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Efficiency Analysis of R&D Productivity within the Korean Renewable Energy Technology Sector

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ABSTRACT In Korea, the bulk of investment in research and development within the renewable energy sector is channeled towards technologies which are close to commercialization. In addition, the majority of financial support from government agencies reflects an investment in firms, rather than universities or small firms. However, the performance, in terms of market share and price competitiveness, of Korean renewable energy technology is still very low in the overseas market. There remains a greater amount of R&D investment is received by large firms rather than smaller firms. However, it has not been shown that the R&D efficiency of larger firms is greater than that of smaller firms.

The paper estimates that a productivity of 1340 R&D projects from 2008 to 2012 in renewable energy technology by performers and by technical progress phase using output-oriented BCC modelling in Data Envelopment Analysis (DEA). The results reveal that the efficiency of basic R&D research is higher in universities and institutes, while the efficiency achieved in applied research is higher within larger firms. However, the efficiencies achieved in development research is low in general, regardless of whether the R&D is carried out in a large firm, smaller form or university.

Key words Korea, New and Renewable energy, R&D Productivity, Efficiency frontier, Data Envelopment Analysis (DEA)

1. Introduction

A policy of support for renewable energies was firstly introduced in the “Alternative Energy Development Promotion Act” in 1987 in light of concerns over Korea’s energy security as a country that depends highly on imported fossil fuels and various environmental problems due to climate change. The support has been strengthened as of the “2nd act on the promotion of development, use and diffusion of new and renewable energy” implemented in 2003. This occurred again in 2008, when “Low Carbon and Green Growth” was proclaimed as the nation’s vision to lead development during the next 50 years and the “National Strategy for Green Growth” was announced to mitigate climate change, to create new engines for economic growth, and to improve the quality of life. The renewable energy support policies are classified largely into “research and development (R&D)”, “diffusion”, and “industry promotion” and this paper particularly focuses on the R&D fields.

1.1 Korea renewable energy technology R&D

The first legal effort into technology development in renewables was discovered in 1987, enacting “Alternative

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Energy Development Promotion Act" to carry forward renewables' technology development as well as start commercializing and diffusing solar-thermal and waste energies after oil crises occurred twice in the 1970s. Currently, the government specifies eight renewable energies (photovoltaic, solar-thermal, wind energy, bioenergy [including combustible renewables], ocean energy, geothermal, hydropower, and wastes [including industrial waste]) and three new energies (fuel cell, hydrogen, and integrated gasification combined cycle (IGCC; hereafter, referred to as renewable energy]) to promote based on the "Act on the promotion of development, use and diffusion of new and renewable energy" since 1997, and the act has been revised three times until now. The current 4th act, announced in September 2014, is aiming at increasing the use of renewable energies to 11% of total primary energy supply (TPES).

Financial support for R&D activities in renewables has been given since 1988, and its total R&D investment combined by government and private sectors until 2013 is KRW 3.71 trillion (USD 3.71 billion if USD 1 = KRW 1,000), which increased especially sharply in the last decade from 2004 to 2013 at a 25% average annual growth rate. The support in 2010 and 2011 accounted for 6.07% and 4.92% respectively out of IEA countries' renewable energy R&D expenditure.[1,2] Despite the current bold renewable energy R&D investment policy, absolute total investment during the last few decades is regarded as far behind those of other countries like the United States, Germany, France, Japan, and the United Kingdom.

The R&D tasks are strategically divided into short-term tasks for technologies with potential to be commercialized in the near future and medium- and long-term tasks performed in order to acquire future core technology. In the short-term tasks, the pragmatic technologies, like photovoltaic (PV), wind energy, and fuel cell, which can be utilized for current early diffusion by lowering electricity generation cost, supporting commercialization and overseas market expansion, and linking R&D with diffusion policy, are subjected preferentially to a heavy investment. PV received the most R&D investment among the eleven renewable energies both in number of projects and in amount of financial investment: 275 projects accounting for KRW 777.2 billion in R&D investment for new and continuous projects. Fuel cell and wind power are the next, representing 120 and 127 new projects, respectively, and KRW 747.38 billion and KRW 513.36 billion, respectively, in R&D investment for new and continuous projects.[3] These three energies, which are designated as priority supporting energies, account for 54.95% of total renewable R&D investment.

R&D activity can be also classified according to performer (university, research institute, and large and smaller firm) or its technical progress phases (basic, applied, and development). By technical progress phase, as shown in Fig. 1, 759 new and continuous R&D projects took place on development phase, which accounts for nearly 70% of total R&D projects, gaining the most financial support, of KRW 556,431.7 million, between 2008–2012.[4] The research on the development

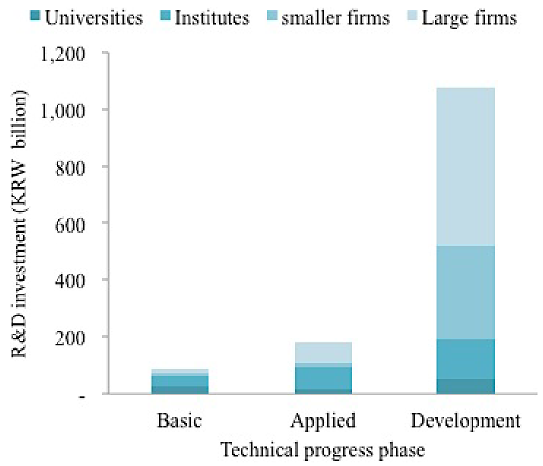

Fig. 1. Renewable energy R&D support by technical progress phase from 2008–2012 (Source; NTIS www.ntis.go.kr)

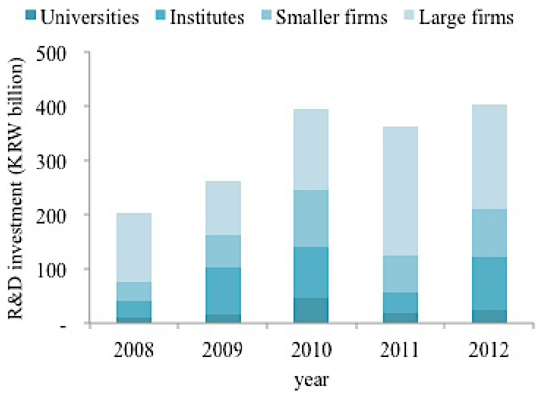

Fig. 2. Renewable energy R&D support by perfroermes from 2008–2012 (Source; NTIS www.ntis.go.kr)

phase was mostly carried out by large and smaller firms and basic and applied researches by universities and institutes.

