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Assessment of Research Collaborations for Improving Intellectual and Economic Performance in Public Renewable Energy R&D

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Abstract. *Public R&D investment in renewable energy has burgeoned at the global level in a concerted effort to expedite energy transition. Unlike traditional energy sources, the renewable energy industry produces a favorable collaboration environment for small and medium enterprises, affecting traits of R&D collaboration in R&D as well. The main purpose of this study is to find relationships between R&D collaboration and intellectual & economic performances in renewable energy R&D. We have analyzed 484 projects completed between 2006 and 2014 in South Korea's public renewable energy R&D program. We found that university-industry-government research institute collaboration is not the most effective for creating intellectual nor economic performance, interpreting as a necessity in the revision on current UIG collaboration policy. For a leader organization, we found that medium enterprises are the most positively related with economic outcomes, interpreting medium enterprises had as much technical competency and investment capacity as large enterprises.*

Keywords: *R&D, performance measurement, collaboration, renewable energy, triple helix, r&d leader*

1. Introduction

Public renewable energy R&D programs are brought up to be an essential area for measuring their economic outcome, since many governments radically increase their expenditures on such programs in order to attain energy transition and withstand climate change (IRENA, IEA, & REN21, 2018; Mission-Innovation, 2015). The economic outcomes are a critical component of renewable energy R&D evaluation, as improvement in economic outcomes indicates the utility and potential of projects to contribute on the expansion of renewable energy capacity. Also, the economic outcomes of renewable energy R&D may send positive signals to both public and private investors and contribute to the continued development of renewable energy technology. Global R&D investments have increased by USD 4.6 billion between 2016 and 2018, a 55% increase from the investment baseline in 2016, with the advent of Mission Innovation (Mission Innovation, 2019). Such a dramatic increase in public expenditure on renewable energy R&D raises a concern for inefficiency in performance; there are many studies showing that public expenditure tends to become inefficient beyond a certain point (De Witte & Moesen, 2010; Pevcin, 2004; Scully, 1995). So, analyzing performance on public renewable energy R&D is timely and pertinent.

The main purpose of this study is to find relationships between R&D collaboration and intellectual and economic performance in renewable energy R&D. Two types of R&D performances are measured in this study: intellectual outputs and economic outcomes. This study measured intellectual outputs with academic publications and patents. Economic outcomes are measured by project sales, cost reduction, technical transfer, and import-substituting effect. This research analyzed 484 projects that participated in South Korea's

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public renewable energy R&D program between 2006 and 2014. South Korea is one of the Mission Innovation member countries, pledging to double its R&D investment by 2021 and set an ambitious goal of 20% of electricity generation from renewable energy sources by 2030 (Park, Barrett, & Gallo Cassarino, 2019). Although South Korea is committed to improving the effectiveness of public renewable energy R&D investment, it is marked by low levels of outputs as opposed to a high level of R&D intensity (IMD, 2017). The public renewable energy R&D program has been criticized for a low R&D commercialization rate compared to other public R&D programs in South Korea (KISTEP, 2018). Analyzing South Korea's case could provide lessons for other countries suffering from low performance in public renewable energy R&D.

Specifically, this study delved into R&D collaboration with two major focuses: types of collaboration and leading organizations. Studies on R&D collaborations are emphasized constantly in R&D performance measurement literature (Dyer & Singh, 1998; Gulati, 1998; Etzkowitz & Leydesdorff, 1995). Also, it is often cited in previous studies that the leader of an R&D collaboration is a decisive factor for research performance (Barry, 1991; Chang, 2010; Hirst & Mann, 2004; McCall, 2010; Mothe & Quélin, 2000), and especially, the size of enterprises are found to have impact on R&D productivity (Kelm, Narayanan, & Pinches, 1995; Tsai & Wang, 2005). Yet previous studies have not investigated which types of collaborations and which types of leaders have the greatest impact on each type of performance.

Findings in our study could widely inform the policy decision-makers of public renewable energy R&D programs by providing information on what type of collaboration and what type of leader would yield better quantitative performance. This paper is structured as follows: first, we review the literature on why measuring the public renewable energy R&D is important. After that, we develop hypotheses based on previous studies on collaboration type and leader organization. Then, we elaborate our data source, specify variables, and conduct statistical and econometrical analysis. Finally, we summarize our findings and review our study.

