient utilization. The third topic focuses on securing a new growth engine for sustainable development in society. The fourth topic is to develop environment-friendly energy technologies for improving health and well-being. The last topic aims to develop energy technologies for creating a new and high value-added industry. The KORP core agenda thus reflects upon and considers the key issues of energy security, environment, and energy technology commercialization. This study analyzes and considers overseas cases of energy technology development trends, policies, and strategic plans, which include the International Energy Agency (IEA) 2006 energy technology perspectives, U.S.'s Department of Energy (DOE) ETRM, New Energy and Industrial Technology Development Organization (NEDO) new sunshine program, and EU framework program. Considering energy technologies and the results of the first and second phases, the third phase focuses on the three upper R&D sectors, namely, accounting for high oil prices, UNFCCC, and hydrogen economy. This study analyzes the five strategic sectors, including nine strategic energy technologies, through SWOT analysis. In the fourth phase, six criteria are shortlisted and the hierarchy structure established. In the fifth phase, the quantitative multiple inputs and outputs for the assessment of nine energy technologies are analyzed using the DEA approach. Two inputs and four outputs are considered for the mid-term strategic energy technology development plan. In the sixth phase, the relative efficiency of nine energy technologies is assessed and the relative efficiency score analyzed using the ratio of outputs over inputs.

3. DEA approach

3.1. Hierarchy of the DEA approach

There are six criteria for Level 1, namely, R&D budget, human resources, patent applications, patent registration, SCI paper, and technology dissemination. Meanwhile, Level 2 is composed of eight sub-criteria, namely, numbers of domestic and overseas patent applications, domestic and overseas patent registrations, domestic and overseas SCI papers, as well as numbers and fees of technology dissemination. Fig. 3 shows the hierarchy of the DEA approach.

3.2. Data envelopment analysis

The DEA is a scientific decision technique and a multi-criteria decision-making method used to measure the relative efficiency of decision making units (DMUs) through the weight limitation of multiple inputs and outputs. The DEA also is a linear programming-based method for measuring the relative efficiency and performance of DMUs.

It measures R&D performance, service industry, and other variable sectors providing the relative efficiency scores of DMUs. Specifically, it can be applied to measure the relative efficiency of R&D programs and technology development portfolio plans for assessing R&D outputs over inputs. The DEA can easily measure and handle multiple inputs and outputs from an economic viewpoint, and measures relative efficiency values by the ratio of outputs over inputs.

Since 1978, the DEA approach has been used in a wide range of applications, including the service productivity assessment of banks, insurance companies, hospitals, and restaurants [11–13]. It has also been widely applied in assessing the efficiency of R&D programs in terms of energy technology development, including energy efficiency and greenhouse gas sectors [14–18]. Additionally, hydrogen energy technology portfolios measured the relative efficiency of R&D performance and productivity in the hydrogen R&D sector from an econometric viewpoint [19], with the input variables of R&D budget allocations and human resources. The outputs consist of the numbers of patents, papers, and technology dissemination as key variables related to the development of energy technologies.

The DEA ratio form was first proposed by Charnes et al. [20], and was designed to measure the relative efficiency or productivity of a specific DMU$_k$. The DEA formulation is given as follows. Assume 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 as represented by:

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

$$s.t \quad \frac{\sum_{r=1}^{s} u_{rk} Y_{rk}}{\sum_{i=1}^{m} v_{ik} X_{ik}} \quad \leq \quad 1, for \quad j = 1, ..., n, \tag{2}$$

$$u_{rk} > 0, \quad \text{for } r = 1, \ldots, s, \tag{3}$$

$$v_{ik} > 0, \quad \text{for } i = 1, \ldots, m, \tag{4}$$

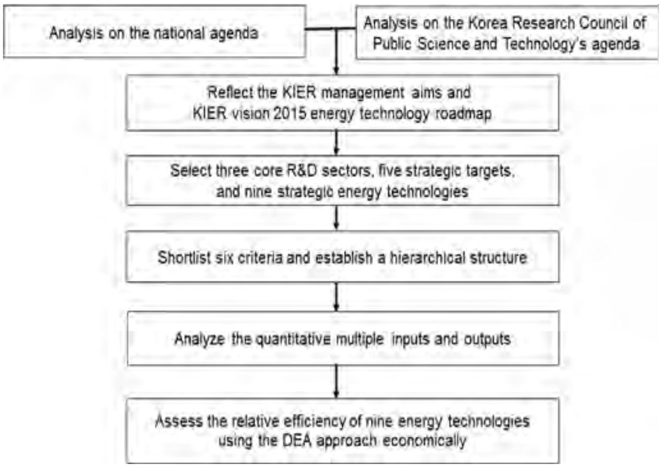

Fig. 2. Execution flow chart.