Fig. 2. shows a trend in R&D investment from 2008–2012 by performer, and the large firms are taking the most advantage of R&D investment among beneficiaries, representing nearly half of the R&D of KRW 243,223.38 (54.01%) from 2008 to 2012, while others like smaller firms, institutes, and universities received KRW 147,461.80 (32.75%), KRW 43,313.50 (9.62%), and KRW 16,311.64 (3.62%) respectively during the same period.[5]1)

While public R&D investment in renewable energy technology has decreased in recent years, with KRW 277,304 million in 2012, KRW 271,963 million in 2013, and KRW 249,305 million in 2014,[6] the investment trend in terms of average amount per project is getting larger, and considerable R&D investment is still being delivered into large firms whose research is mainly big and on the development phase that can generate economical profits in the short term and focus on a system field that includes activities such as standardization, planning, demonstration, operation, performance evaluation, and so on.

In this context, the approach of delivering heavy investment to large firms may need to be reconsidered. As firms grow large, efficiency in R&D is weakened due to the loss of managerial control or excessive bureaucratic control as well as the incentives of individual researchers being weakened due to decreasing their ability to capture the benefits from their individual efforts or conservative characteristics of the hierarchies of large firms that may frustrate their creativity.[7]

However, there are distinctive benefits that favor the large firms over the smaller firms.[8] For instance, the large firms are able to conduct risky R&D in an imperfect capital market by utilizing their internally generated funds, which are more available and stable as firms grow and provide economies of scale to reduce the risk associated with the prospective return from R&D activity. In addition, there are economies of scale in R&D activity and the returns from R&D are higher in firms that have a larger volume of sales that can be used to spread out the fixed cost generated during R&D activity.

In Korea, the selectively concentrated R&D investment on large firms that conduct systematic researches mostly on development phase in order to achieve a short–term diffusion goal may slow development in core technology development on components, equipment, and materials in which smaller firms are interested.[9] For instance, the industrial import dependency in the PV module, a core component for PV, is highly dependent on import (46.6% in 2008) because of the lack of reliability, the shortage of skill, low price

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1) Here, the criteria classifying larger and smaller is based on “smaller enterprises basic law.” The term “large firms” applies to several conditions: that number of full–time labor is more than 1,000, the equity capital is over KRW 100 billion, or average sales are more than KRW 150 until 2014. The law was revised in 2015 with new revised applications, for instance the firms whose 3–year average sales is suited to the criteria by type of industry, total amount of assets is less than KRW 500 billion, and who do not belong to the firm group of limited mutual investment are defined as smaller firms.

competitiveness, and so on.[10] Moreover, the import dependency in wind energy power plant installed in the country was 99.6% in 2008, since the generating firms prefer the foreign product due to the low technological competitiveness in supporting core components and materials in charge of domestic smaller firms.[11,12]

Despite extensive efforts in R&D since 2008 to catch up with advanced technology, the level of commercialization derived from technology supported by Korean R&D activity and export of domestic goods (that is considerably important for Korea whose domestic renewable energy market was only 0.5% of the global market in 2011) remain sluggish. This is largely due to the lack of core technology needed to lead in the international market. The Korean market share in the international renewable energy technology was 0.27% in 2012, increased slightly compared to 0.18% in 2008.[13] Sales in renewables were KRW 3,268 billion in 2008 and increased to KRW 7,515 in 2013; exports were USD 1,706 million in 2008 and increased to USD 4,770 million in 2011; this trend then entered a downturn, with USD 2,523 million in 2012.[14]

1.2 Previous researches on Korea renewable energy technology R&D

There have been several quantitative and qualitative analyses on renewable energy R&D productivities in Korea. Korea still has a lower interest in R&D investment in renewable energy technology compared to other OECD countries under the condition that GDP per capita is excluded due to R&D increasing as GDP increases.[15] It seems that return on R&D is becoming more visible in sales and export along with recent R&D increases, especially in PV and wind energy technology; however, the technologies are not yet sufficient to compete in the international market, and the requisite R&D has been lacking, partly due to a lack of national R&D support.[16]

As results of quantitative research, the extended R&D support in renewable energy technology would be desirable in Korea to increase GDP.[17] The efficiencies of renewable energy R&D in terms of paper, patent, and engineering fee increased yearly as well as being shown to be comparatively more efficient than other energy programs such as nuclear energy.[18] By energy source, wind power is shown to be the most efficient in terms of the government support including R&D and promotion compared to other renewables such as fuel cells and PV.[19] On the other hand, it has been also shown that if renewable energy R&D performance described representatively as paper and patent are relative to the economical value, stability, profitability, growth, and innovation in firms who received R&D support to spend for renewable energy technology are not increased significantly compared to the firms that did not receive R&D support. This indicates that R&D support in renewable energies is not being connected to the firms' performance by technical commercialization.[20]

The results of research may be interpreted variously according to analysis methodology and research purpose, but there is not doubt that the aim for R&D activity is to achieve profits in the future. The concept of productivity is naturally valid in the renewable energy technology that is regarded to be significant as a future growth engine for Korea, and it is important to assess and enhance the R&D productivity in a qualitative way beyond quantitative growth. However, there have been no empirical studies to estimate Korea R&D productivity in renewable energy technology by performers (larger and smaller firms as well as institutes and universities) that are playing an essential role in conducting public R&D activity as well as by technical phases (basic, applied and development) whose purpose to perform are dissimilar one another.

2. Empirical studies on the Schumpeterian hypotheses

The technical change can occur in two directions, technology-push and demand-pull. The studies on the role of science and technology-push emphasize that technological advance will lead and determine the rate and direction of innovation.[21,22] On the other hand, the counterpart studies claimed that market demand drives innovation, creating opportunities for firms to invest more in safe innovative activities that will bring more predictable profits.[23,24]

Schumpeter is held to be the first to highlight a fundamental role of technical progress in affecting economic growth and social welfare in his book *Capitalism, Socialism, and Democracy* focuses on structural changes in firm, industry, or nation and their market to increase their R&D efforts for improving long-run economic performance.[25] He formulates two hypotheses that there is a positive relationship between innovative activity and firm size and between innovative activity and concentrated market structure. That is, large firms operating in a concentrated market will generate the technological progress that will bring economic development at the end. He argued that the process of creative destruction and innovation competition should replace price competition, which would justify monopolistic or oligopolistic competition.

There are also qualitative studies of that counter-argument that the large firms are less favorable in terms of innovation.[26,27,28] As firms grow large, they may either lose managerial control of or become more bureaucratic toward scientists and technologists who perform R&D. Moreover, the incentives given to the scientist or entrepreneurs may not be explicit, as either their ability to capture the benefits of individual efforts weakens or their creativity is frustrated by the conservative hierarchies of large firms.

A number of empirical studies that examine a relationship between R&D and firm size are based on individual industries or across industries. These are done either by regression analysis in which R&D intensity is the dependent variable and firm size or other influential factors are independent variable or by a cross-sectional analysis restricted to R&D performers and spied in a logged form. They all fail to reject a null hypothesis that a proportionality between R&D and firm size would be correlated in most industries regardless of restricting industry effects.[29,30] However, the studies are subject to the controversy that most of the data used for the regression analysis, especially in the earlier firm-level studies, are non-random and that, with fewer exceptions to study presence or the effects of data selection bias, there would be stronger features other than size in the R&D.