2. Literature Review/ Hypotheses Development

2.1. Why measuring Renewable Energy R&D performance?

With the advent of Mission Innovation, which is a global initiative established after the Paris Agreement to promote clean energy innovation, global RD&D investment is growing fast. Such a dramatic increase of public expenditure may lead to inefficiency in resource allocation. Scully (1995) proposed the "Armey Curve" to describe the efficiency of public expenditure; this curve shows that public expenditure tends to become inefficient beyond a certain amount (De Witte & Moesen, 2010; Pevcin, 2004; Scully, 1995). Thus, people with decision-making authority are tasked with preventing such inefficiency or misallocation of resources by assessing the performance of their investments and reallocating resources to maximize social benefits such as economic growth (Kim, Shin, & Lee, 2019; Romer, 1990; Scully, 1995). The performance-based budget allocation approach has proven its effectiveness, as more and more countries and sectors have employed this approach (Auranen & Nieminen, 2010; Barker, 2007; Liefner, 2003; Wang, 2019). The performance-based budget allocation could be strengthened by providing more information through proper assessment of R&D performance.

Analysis on the performance of public renewable energy R&D should be separated from the rest of the energy sector because there is a major difference between traditional energy sources and renewable energy sources. Along with traditional power generation sources such as nuclear and clean coal, renewable energy is an important pillar of power generation. Unlike traditional power sources, however, renewable energy is considered a distributed energy source. Traditional power sources rely on a centralized energy supply system with a few enormous power plants, managed and supervised by few public and large enterprises. Therefore, the marketing channel for traditional energy sources are restricted. On the other hand, renewable energy has many different marketing channels because it could be operated by many different entities such as local governments, private corporations, and even households. Diversification in target markets has also influenced the structure of renewable energy R&D, especially collaboration networks. It is not too much to say that nuclear and clean coal R&D must cope with public or large enterprises, either directly or indirectly, because these enterprises have the authority of approving the application of new technologies on their handful power plants. On the other hand, renewable energies are relatively free of such restrictions, creating more avenues for small and medium enterprises to lead projects with relatively less interference from public and large enterprises. Therefore, renewable energy R&D has a more favorable environment for small and medium enterprises to lead publicly funded research projects than traditional energy power generation R&D.

2.2. University-Industry-Government Collaboration in Renewable Energy R&D

Research activities inherently call for collaboration between multiple researchers and organizations because exchanges of information reinforce discussion, creation of new knowledge, and complementary skills from partners (Katz & Martin, 1997; Lei et al., 2012; Varadarajan & Cunningham, 1995). Study of inter-organizational collaboration has been emphasized through previous literatures (Dyer & Singh, 1998; Gulati, 1998; Etzkowitz & Leydesdorff, 1995; Mora-Valentin, Montoro-Sanchez, & Guerras-Martin, 2004); and some of these previous findings were situated in empirical studies (Czarnitzki & Fier, 2003; de Moraes Silva, Furtado, & Vonortas, 2018; Lei et al., 2012). Many of these studies emphasized the importance of cooperative research activities and understanding how university, industry, and government function both individually and collaboratively in the context of university-industry-government (UIG) relationships. Yet previous studies have not examined how each type of collaboration contributes to quantitative performance of public R&D.

In the context of renewable energy R&D, South Korean governments are committed to the creation of a research environment that facilitates the UIG collaboration with the hope of improvement in research performance. The renewable energy industry of South Korea has a relatively insubstantial industrial base compared to its centralized power supply industry, leading the government of South Korea to attempt to overcome such challenges through UIG-based collaboration in photovoltaics, wind power, and fuel cell. In 2008, the government promulgated *The Third Basic Plan for Renewable Energy Technology Development and Supply* to cultivate cooperation between UIG to secure original technologies and human resources in renewable energy industry. *The Fourth Renewable Energy Basic Plan*, which published in 2014, also emphasized the establishment of the UIG cluster for equipment testing and assessment for renewable energy sources. Such inclination was reflected in public renewable energy R&D. Based on all these finding, this study has drawn our hypothesis 1 as follows.