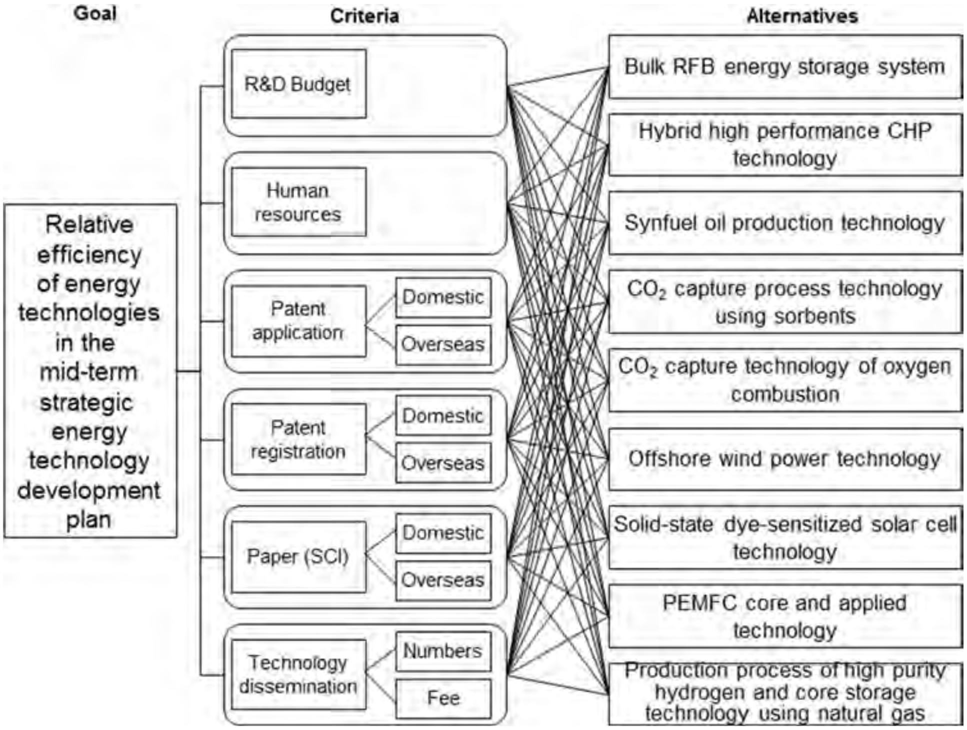

Fig. 3. Hierarchy of the DEA approach.

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 the 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, and is less than or equal to 1. When the efficiency score h_k takes the value 1, DMU$_k$ is regarded as an efficient frontier.

Eqs. (1) and (2) can be transformed into (5) and (6). Here, the total number of DMUs is nine, indicating the nine energy technologies of the mid-term strategic energy technology development plan.

$$Max\ \ \mathrm{h_k} = \frac{u_{1k}Y_{1k} + u_{2k}Y_{2k} + u_{3k}Y_{3k} + ...+u_{sk}Y_{sk}}{v_{1k}X_{1k} + v_{2k}X_{2k} + v_{3k}X_{3k}....+v_{mk}X_{mk}}, \tag{5}$$

$$s.\ t\quad \frac{u_{1k}Y_{1k} + u_{2k}Y_{2k} + u_{3k}Y_{3k} + ...+u_{sk}Y_{sk}}{v_{1k}X_{1k} + v_{2k}X_{2k} + v_{3k}X_{3k}....+v_{mk}X_{mk}} \quad \leq \quad 1, for \quad \mathrm{j} = 1, ..., \mathrm{n}, \tag{6}$$

$$u_{rk} > 0, \quad \text{for} \quad r = 1, \ ..., s \tag{7}$$

$$v_{ik} > 0, \quad \text{for} \quad i = 1, \ ..., m. \tag{8}$$

There are two types of CCR models. One is the input-oriented model, in which inputs are maximized, while the other is the output-oriented model, in which the outputs are maximized. Given that the focus is on maximizing multiple outputs, this paper uses the following output-oriented CCR model:

$$\min\ px_0 \tag{9}$$

$$\text{s.t} \quad qy_0 \ \ = 1 \tag{10}$$

$$-\ pX + qY \leq 0 \tag{11}$$

$$p \geq 0,\ q \geq 0 \tag{12}$$

where x_o and y_o are the input and output vectors of DMU$_o$. In (10), the X and Y variables refer to matrices of inputs and outputs, respectively. Let an optimal solution of LP$_o$, which stands for the linear programming, be (v*, u*). The optimal solution of the output-oriented model is obtained from

$$p^* = v^*/\theta^*,\ \mathrm{q}^* = \mathrm{u}^*/\theta^* \tag{13}$$

It is clear that (p*, q*) is feasible for LP$_o$, which stands for the linear programming. θ^* is the optimal efficiency value of DMU$_o$. DMUs for which $\theta^* < 1$ are inefficient, while DMUs for which $\theta^* = 1$ are efficient and also boundary values. The optimal solution is Eq. (14):

$$p^*\mathrm{x}_0 = v^*\mathrm{x}_0\ /\theta^* = \eta^* \tag{14}$$

$$\hat{\mathrm{x}}_0 = \mathrm{x}_0 - \mathrm{t}^{-*} \tag{15}$$

$$\hat{y}_0 = \eta^*\mathrm{y}_0 + \mathrm{t}^{+*} \tag{16}$$

where t-* and t+* are the slack variables of inputs and outputs related to DMU$_0$.

4. Results and discussion

4.1. Classification and technological targets for the mid-term strategic energy technology development plan

The mid-term strategic energy technology development plan fosters and produces world-class R&D outcomes within five years, particularly from 2007 until 2011, with the support of KORP and KIER. The five sectors of mid-term strategic energy technology development plan are closely related to three upper main sectors, namely, high oil prices, UNFCCC, and hydrogen economy that account for the KIER 10-year ETRM of 2006–2015.