Finally it is necessary to reconsider the Schumpeterian hypothesis with respect to the current condition that most large firms operate business units in diverse industries. Cohen and Klepper (1996) arranged some empirical studies regarding R&D, innovation, and firm size into four stylized facts, "(1) the likelihood of performing R&D rises with firm size; (2) R&D and firm size are closely and positively related within industries; (3) R&D rises proportionately with firm size in most industries; (4) the number of patents or innovations generated per dollar of R&D declines with firm size" and prove them through R&D cost spreading.[31]

The cost-spreading model is based on the idea that large firms have an advantage of size given that the fixed cost generated by R&D can be spread out over a larger amount of output than in smaller firms and, through this process, the return on R&D will increase along with the level of output. It also implies that the rate of technical progress in an industry depends not only on total R&D investment but also on its market structure, such as that the fewer and cooperative firms engaging in R&D activity reduces chance of duplication in R&D spending. Moreover, it is more feasible to see large firms at the level of the business unit rather than overall size of the firm, and the relationship between R&D size is weaker in the industries where innovations are more saleable or the prospects for rapid growth due to innovation are stronger. However, it also emphasizes a role of smaller firms that have peculiar R&D competence on the diversity of projects that enable them to coexist with large firms.

Korean renewable energy R&D is mainly firm-based. That is, the large and smaller firms account for 74.2% of the R&D of renewable energy from 2008–2012 as described earlier in Figure 1. Various studies explain how the large firms are favorable for R&D productivity, as per the cost-spreading model, that expects large firms who perform renewable energy R&D to show higher productivity than smaller ones. Thus, the hypothesis is set for this paper as below,

Hypothesis: R&D productivity in large firms is higher than in other performers.

3. Methodology

There are two main approaches to analyze R&D productivity: production function and production frontier. Cobb–Douglas specification is one of the representative approaches in production function, which focuses on mathematical equations that relate quantities of inputs to quantities of maximum level of outputs. That is, its interest lies in estimating the coefficient of regression equations that explain an average propensity of correlation between inputs and outputs. On the other hand, production frontier is based on estimating a frontier to measure the distance between the frontier and each observed unit, called decision-making units (DMUs), and compare DMUs to know which one is the most efficient. DMUs on the frontier line are described as the best performer in the reference group and benchmarking units to the less efficient DMUs.

Scholars researching innovation and wealth creation generated by technological push simplify a process from R&D activity to invention, design and development, and innovation as a linear model.[32] Research and creativity will generate inventions, which are only ideas without economic value, and then some economically feasible invention will be innovated after going through the design and development process. Therefore, firms investing in R&D activity are aiming at gaining economic profits from the innovation by leading the early market in new products' commercialization. A number of input factors are employed throughout the innovation process in various forms, such as scientific and technological knowledge as intangible resources and human resources, and time and salary as tangible resources, to result in desired outputs like research papers, patents, engineering fees, and economic outcomes through commercial use. Outputs can be divided into direct and indirect outputs; the former are created directly from the R&D activity and latter refer to the economic outcome that is the ultimate purpose for R&D activity.

3.1 Data Envelopment Analysis (DEA)

DEA is developed as one of nonparametric production frontier methodologies to analyze efficiency for like public projects or non-profit firms that the price information on input or/and output is normally not given or units of measure to be estimated are different or difficult to synthesize as one index. In addition, it allows to handle multiple inputs and multiple outputs generated sporadically through out the process, namely the methodology is useful for estimating R&D productivity since it owns intrinsically various inputs and output. It assumes that a condition of Pareto-Koopman efficiency that a unit's efficiency cannot be increased unless other's efficiency decreases.[33]

Farrell (1957) firstly introduced the efficiency analysis using multiple inputs and multiple outputs to measure a firm and it was developed by Charnes, Cooper and Rhodes (1978) who proposed DEA for the first time, which is input-oriented DEA model on a constant return to scale (CRS); CCR model, and by Banker, Charnes and Cooper (1984) who distinguishes technical efficiency (TE) and scale efficiency (SE) since the firms' R&D activity is not possible to operate at optimal scale in practical; BCC model.[34,35,36]

According to Golany et al. (1989), DMUs used for DEA analysis should satisfy some homogeneity conditions in order to have the result with economic significance.[37] The conditions are the projects are performed under similar purpose, the DMUs are existing in the homogeneity market, and all input and output data are in every DMUs and the data are different each other. In addition, the proper number of DMUs should be existed since it is less plausible that majority of DMUs would be efficient if the number of DMUs are less than the number of input and output variables. There is not a unified standard as to the number of DMU but most of papers use the standard suggested by Fitzsimmons et al. (1994) described as below

$$K \geq 2(N+M) \qquad (1)$$

K stands for number of DMU and N and M are the number of variables of input and output data.[38]

When n decision-making units (DMUs) are to be evaluated, each $DMU_j(j=1,...,n)$ consumes m inputs $(i=1,2...,m)$ in order to produce s outputs $(r=1,2...,s)$. Clearly, $DMU_j(j=1,...,n)$ uses amounts $X_j=x_{ij}$ of inputs ($i=1,2...,m$ and $x_{ij}>0$) and produces amounts $Y_j=y_{rj}$ of outputs ($r=1,2...,s$ and $y_{rj}>0$). In addition, there are two properties to ensure a piecewise linear approximation to the efficient frontier and the area dominated y the frontier; convexity and inefficiency. That is, $\sum_{j=1}^{n}\lambda_j x_{ij}(i=1,2,...,m)$ and $\sum_{j=1}^{n}\lambda_j y_{rj}(r=1,2,...,s)$ are possible inputs and outputs attainable by the DMU_j, where $\lambda_j(j=1,...n)$ are positive scalars and the same outputs can be produced by using more inputs; the same inputs can be used to produce less outputs.

The CRS assumption is suitable when all firms are operating at an optimal scale, but it is not possible in practical due to external factors like imperfect market condition, government regulation, etc.. Therefore, BCC model based on variable returns to scale (VRS) conditions, which can divide TE and SE simply by adding the convexity constraint; λ_j=1. The input-oriented model estimates the inputs in each DMU that can be minimized while the outputs are maintained; on the contrary the output-oriented model finds the outputs in each DMU that can be maximized at the current inputs.

Either input or output oriented DEA model is optionally selectable to use for the analysis for R&D productivity according to its research purpose. Input oriented model is suitable to the case in order to estimate minimum input variables at the current output maintained, that is the model is capable to acquire minimum R&D investment or/and human resources retaining current output level like number of patent, paper, or volume of sales. In this paper, the efficiency is estimated based on output-oriented BCC model due to the researches and public opinion that the R&D performance is not sufficient to the current level of R&D investment on the increase and the qualitative improvement in R&D productivity is necessary bringing up maximum outputs under the present R&D support.

The efficiency score of output-oriented DEA based on VRS condition (output-oriented BCC model), $\varnothing^*$, is calculated as below

$$\varnothing^* = \max \varnothing \tag{2}$$

subject to

$$\sum_{j=1}^{n} \lambda_j x_{ij} \leq x_{io} \qquad i = 1, 2, \ldots, m; \tag{3}$$

$$\sum_{j=1}^{n} \lambda_j y_{rj} \geq \varnothing y_{ro} \quad r = 1, 2, \ldots, s; \tag{4}$$

$$\sum_{j=1}^{n} \lambda_j = 1 \tag{5}$$

$$\lambda_j \geq 0 \qquad i = 1, 2, \ldots, n \tag{6}$$

If $\varnothing^* \neq 1$ input and outputs slacks can be expressed as

$$\mathrm{s}_{\mathrm{i}}^- = \mathrm{x}_{\mathrm{io}} - \sum_{\mathrm{j}=1}^{\mathrm{n}} \lambda_{\mathrm{j}} \mathrm{x}_{\mathrm{ij}} \qquad i = 1, 2, \ldots, m; \tag{7}$$

$$\mathrm{s}_{\mathrm{i}}^+ = \sum_{\mathrm{j}=1}^{\mathrm{n}} \lambda_{\mathrm{j}} \mathrm{y}_{\mathrm{ro}} - \varnothing^* \mathrm{y}_{\mathrm{ro}} \qquad r = 1, 2, \ldots, s. \tag{8}$$

DMU_o is less efficient not only if $\varnothing^* \neq 1$ but also if $\varnothing^* = 1$ and s_i^- and/or s_r^+ are non-zero for all i. Then, the input and output slacks are estimated, which make $\varnothing^*$ optimize, are also estimated

$$\max \sum_{i=0}^{m} s_i^- + \sum_{r=0}^{s} s_i^- \tag{9}$$

subject to

$$\sum_{j=1}^{n} \lambda_i x_{ij} + s_i^- = x_{io} \tag{10}$$

$$\sum_{j=1}^{n} \lambda_i x_{ij} - s_r^+ = \varnothing^* y_{rc} \qquad i = 1,2,\ldots,n \tag{11}$$

$$\sum_{j=1}^{n} \lambda_j = 1 \qquad j = 1,2,\ldots,n \tag{12}$$

$$\lambda_j \geq 0 \tag{13}$$

Finally the two-state output-oriented BCC model can be evaluated as

$$\max \varnothing + \varepsilon \left(\sum_{i=1}^{m} s_i^- + \sum_{r=1}^{s} s_r^+ \right) \tag{14}$$

subject to

$$\sum_{j=1}^{n} \lambda_i x_{ij} + s_i^- = x_{io} \qquad i = 1,2,\ldots,m; \tag{15}$$

$$\sum_{j=1}^{n} \lambda_i x_{rj} - s_r^+ = \varnothing^* y_{ro} \qquad r = 1,2,\ldots,s; \tag{16}$$

$$\sum_{j=1}^{n} \lambda_i = 1 \tag{17}$$

$$\lambda_j \geq 0 \qquad j = 1,2,\ldots,n \tag{18}$$

Next, the VRS model is able to separate TE and SE, which may be calculated as the ratio of TE on the assumption of CRS to TE on the assumption of VRS. The technical efficiencies on the basis of VRS, θ^* for the input-oriented model and $\varnothing^*$ for the output-oriented model, are given already by calculations above and the TE under the CRS can be estimated without the convexity constraint; λ_j=1. Therefore, TE under input-oriented based on CRS assumption is estimated as

$$\theta^{*} = \min\theta \tag{19}$$

subject to

$$\sum_{j=1}^{n} \lambda_j x_{ij} \le \theta x_{io} \qquad i = 1,2,\ldots,m; \tag{20}$$

$$\sum_{j=1}^{n} \lambda_j y_{rj} \ge y_{ro} \qquad r = 1,2,\ldots,s; \tag{21}$$

$$\lambda_j \ge 0 \tag{22}$$

and TE under output-oriented based on CRS assumption is described as

$$\varnothing^{*} = \max\varnothing \tag{23}$$

subject to

$$\sum_{j=1}^{n} \lambda_i x_{ij} \le x_{io} \quad i = 1,2,\ldots,m \tag{24}$$

$$\sum_{j=1}^{n} \lambda_i y_{rj} \ge \varnothing y_{ro} \quad r = 1,2,\ldots,s; \tag{25}$$

$$\lambda_j \ge 0 \tag{26}$$

Finally, $SE(X_j, Y_j)$ and $TE(X_j, Y_j)$ for each DMU is

$$SE(X_j, Y_j) = \frac{\theta_j^{*} CCR}{\theta_j^{*} BCC} \qquad j = 1,\ldots,n \tag{27}$$

for input-oriented BCC model,

$$TE(X_j, Y_j) = 1 - SE(X_j, Y_j) \qquad j = 1,\ldots,n. \tag{28}$$

for output-oriented BCC model,

$$TE(X_j, Y_j) = 1 - SE(X_j, Y_j) \qquad j = 1,\ldots,n. \tag{29}$$

and for TE.

4. Analytical framework

This paper uses the output-oriented BCC model to estimate an econometric efficiency of R&D productivity in 1340 national R&D projects of Korea renewable energy technology who received public R&D in order to test the hypothesis “R&D productivity in large firms is higher than that in other performers,” where performers include large firms and smaller firms as well as universities and government-supported research institutes (institutes, in short).

An assumption of technological push that will enhance economical growth and social welfare is utilized for the analysis. In addition, in order to satisfy the homogeneity condition that the DMU should be operated under a similar purpose, the projects are distinguished by the technical progress phase (basic, applied, and development). Basic research is performed to obtain new knowledge, applied research to acquire knowledge for the practical application of science, and development research to have practical products with economical value to sell in the market.

Furthermore, two input and five output variables whose data in every DMU are accessible through the National Technical Information Service (NTIS) system are chosen to analyze. The input and output data from the 1340 projects called DMUs are yearly-based data, and the DMUs that did not received R&D support are not counted. In other words, data of the R&D project whose research period is at least more than two or three years are divided by year from 2008 to 2012. The input variables considered are pubic R&D financial support as well as firms’ private R&D investment and number of workers, regardless of their academic background. As output variables, five direct outputs without economic value—number of Scientific citation index (SCI) and non-SCI paper publications, number of applied and registered patents, and others without economical value such as report, prototype, etc.—and two economic outputs—number of receiving engineering fee and number of commercialization—are considered. The time lag from inputs to outputs is naturally not needed to consider for this analysis, since the output data is discovered in practice if occurred in the NTIS system and the efficiency of DMUs that have fewer or no outputs is to appear less efficient compared to other DMUs.