High oil prices focus on developing conversion technologies for coal and waste, aiming to increase energy efficiency by 10% by 2012. The high oil prices are linked to the lower strategic sectors of energy efficiency and synfuel oil production. The UNFCCC is to foster the expansion of new and renewable energy ratios in the power generation sector by 20% in 2030 as the Korean government's goal. The UNFCCC is directly and indirectly combined with five lower sectors, namely energy efficiency, synfuel oil production, carbon capture and storage, renewable energy, and hydrogen infra-fuel cells. The hydrogen economy sector fosters the development of low-cost hydrogen production within the economy. Hydrogen energy technology could be one of the best future energy sources considering the Korean energy environment. It also considers the commercialization and dissemination of hydrogen infra-fuel cells for coping with the potential reduction of GHGs under UNFCCC. It is connected to hydrogen infra-fuel cells.

Fig. 4 describes the technical positions of the nine strategic energy technologies, considering the inner capacity and growth potential of the market. Additionally, the four energy technologies, including synfuel oil production, offshore wind power, PEMFC, and hydrogen production technologies, are classified with top-brand technologies, which KORP and KIER have been focusing on prior to their preoccupation with the future energy market and production of world-class outputs.

Table 1 shows the nine energy technologies in the mid-term strategic energy technology development plan.

Table 1
Nine energy technologies in the mid-term strategic energy technology development plan.

Sector	Energy technology
Energy efficiency	– Bulk redox flow battery energy storage system (RFB)
	– Hybrid high-performance combined heat and power plant technology (CHP)
Synfuel oil production	– Synfuel oil production technology (Synfuel)
CCS	– CO_2 capture process technology using sorbents (CO_2_sorbent)
	– CO_2 Capture technology of oxygen combustion (CO_2_OC)
Renewable energy	– Offshore wind power technology (OW)
	– Solid-state dye-sensitized solar cell technology (DSSC)
Hydrogen infra-fuel cell	– PEMFC core and applied technology (PEMFC)
	– Production process of high purity hydrogen and core storage technology using natural gas (HPHS)

The bulk RFB energy storage system (RFB) technology targeted 70% energy efficiency, a 50-kW power rating, and an 800-W life cycle in 2011, which are improved from the 55% energy efficiency, 500 W power rating, and zero lifecycle in 2006. Hybrid high-performance CHP technology (CHP) will accomplish 40% power generation efficiency and 85% cogeneration efficiency in 2011. There are no technical data on the status of CHP in 2006, since KIER begun developing CHP recently. Synfuel oil production (Synfuel) technology is targeted to develop a localized production process technology of coal to liquid, which can produce five barrels per day using the Coal to Liquid (CTL) process. The latest data show that, in 2006, production was only at 0.01 barrels per day. The 2011 target involving the use of a CO_2 capture process technology with sorbent (CO_2_sorbent) technology represents an over 80% CO_2 removal rate, over 90% regeneration efficiency, and 60 USD/ton of CO_2 capture cost using dry sorbents. In 2006, CO_2_sorbent technology was developing a 100 Nm^3-sized second-floor fluidized bed process. The 2011 target for CO_2 capture technology of oxygen combustion (CO_2_OC) is the commercialization of an oxy-fuel combustion furnace of the 10 t/charge batch type and 100 t/day continuous type. In 2006, CO_2_OC acquired oxy-fuel combustion technology with a 10-ton-steel/charge furnace and a burner with a size of 0.5 MW. Offshore wind power technology (OW) in 2011 acquired core technologies for mid- and large-sized blade designs with system integration and control algorithm development technologies. OW achieved a 70–80% technological status compared with the advanced nations. Solid-state dye-sensitized solar cell technology (DSSC) was targeted to have unit cell efficiency of over 13% and over 8% sub-module efficiency in 2011. The targeted unit cell efficiency is better than the 5% unit cell efficiency registered in 2006. The target related to PEMFC core and applied technology (PEMFC) in 2011 was the development of a low-cost and high-durability membrane electrode assembly with the highest level of PEMFC. The status of membrane electrode assembly in 2006 was a platinum loading amount of 0.9 mg/cm^2 platinum loading with 1000-h durability. The target related to the production process of high purity hydrogen and core storage technology using natural gas (HPHS) is the

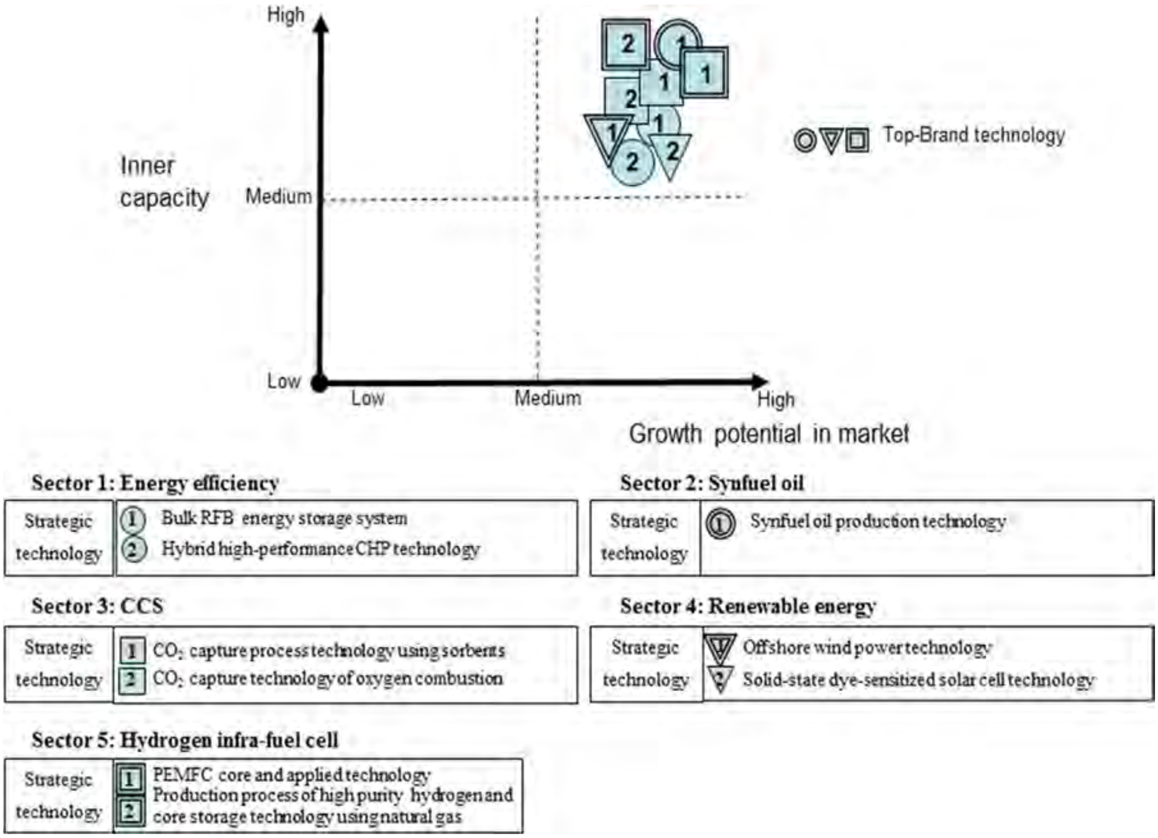

Fig. 4. Technical positions of the nine strategic energy technologies.

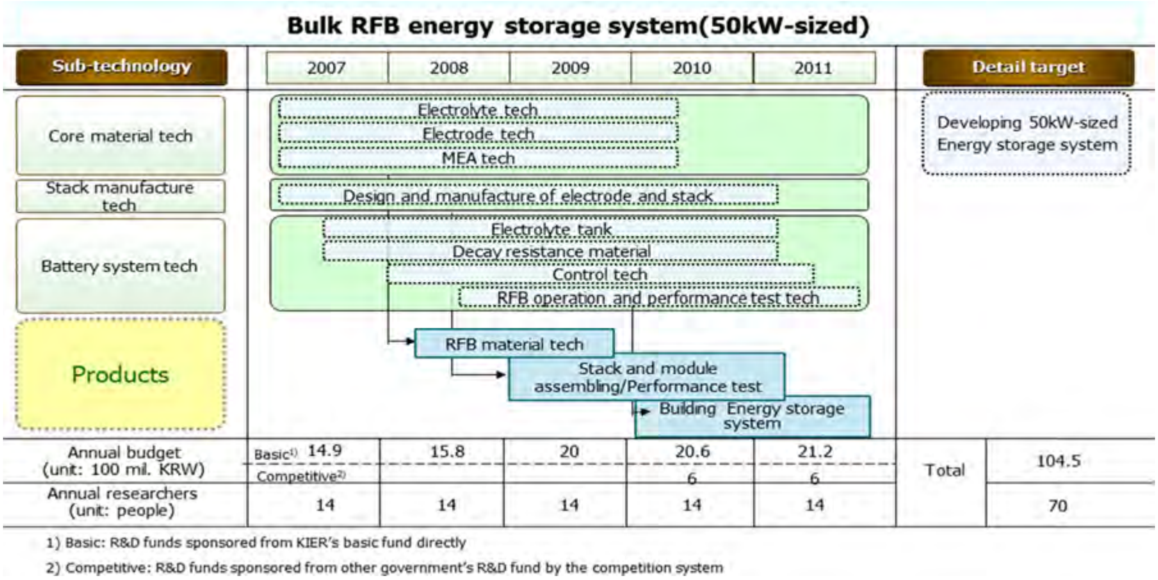

Fig. 5. ETRM of bulk RFB energy storage system.

development of high-purity hydrogen production technology with over 75% natural gas steam reforming efficiency and 6 wt% hydrogen storage capacity, compared with the current 70% natural gas steam reforming efficiency and 2 wt% hydrogen storage capacity.

The ETRM was established from 2007 to 2011 for nine energy technologies in the mid-term strategic energy technology development. As a result, nine ETRMs for guiding innovation in energy technology development are identified. ETRM includes the sub-technology, products, detail targets for each sub-technology, annual budget, and number of researchers. ETRM of the bulk RFB energy storage system technology is shown in Fig. 5 as composed of three sub-technologies, namely core material technology, stack manufacture technology, and battery system technology.