Paper publication is an objective indicator for basic research, and SCI papers are regarded to have higher quality than non-SCI papers. However, due to the lower number of publications that would not be representative as output variable and the language barrier that SCI paper are generally written in English, non-SCI papers are also counted as one of the output variables. Likewise, the registered patent, which is obtainable when the invention is considered to have new technological characteristics, is superior in quality but smaller in number than the applied patent; nevertheless, the applied patent is brought to supplement the quantitative profile. As an economic output, engineering fee in the private sector is generated when one party uses the right in asset or intellectual property owned by others. On the other hand, the engineering fee that is supported by public R&D is obtained when the relevant R&D is successfully commercialized, and some part of benefit is returned to the government. In addition, when the product is sold in the market, the product can be considered commercialized.

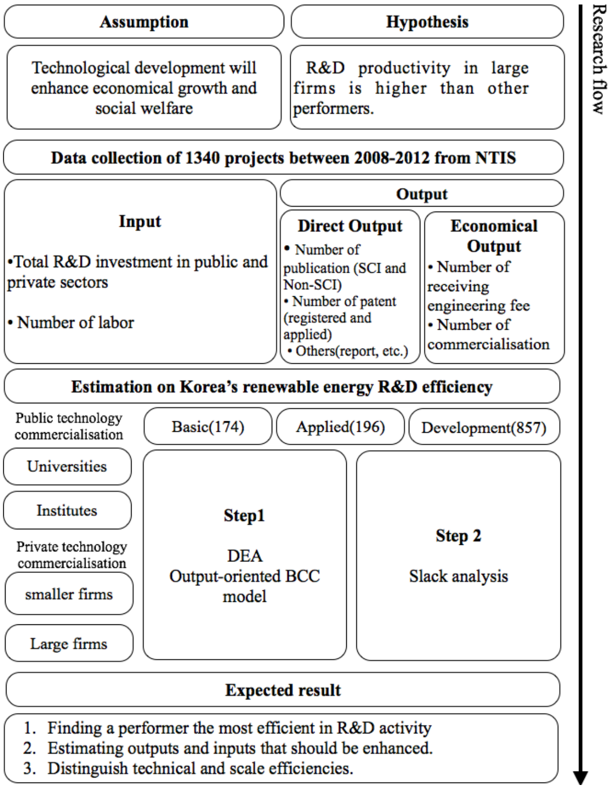

Fig. 3. Analytical framework to analyze R&D efficiency in Korea renewable energy

Thus, the projects are classified into basic, applied, and development as a first step and estimated by output-oriented BCC model of DEA and slack analysis by performer as follows. The data are collected from the NTIS and the period of interest is from 2008 to 2012, when R&D investment was geometrically increased and the project that is expected to commercialize was realized in the Korean renewable energy technology. The NTIS data shows the direct inputs on each R&D project as an amount of investment and human resources in number as well as direct performances as SCI paper, non-SCI paper, registered patent, applied papers, engineering fee and commercialization by year. That is, the time lag from R&D investment to commercialization stage is automatically considered.

5. Empirical research

5.1 Data

The descriptive statistic of data from 2008 to 2012 is shown in Table 1 as below. During the period, 1340 projects were performed for renewable energy technologies under the supervision of Korea Energy Technology Evaluation and Planning (KETEP): 280 for large firms, 380 for medium-sized firms, 343 for institutes, 316 for universities, and 21 for others.

Table 1. Descriptive statistics of renewable energy R&D in Korea in 2008–2012

Basic						
		Sum	Average	S.D.	Max	Min
Universities	R&D investment	27,132.61	330.89	257.91	1,124.56	30.00
	labor	1,586.00	19.34	18.78	95.00	-
	SCI paper	139.00	4.48	4.52	20.00	1.00
	Non-SCI paper	62.00	2.48	2.21	10.00	1.00
	registered patent	30.00	2.14	1.92	7.00	-
	applied patent	64.00	2.67	2.58	12.00	-
	others	55.00	1.53	1.14	6.00	-
	engineering fee	-	-	-	-	-
	commercialization	1.00	0.50	0.50	1.00	-
Institutes	R&D investment	34,406.00	573.43	391.14	2,700.00	-
	labor	1,187.00	19.78	14.27	63.00	-
	SCI paper	59.00	3.11	2.12	9.00	1.00
	Non-SCI paper	47.00	2.35	1.65	6.00	1.00
	registered patent	14.00	1.56	0.68	3.00	1.00
	applied patent	70.00	2.80	2.45	11.00	1.00
	others	37.00	1.95	1.70	8.00	1.00
	engineering fee	1.00	1.00	-	1.00	1.00
	commercialization	3.00	1.00	-	1.00	1.00
Smaller firms	R&D investment	10,875.28	604.18	489.67	1,882.00	70.27
	labor	414.00	23.00	16.09	59.00	4.00
	SCI paper	3.00	3.00	-	3.00	3.00
	Non-SCI paper	1.00	1.00	-	1.00	1.00
	registered patent	4.00	1.00	-	1.00	1.00
	applied patent	5.00	1.67	0.94	3.00	1.00
	others	7.00	1.17	0.37	2.00	1.00
	engineering fee	5.00	1.67	0.94	3.00	1.00
	commercialization	-	-	-	-	-
Large firms	R&D investment	13,879.72	1,387.97	1,409.39	4,363.05	362.00
	labor	438.00	43.80	24.05	106.00	23.00
	SCI paper	1.00	1.00	-	1.00	1.00
	Non-SCI paper	7.00	1.75	1.30	4.00	1.00
	registered patent	3.00	3.00	-	3.00	3.00
	applied patent	3.00	3.00	-	3.00	3.00
	others	3.00	1.00	-	1.00	1.00
	engineering fee	3.00	3.00	-	3.00	3.00
	commercialization	2.00	2.00	-	2.00	2.00
Applied						
		Sum	Average	S.D.	Max	Min
Universities	R&D investment	13,913.45	323.57	200.34	945.00	5.00
	labor	874.00	20.33	13.86	53.00	1.00
	SCI paper	114.00	4.96	7.67	37.00	1.00
	Non-SCI paper	67.00	4.79	6.21	24.00	-
	registered patent	14.00	2.00	2.45	8.00	1.00
	applied patent	26.00	2.00	1.41	6.00	1.00
	others	35.00	1.67	1.28	6.00	1.00
	engineering fee	-	-	-	-	-
	commercialization	-	-	-	-	-
Institutes	R&D investment	78,020.38	896.79	934.50	6,205.00	70.00
	labor	2,432.00	27.95	23.64	132.00	3.00
	SCI paper	157.00	4.13	4.09	16.00	-
	Non-SCI paper	73.00	2.35	1.98	9.00	-
	registered patent	17.00	1.00	0.77	3.00	-
	applied patent	140.00	3.33	3.01	13.00	1.00
	others	95.00	1.79	1.52	10.00	1.00
	engineering fee	6.00	0.67	0.67	2.00	-
	commercialization	1.00	0.20	0.40	1.00	-
Smaller firms	R&D investment	16,298.51	493.89	313.49	2,000.00	50.00
	labor	573.00	17.36	10.56	57.00	-
	SCI paper	1.00	1.00	-	1.00	1.00
	Non-SCI paper	5.00	1.25	0.43	2.00	1.00
	registered patent	6.00	1.50	0.50	2.00	1.00
	applied patent	7.00	1.75	0.83	3.00	1.00
	others	8.00	1.00	-	1.00	1.00
	engineering fee	8.00	1.14	0.35	2.00	1.00
	commercialization	5.00	2.50	1.50	4.00	1.00
Large firms	R&D investment	71,995.64	3,130.25	2,993.17	11,600.00	150.00
	labor	2,037.00	88.57	67.41	317.00	10.00
	SCI paper	9.00	1.80	0.98	3.00	1.00
	Non-SCI paper	9.00	2.25	1.64	5.00	1.00
	registered patent	7.00	2.33	0.94	3.00	1.00
	applied patent	33.00	4.13	6.15	20.00	1.00
	others	17.00	2.13	1.96	7.00	1.00
	engineering fee	4.00	1.00	-	1.00	1.00
	commercialization	1.00	1.00	-	1.00	1.00
Development						
		Sum	Average	S.D.	Max	Min
Universities	R&D investment	49,677.12	420.99	619.43	6,467.12	1.00
	labor	2,412.00	20.44	13.44	66.00	1.00
	SCI paper	298.00	4.97	8.89	50.00	-
	Non-SCI paper	215.00	4.48	6.01	36.00	-
	registered patent	40.00	1.67	1.62	7.00	-
	applied patent	153.00	2.51	2.27	12.00	-
	others	125.00	1.81	1.40	7.00	-
	engineering fee	4.00	0.80	0.75	2.00	-
	commercialization	5.00	1.00	1.26	3.00	-
Institutes	R&D investment	106,636.40	903.70	1,353.85	10,000.00	60.00
	labor	2,822.00	23.92	22.17	126.00	-
	SCI paper	120.00	2.86	2.82	17.00	1.00
	Non-SCI paper	141.00	3.20	4.65	29.00	-
	registered patent	50.00	2.00	1.77	6.00	-
	applied patent	226.00	3.90	3.90	16.00	-
	others	100.00	1.59	1.27	9.00	-
	engineering fee	10.00	0.67	0.47	1.00	-
	commercialization	14.00	1.17	1.86	7.00	-
smaller firms	R&D investment	314,032.92	1,019.59	1,208.88	9,408.00	1.00
	labor	7,764.00	25.21	22.76	121.00	-
	SCI paper	126.00	3.71	8.13	44.00	-
	Non-SCI paper	96.00	1.81	1.29	5.00	-
	registered patent	62.00	1.59	1.48	8.00	-
	applied patent	228.00	2.38	2.51	17.00	-
	others	226.00	1.54	1.54	15.00	-
	engineering fee	116.00	1.21	0.61	4.00	-
	commercialization	96.00	1.92	1.47	7.00	-
Large firms	R&D investment	556,431.74	2,588.05	3,181.99	24,456.85	32.00
	labor	15,001.00	69.77	151.11	2,072.00	-
	SCI paper	153.00	2.89	4.11	26.00	-
	Non-SCI paper	205.00	3.15	5.92	44.00	-
	registered patent	89.00	2.34	3.21	14.00	-
	applied patent	403.00	4.80	6.91	39.00	-
	others	284.00	2.51	2.59	15.00	-
	engineering fee	131.00	2.08	5.00	40.00	-
	commercialization	49.00	1.69	1.58	6.00	-