The ETRM of synfuel oil production technology is shown in Fig. 6. It accounts for F/T synfuel process localization and coal gasifier and gas purification technology.

The ETRM of the CO_2 capture process technology using sorbents, shown in Fig. 7, is composed of the CO_2 capture process with wet and dry sorbents.

Regarding the renewable energy sector, the offshore wind power technology's ETRM, including wind power control, blade, and complex, is shown in Fig. 8.

The ETRM of PEMFC technology, which is composed of PEMFC core technology and fuel cell integration and applied technology, is shown in Fig. 9.

4.2. Relative efficiency of energy technologies

As shown in Table 2, there are two multiple inputs and three multiple outputs for measuring the relative efficiency of the nine energy technologies in the mid-term strategic energy technology development plan with the use of DEA.

Here, the outputs and inputs are classified for the application of the DEA approach. Outputs are composed of three major variables, namely, patent application, patent registration, and paper, with the numbers of the domestic and overseas cases. Inputs account for two major variables: R&D budgets and human resources. The datasets from 2007 to 2008 are used to measure the relative efficiency scores of the nine energy technologies in the mid-term strategic energy technology development plan. Offshore wind technology is allotted the largest budget

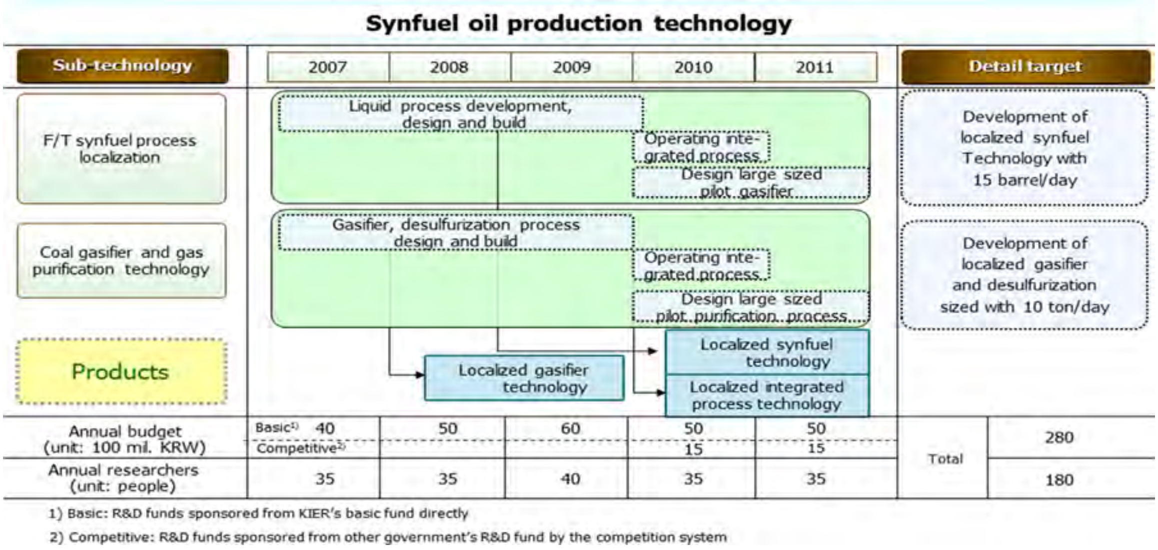

Fig. 6. ETRM of synfuel oil production technology.

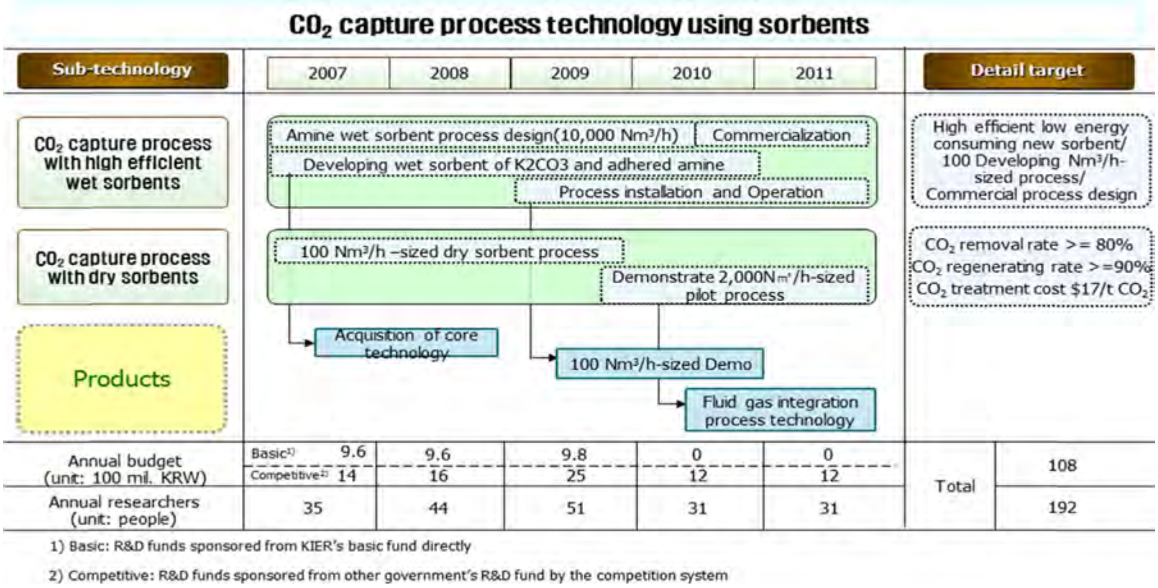

Fig. 7. ETRM of CO_2 capture process technology using sorbents.

due to the construction of an offshore wind farm with capacity for 4 MW wind turbines. Synfuel oil production and solid-state DSSC are allotted the largest amounts of human resources. The CO_2 capture process technology using sorbents produces the largest domestic patent applications. Synfuel oil production and solid-state DSSC produce the largest overseas patent application. Related to the domestic patent registration, the CO_2 capture process technology using sorbents provides the most applications. Overseas patent registration is overall lower than all other criteria. Offshore wind produces the most domestic paper publications, while PEMFC the most overseas ones. The CO_2 capture technology involving oxygen combustion is the greatest technology dissemination outcome.

Table 3 displays the relative efficiency of the nine energy technologies in the mid-term strategic energy technology development plan, using the DEA approach. Seven energy technologies, namely, synfuel, CO_2_sorbent, CO_2_OC, OW, DSSC, PEMFC, and HPHS, resulted in an efficient frontier group that had a maximum efficient score using cumulated performance data from 2007 to 2008. These seven energy technologies are the most competitive and effective, followed by the bulk RFB energy storage system and the hybrid high performance CHP technology. The above seven energy technologies are much more efficient than the last two.

Regarding the energy policymakers and decision makers considering the limitations of R&D budgets and the urgency of producing advanced outcomes for becoming a world-class research institute, energy policymakers have to exclude RFB and CHP technologies from the mid-term strategic energy technology development plan because they must determine whether the current Korean strategic mid-term energy technology development plan should be carried out or not as planned. In addition, although the Korean mid-term energy technology

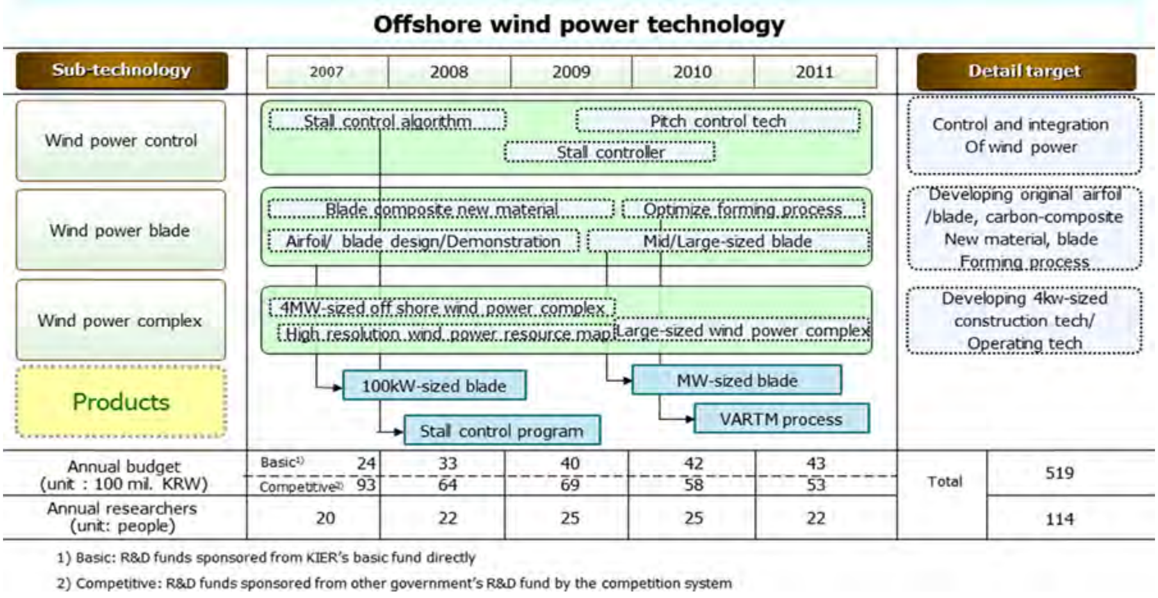

Fig. 8. ETRM of offshore wind power technology.