Data are classified according to technical progress phase and performers. In basic research, a large amount of R&D investment and workers are dedicated to universities and institutes, accounted for 71.3% of total R&D investment and 76.5% in total number of workers. On the other hand, average R&D investment and number of R&D workers are the higher in the large firms, which performed only 10 basic research programs, compared to the universities and institutes, which conducted 82 and 60, respectively, during the same period. R&D investment and workers in smaller firms are the least among the performers, but the average is higher than those for universities and institutes, though lower than that for large firms. In terms of the outputs, the direct outputs are more produced in universities and institutes both in total and average, but less in economical outputs presented as engineering fee and commercialization The outputs as applied research accomplished in number gives weight to institutes.

In applied research, a share of R&D investment and workers in the institutes are the most between performers but the large firms are still the largest beneficiary per project. Similarly for basic research, the institutes beside the inputs, and the economical outputs are lower than the firms'. It is notable that the smaller firms produce more economic outputs than large firms compared with the inputs, the least in total amount among performers.

The researches on development phase has the largest share of R&D investment and workers in total compared to other research phases since they are believed to generate economical returns on the R&D spend. The large firms account for the largest proportion of R&D investment and workers, with 67.6% and 65.7%, respectively, and are assumed to perform larger projects relative to those of other performers. Smaller firms have the next highest proportions for both figures. The absolute total figures in outputs are superior to those of other research in different technical phases, but it is noticeable that the averages are not distinctly different among performers.

5.2 Result

The result gained using the output-oriented VRS model is described in Table 2 as below. First of all, efficiency of the 1,227 DMUs out of the 1340 DMUs including the researches that did not belong to any other technical progress phase is estimated by basic, applied, and development and then classified by performer as large and smaller firms, institutes, and universities. Thus, the results of efficiency and slack analysis shown in Table 2 are the average figures for each group by technical progress phase and by performer.

The overall average efficiency was 0.72 for basic, 0.60 for applied, and 0.50 for development research, which indicates the lowest efficiency score. Distinguishing the efficiencies by performer, universities' efficiency in basic research shows the highest 0.78 more than average, and the efficiencies in other performers are nearly similar, though the large firms' are slightly lower. In DMUs in applied research, the efficiency in smaller firms is exceptionally higher than other performers', with 0.75, followed by large firms with 0.69; thus, the average efficiency scores of applied research in the firms exceed total average efficiency score of 0.60. The level of efficiencies in development research is almost alike among performers and it is also conspicuous that they are somewhat lower than those of other technical progress phases.

According to the result allowing to show the amount

Table 2. Econometric efficiency of R&D productivity of Korea national R&D projects in renewable energy technology

		Total			Universities						Institutes						Smaller firms						Large firms					
Technical progress phase		Basic	Applied	Development	Basic		Applied		Development		Basic		Applied		Development		Basic		Applied		Development		Basic		Applied		Development	
Efficiency		0.72	0.60	0.50	0.78		0.58		0.50		0.68		0.53		0.47		0.69		0.75		0.52		0.61		0.69		0.50	
Input Slacks	Gov. R&D	170.60	310.73	571.55	76.02		72.20		126.80		226.94		230.07		335.91		227.82		239.80		458.14		505.13		1144.91		1146.15	
	Pri.R&D	46.86	148.77	220.74	23.23		33.36		17.04		4.38		17.09		4.73		55.05		71.58		129.97		480.77		968.16		588.22	
	Labor	4.37	11.27	18.43	2.98		5.91		10.85		5.06		6.11		8.09		3.38		10.19		13.70		13.38		43.64		36.43	
Output Slacks	SCI Paper	0.77	3.95	0.32	0.70		2.10		0.03		0.43		4.28		0.51		1.18		3.35		0.35		2.59		5.61		0.32	
	Non-SCI Paper	0.74	2.00	0.72	0.62		2.45		0.98		0.94		2.82		1.17		0.95		0.64		0.44		0.19		0.65		0.71	
	Reg. Patent	0.51	1.03	0.47	0.44		1.36		0.47		0.51		1.26		0.64		0.34		0.23		0.51		1.40		0.55		0.34	
	App. Patent	0.48	0.51	0.84	0.43		0.64		0.75		0.37		0.60		0.93		0.26		0.34		0.76		2.01		0.23		0.92	
	Others	0.38	0.75	0.95	0.26		0.76		0.94		0.44		0.67		0.89		0.49		0.62		1.00		0.83		1.08		0.95	
	Engineeringfee	0.05	0.04	0.22	0.04		0.02		0.29		0.08		0.02		0.23		0.00		0.05		0.20		0.02		0.05		0.20	
	Commercilisaiton	0.08	0.00	0.02	0.07		0.00		0.00		0.11		0.00		0.00		0.00		0.00		0.03		0.04		0.00		0.01	
Efficient Input Target	Gov. R&D	269.49	500.53	522.09	215.14	Variation	213.96	Variation	249.11	Variation	334.92	Variation	648.65	Variation	628.81	Variation	255.56	Variation	163.26	Variation	414.31	Variation	347.67	Variation	1017.18	Variation	773.77	Variation
	Pri.R&D	7.60	3.77	6.38	3.15		0.14		3.89		1.24		0.97		2.59		40.52		19.25		4.88		23.00		0.00		12.52	
	R&D investment	277.09	504.30	528.47	218.29	-34.03%	214.10	-33.83%	253.00	-39.90%	336.16	-41.38%	649.62	-27.56%	631.39	-30.13%	296.09	-50.99%	182.52	-63.05%	419.19	-58.89%	336.16	-75.78%	649.62	-79.25%	631.39	-75.60%
	Labor	16.54	30.41	17.84	15.88	-17.91%	60.46	197.47%	10.44	-48.92%	14.76	-25.39%	21.84	-21.87%	14.78	-38.19%	18.68	-18.77%	7.17	-58.71%	11.77	-53.30%	29.80	-31.97%	44.93	-49.27%	32.13	-53.95%
Efficient Output Target	SCI Paper	2.77	8.21	3.33	3.24	-27.63%	9.23	86.22%	6.33	27.44%	2.34	-24.58%	9.80	137.09%	4.68	63.91%	2.09	-30.44%	3.79	279.23%	1.59	-57.21%	2.69	169.17%	6.20	244.47%	3.34	15.86%
	Non-SCI Paper	1.88	4.42	3.62	1.70	-31.47%	5.50	14.84%	5.12	14.33%	2.22	-5.69%	5.53	134.87%	4.62	44.10%	1.01	0.93%	1.30	4.33%	1.97	8.75%	2.94	67.87%	2.14	-4.95%	4.09	29.55%
	Reg. Patent	0.96	1.42	1.05	0.91	-57.67%	1.78	-10.90%	1.24	-25.51%	0.85	-45.22%	1.66	65.71%	1.32	-33.77%	0.93	-7.12%	0.58	-61.62%	0.90	-43.35%	2.04	-32.05%	0.96	-59.06%	1.02	-56.57%
	App. Patent	1.95	2.67	4.86	1.64	-38.59%	1.96	-2.22%	4.10	63.41%	2.39	-14.62%	3.61	8.25%	7.21	84.95%	1.53	-8.19%	0.70	-60.13%	3.79	59.43%	2.65	-11.58%	3.63	-12.01%	5.53	15.25%
	Others	1.37	2.61	4.68	1.27	-16.83%	2.44	46.45%	4.36	140.82%	1.38	-29.18%	3.26	81.63%	4.02	153.55%	1.46	24.83%	1.40	39.64%	4.59	198.27%	1.98	97.93%	2.54	19.59%	5.31	111.13%
	Engineeringfee	0.10	0.14	1.27	0.04	0.00%	0.02	0.00%	0.36	-54.47%	0.10	-90.31%	0.09	-85.90%	0.65	-3.15%	0.29	-82.78%	0.36	-68.63%	1.67	38.21%	0.32	-89.20%	0.23	-77.38%	1.68	-19.25%
	Commercilisaiton	0.11	0.06	0.42	0.08	-83.48%	0.00	0.00%	0.05	-95.08%	0.16	-83.88%	0.01	-92.56%	0.24	-79.26%	0.00	0.00%	0.16	-93.59%	0.63	-67.22%	0.24	-88.00%	0.04	-95.65%	0.43	-74.48%
Frequency(%)	0.00	0 (0%)	0 (0%)	0 (0%)	0 (0%)		0 (0%)		0 (0%)		0 (0%)		0 (0%)		0 (0%)		0 (0%)		0 (0%)		0 (0%)		0 (0%)		0 (0%)		0 (0%)	
	0.01 -0.10	3 (1.8%)	12 (6.5%)	128 (15.4%)	1 (1.2%)		2 (4.7%)		15 (11.2%)		0 (0%)		6 (6.9%)		11 (8.1%)		1 (5.6%)		2 (6.1%)		59 (18.2%)		1 (10.0%)		2 (8.7%)		43 (18.1%)	
	0.11 - 0.20	13 (7.6%)	21 (11.3%)	155 (18.7%)	5 (6.1%)		5 (11.6%)		25 (18.7%)		5 (8.2%)		11 (12.6%)		31 (23.0%)		1 (5.6%)		2 (6.1%)		57 (17.6%)		2 (20.0%)		3 (13.0%)		42 (17.7%)	
	0.21 - 0.30	14 (8.2%)	29 (15.6%)	92 (11.1%)	3 (3.7%)		10 (23.3%)		22 (16.4%)		7 (11.5%)		14 (16.1%)		22 (16.3%)		3 (16.7%)		3 (9.1%)		31 (9.6%)		1 (10.0%)		2 (8.7%)		17 (7.2%)	
	0.31 - 0.40	9 (5.3%)	18 (9.7%)	63 (7.6%)	4 (4.9%)		3 (7%)		6 (5.7%)		5 (8.2%)		14 (16.1%)		13 (9.6%)		0 (0%)		0 (0%)		19 (5.9%)		0 (0%)		1 (4.3%)		22 (9.3%)	
	0.41 - 0.50	13 (7.6%)	10 (5.4%)	45 (5.4%)	6 (7.3%)		2 (4.7%)		5 (3.7%)		4 (6.6%)		7 (8.0%)		6 (4.4%)		2 (5.6%)		1 (3.0%)		18 (5.6%)		1 (10.0%)		0 (0%)		16 (6.8%)	
	0.51 - 0.60	9 (5.3%)	7 (3.8%)	32 (3.9%)	4 (4.9%)		1 (2.3%)		7 (5.2%)		5 (8.2%)		2 (2.3%)		8 (5.9%)		0 (0%)		3 (9.1%)		9 (2.8%)		0 (0%)		1 (4.3%)		8 (3.4%)	
	0.61 - 0.70	7 (4.1%)	6 (3.2%)	22 (2.7%)	2 (2.4%)		2 (4.7%)		6 (4.5%)		4 (6.6%)		4 (4.6%)		5 (3.7%)		1 (5.6%)		0 (0%)		8 (2.5%)		0 (0%)		0 (0%)		3 (1.3%)	
	0.71 - 0.80	11 (6.4%)	3 (1.6%)	12 (1.4%)	7 (8.5%)		1 (2.3%)		3 (2.2%)		4 (6.6%)		0 (0%)		3 (2.2%)		0 (0%)		2 (6.1%)		1 (0.3%)		0 (0%)		0 (0%)		5 (2.1%)	
	0.81 - 0.90	5 (2.9%)	1 (0.5%)	12 (1.4%)	4 (4.9%)		0 (0%)		3 (2.2%)		0 (0%)		1 (1.1%)		2 (1.5%)		1 (5.6%)		0 (0%)		6 (1.9%)		0 (0%)		0 (0%)		1 (0.4%)	
	0.91 - 0.99	5 (2.9%)	4 (2.2%)	8 (1.0%)	5 (6.1%)		1 (2.3%)		2 (1.5%)		0 (0%)		3 (3.4%)		2 (1.5%)		0 (0%)		0 (0%)		1 (0.3%)		0 (0%)		0 (0%)		3 (1.3%)	
	1.00	82 (48%)	75 (40.3%)	261 (31.4%)	41 (50%)		16 (37.2%)		37 (27.6%)		27 (44.3%)		25 (28.7%)		32 (23.7%)		9 (50%)		20 (60.6%)		115 (35.5%)		5 (50.0%)		14 (60.9%)		77 (32.5%)	
Efficiency	Technical Efficiency	0.76	0.67	0.69	0.83		0.67		0.79		0.75		0.53		0.68		0.81		0.84		0.74		0.67		0.64		0.56	
	Scale Efficiency	0.24	0.33	0.31	0.17		0.33		0.21		0.25		0.47		0.32		0.19		0.16		0.26		0.33		0.36		0.44	