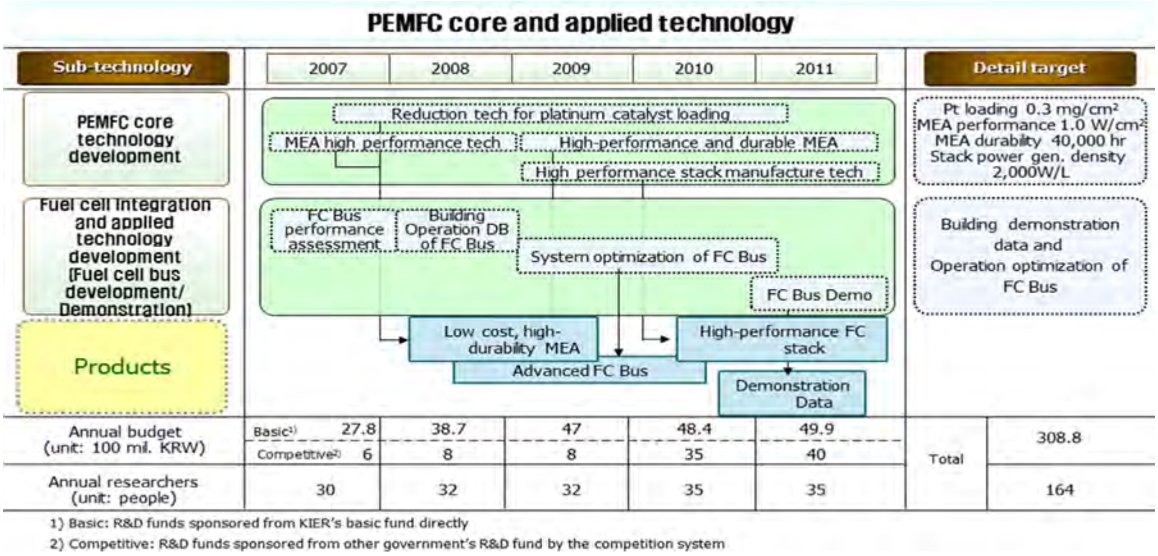

Fig. 9. ETRM of PEMFC technology.

Table 2

Multiple inputs and outputs of the nine energy technologies.

Energy technology	B (100 mil. KRW)	HR	Patent application		Patent registration		Paper		TD	
			D	O	D	O	D	O	N	F
RFB	30.7	28	3	0	1	0	0	2	0	0
CHP	26.8	50	2	0	1	0	2	1	0	0
Synfuel	90	70	7	3	0	0	0	5	0	0
CO_2_sorbent	33.2	51	11	1	6	0	0	9	0	0
CO_2_OC	22	55	4	1	0	0	4	4	2	3
Offshore wind	214	42	7	2	4	1	22	2	0	0
DSSC	48	70	5	3	3	1	6	4	1	1
PEMFC	80.5	62	6	2	4	0	0	9	0	0
HPHS	25.8	58	5	2	3	2	0	8	0	0

*B: budget, HR: human resources, D: domestic, O: overseas, TD: technology dissemination, N: number, F: fee.

development plan for 5 years is implemented, Korean strategic energy technology development plan can be easily changed due to the R&D budget limitations and short-term performance-oriented energy policy. If some energy technologies are not relative efficient with the Korean R&D budget limitations, they have to be considered whether to conduct or not. On the other hand, if they wish to maintain the development of the nine selected energy technologies, they have to enhance the outputs of both RFB and CHP technologies to be efficient.

4.3. Sensitivity analysis

This study executes a sensitivity analysis of RFB and CHP technologies by changing the output variables. Sensitivity analysis includes three scenario cases, namely the change of the numbers of oversea patent, papers, and technology transfer related to RFB and CHP technologies. Case 1 focuses on the change in the number of overseas patent registrations for RFB and CHP technologies. Case 2 shows the scenario changing the numbers of overseas publications, which is a science citation paper (SCI). Case 3 describes the changing of the numbers of technology transfer. Fig. 10 shows RFB and CHP can reach the efficient technologies like the other seven energy technologies and describes three scenarios of changing output variables related to RFB and CHP technologies.

Table 3

DEA efficiency score and rank.

Energy tech	Efficiency score	Rank	Energy tech	Efficiency score	Rank
RFB	0.4968	9	OW	1.0000	1
CHP	0.6001	8	DSSC	1.0000	1
Synfuel	1.0000	1	PEMFC	1.0000	1
CO_2_sorbent	1.0000	1	HPHS	1.0000	1
CO_2_OC	1.0000	1			

In case 1, increasing one and two overseas patents related to RFB and CHP technologies can be the relative efficiency of their R&D status included the efficiency group with efficiency score 1 like the other seven energy technologies. In case 2, by changing the overseas papers to six and seven overseas papers in RFB and CHP these two technologies can achieve the relative efficiency of their R&D status. For case 3, by increasing by one and two the numbers of technology disseminations of RFB and CHP technologies, they can be the efficient group with efficiency score 1. As a result, energy policy makers can determine whether to continue to develop RFB and CHP technologies through sensitivity analysis, taking into account the R&D budget limitations.

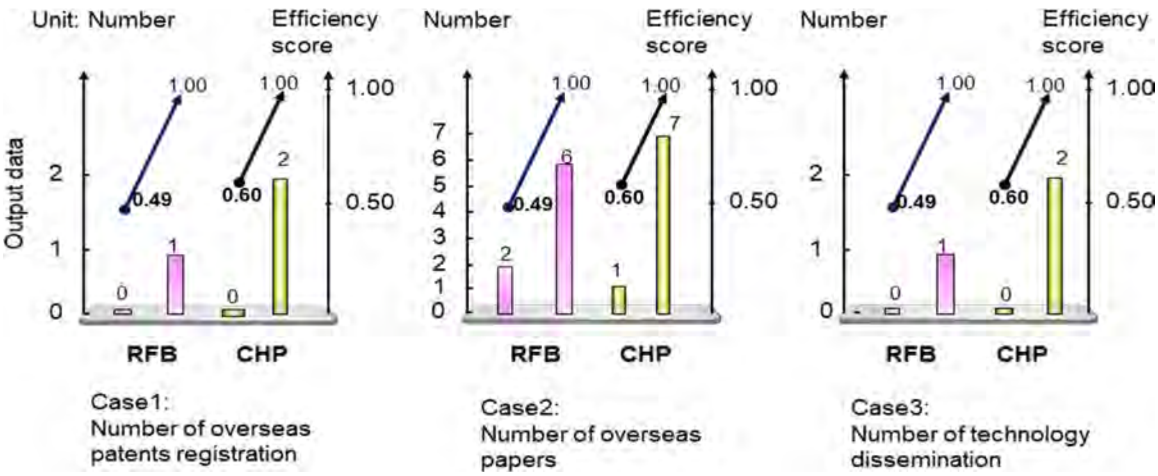

Fig. 10. Efficiency scores of RFB and CHP obtained through changing outputs.