of input and output slacks that would be increased or decreased for improving efficiency, the estimated numerical values vary considerably among performers and technical progress phases. Regardless of performer, the results of efficient target that maximizes efficiency by manipulating inputs in R&D investment and labor to have maximum output level show that the current level of inputs are not required to achieve the current level of outputs. That is, outputs could be increased without increasing the current amount of inputs.

Moreover, DEA can provide information to show the DMUs whose efficiency score is 1. The DMUs in basic research phases are the most efficient, while almost two thirds of DMUs in development phase, whose project accounts for nearly 70% of R&D in number, are inefficient. In other words, the projects in the development phases show the lowest efficiency in terms of number with score '1' compared to basic and applied researches. Looking at the results more in detail by performer, the combined smaller and large firms seem to perform more efficient R&D projects on average, with relatively more efficient value in applied research than universities and institutes. The number of DMUs with efficiency with score '1' in development research in the firms is slightly higher than in the universities and institutes. In addition, the efficiencies between small and large firms are also not notably different, and the efficiency in smaller firm is rather higher than large firms, at 35.5% and 32.5%, respectively.

It is necessary to consider for this study if there are efficiency of scale between DMUs since the efficiency can be increased or decreased as scale increases. The scale of R&D investment and labor as input variables, as well as their outputs produced in various forms, vary by performer and technical progress phase. As a result, regardless of characteristics divided by performer and technical progress phase, there is more in efficiency of scale than technical efficiency, meaning the efficiency is increased as of the size of the DMU is increased.

6. Conclusion

This study uses the output-oriented BCC model of the DEA to estimate econometric efficiency of R&D productivity among 1340 national R&D projects in renewable energy technology in Korea by performer and by technical progress phase. The DMUs are classified by level of technical progress phase ((basic, applied, and development) as a first step to satisfy the homogeneity condition and the result of efficiencies are averaged by performer to verify the hypothesis.

The result explains that one of the reasons why the industry development in renewable energy in Korea is not growing fast is that firms' R&D productivity in the renewable energy technology is low. In fact, the large firms are proved to have several benefits in performing R&Ds compared to smaller firms, in spite of some weakness such as inflexible bureaucratic R&D management, and expect to have more fruitful results in outputs than another performers. Therefore, they invest a large amount of their funds, including public financial support from government, as well as and human resources into the renewable technology, especially on development phase, for which they anticipate economic outcome in the short term.

However, while the efficiencies on basic and applied research are rather high in most performers, since direct outputs from R&D support are sufficiently created, most research on the development phase correlated to profitability performed mostly by firms are rather inefficient. This is because its economical outputs compared to initial R&D support are inadequately produced, though those performers are expecting

R&D results with economic value. In addition, the efficiencies on the development phases show the efficiency in the smaller firms is slightly higher than large firms, who received the R&D support the most in amount as well as per project; thus, the hypothesis is rejected.

The resulted efficiencies are shown to derive more from efficiency of scale than technical efficiency, meaning the R&D efficiency increases as quantities of R&D inputs increase, which should be considered in tackling how to improve R&D in a qualitative aspect. According to the research by Cohen and Klepper (1996) described earlier, the cost-spreading model is valid in the large business unit where the firm operates as one of diverse business rather than the whole size of the firm. Thus, it is needed to review whether the R&D investment and number of workers data should be made only according to the firm size rather than with consideration that the firm's business unit per se has an ability to make a result of the R&D culminate in real commercialization. Therefore, both ex-ante and ex-post analysis to understand firms' ability to complete R&D activity and to assess the R&D activity terminated are required to further enhance R&D productivity.

In addition, securing industrial competitiveness in the overseas renewable energy market is necessary through more efforts into R&D focused on the core technology. For the purpose of expanding the market share, smaller firms that possess unique R&D on the diversity of projects are able to play an important role, which also enables them to coexist with large firms. There is a mutual agreement of systemic cooperation between large firms that focus on systemic R&D process and smaller firms that improve components, equipment, or/and materials in Korean industry. Therefore, it is desirable to encourage more knowledge and technology sharing between smaller and large firms for mutual growth by localizing the renewable energy technology and further broadening markets overseas.

The limitation of this paper is that it focuses on quantity-based output data for the analysis. For instance, some DMUs that produce a smaller number of papers or patent might produce papers or patents that are superior in quality. By the same logic, economical benefits counted in number of commercialization and engineering fee would increase for such DMUs.

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