5. Conclusion

The mid-term strategic energy technology development plan was launched by the Korean government, targeting a well-focused R&D performance and creating a world-class research institute within five years. We focused on analyzing the relative efficiency of nine selected energy technologies in the mid-term strategic energy technology development plan for determining whether the current Korean mid-term strategic energy technology development plan should be carried out continuously as plan with the R&D limitation. Before we carry out the third year plan of it with the limited R&D budgets, Korean policymakers have to measure the relative efficiency of the nine energy technologies whether the R&D status of the selected nine energy technologies is on the efficiency frontier group or not and enhance the weak points of them. We applied DEA to measure the relative efficiency of the nine selected energy technologies considering R&D budget limitations, R&D outputs and outcomes. As a result, seven energy technologies, that us, synfuel oil production technology, CO_2 capture process technology using sorbents, CO_2 capture technology of oxygen combustion, offshore wind power technology, solid-state DSSC technology, PEMFC core, and applied technology and production processes of high purity hydrogen, and core storage technology using natural gas were included in the efficient frontier group regarding the production of efficient outputs and outcomes in view of the mid-term strategic energy technology development plan.

On the other hand, the status of RFB and CHP technologies must be re-evaluated in terms of their performance to produce more competitive outputs and outcomes comparing with the other seven technologies. This can be done by changing the outputs and outcomes, including the numbers of overseas patent registrations, overseas papers, and technology dissemination in terms of RFB and CHP technologies. Sensitivity analysis shows that the increase in the quantity of overseas patents, papers, and technology transfers by changing one and two of them can move them to the efficiency group. For the mid-term strategic energy technology development plan with limited R&D budget and resources, energy policymakers can assess the relative efficiency of energy technologies considering the R&D investment fund. If they have to maintain the nine selected energy technologies for five years in the mid-term strategic energy technology development plan as planned, RFB and CHP technologies have to enhance their outcomes and outputs, respectively. Additionally, the government and policymakers also have to focus on expanding the investment and stable R&D environment for producing more outputs and outcomes in view of the mid-term strategic energy technology development plan. If the government and energy policy makers have to decrease the number of R&D programs in the mid-term strategic energy technology development plan, RFB and CHP technologies should be excluded from the plan according to the results of the DEA analysis. If perhaps RFB and CHP technologies are to be continuously developed, their outputs should be enhanced in terms of producing more overseas patent registrations, overseas papers, and amount of technology dissemination.

Although this study is analyzed and measured the relative efficiency of the R&D performance of the nine selected energy technologies in the mid-term strategic energy technology development plan for 5 year from 2007 to 2011 with the limited inputs and outputs, the research results can provide domestic and overseas energy policymakers with the fundamental decision making data with the limitations of R&D budget and resource when they implement a mid-term strategic energy technology development plan and determine whether it has to be carried out or not at midpoint of the entire planning period. Our results are calculated using the scientific procedure of multi-criteria decision-making. Moreover, these results can also offer optimal alternatives to policymakers in the creation and establishment of sound energy policies.

In future studies, we will carry out research using an integrated AHP or fuzzy AHP/DEA model with scale efficiency to allocate relative weights to the criteria in the first stage [21–23], while the second stage would include and more precisely measure relative efficiency to reflect the relative weights of the criteria.

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Appendix A

The excel data set of input and output variables is described as follows:

	(I) Budget	(I) Human resources	(O)Patent application-domestic	(O)Patent application-overseas	(O)Patent registration-domestic	(O)Patent registration-overseas	(O)Paper-domestic	(O) Paper-overseas	(O)Technology dissemination number	(O)Technology dissemination fee
Bulk redox flow battery energy storage system (RFB)	30.7	28	3	0	1	0	0	2	0	0
Hybrid high-performance combined heat and power plant technology (CHP)	26.8	50	2	0	1	0	2	1	0	0
Synfuel oil production technology (Synfuel)	90	70	7	3	0	0	0	5	0	0
CO2 capture process technology using sorbents (CO2_sorbent)	33.2	51	11	1	6	0	0	9	0	0
CO2 Capture technology of oxygen combustion (CO2_OC)	22	55	4	1	0	0	4	4	2	3
Offshore wind power technology (OW)	214	42	7	2	4	1	22	2	0	0
Solid-state dye-sensitized solar cell technology (DSSC)	48	70	5	3	3	1	6	4	1	1
PEMFC core and applied technology (PEMFC)	80.5	62	6	2	4	0	0	9	0	0
Production process of high purity hydrogen and core storage technology using natural gas (HPHS)	25.8	58	5	2	3	2	0	8	0	0

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