Hypothesis 1. The UIG collaboration type is more likely to be effective than other types of collaborations in improving renewable energy R&D performance.

2.3. Types of Leader Organization in Renewable Energy R&D

Previous studies have been shown that the leader of an R&D collaboration is a decisive factor for research performance (Barry, 1991; Kim, Min, & Cha, 1999; McCall, 2010; Mohrman, Cohen, & Morhman, 1995; Mothe & Quélin, 2000; Yukl, 2012). An incompetent leader or leading organization may lead to either low efficiency of a project outcome, or, even worse, a failure of the project. In South

Korea's public R&D system, the leading organization takes major responsibility for the project's outcome reports and the management of the collaboration participants' research activities (MOTIE, 2018). Also, the study of Mothe & Quélin (2000) showed that the overall performance of a project was shaped largely by the leader's capacity in the European EUREKA R&D consortia. However, previous studies did not investigate whether a specific type of leading organization leads to desirable performance.

Moreover, there are mixed views on R&D productivity for the size of enterprises. Some argue that small enterprises value new products highly (Chaney, Devinney, & Winer, 1991) and invest a relatively larger portion of their available resources in research and development than do large firms (Kelm et al., 1995). Chang (2010) found that large enterprises perform better in terms of patents (Chang, 2010). Tsai and Wang (2005) showed that a U-shaped relationship exists between firm size and R&D performance (Tsai & Wang, 2005). Therefore, it is important to consider whether different size of enterprises affect the R&D performance.

This study focuses on finding differences between each type of leader organization, especially based on the size of enterprises. Although there are mixed views on the literature of firm size and performance, it is certain that small and medium enterprises have received much more supports from the government. The renewable energy market for small and medium enterprises is growing and expected to reach $1.6 trillion by 2023 (World Bank, 2014). The World Bank (2014) estimated that the renewable energy market for small and medium enterprises is growing because they have more knowledges of local markets, more needs for specialization, and lower financial and technical barriers to entry compared to large enterprises. Especially for the case of Korea, small and medium enterprises received many supports in the domain of public renewable energy R&D. Also, the Korean government stipulated in *The Fourth Renewable Energy Basic Plan*, published in 2014, that the government will provide low loan financial services, exceptions for trade insurance, information, and training services exclusive to small and medium enterprises. Also, operation guidelines for renewable energy R&D specify that small and medium enterprises have less payment burden for the "matching fund" and "royalties"[1] than large enterprises. Under these political directions, it is reasonable to infer that projects led by small and medium enterprises would have better performance than other projects.

Hypothesis 2. Small and medium enterprises are more likely to be effective than large enterprises as leader organizations at improving renewable energy R&D performances.

3. Methodology

3.1. Data Collection and Research Model

This study uses panel data obtained from the "Energy R&D Result Analysis Reports" issued by the Korea institute of Energy Technology Evaluation and Planning (KETEP). They are annual reports issued from 2010 to 2019 based on surveys collected from researchers who participated in public energy research projects. The population of the survey includes public energy R&D projects completed within five years from the year of survey, so there are overlaps in the population; later surveys contain more updated information of the same project. The response rate to this survey is above 99%. More than 10,000 surveys were collected from 2010 to 2019. From these, we have sorted 2,683 R&D projects for renewable energy technologies. Then, to avoid duplication of counting the same projects, we have selected projects from the fifth year of surveys, so that the most updated data of the project could be counted. As a result, we have selected 484

[1] *Operation Guidelines for Projects for Innovation of Industrial Technology* (announced by the Ministry of Trade, Industry, and Energy in South Korea) requires for-profit organizations to provide "matching fund" proportion to the amount of R&D grants they received. "Royalties" are a price for acquiring the right to implement outcomes of a project. Since government provides grants for R&D projects, only by paying royalties, the possession of outcomes is transferred to for-profit organizations.

projects completed between 2006 and 2014. These data contain various items of information, such as leader and participant organizations, investments from government and the private sector, number and quality of patents, academic papers, number of participating researchers, R&D stage, and cooperation type. Also, within last few years of reports, this survey also collects reasons of project success and failure; for this research, we are using failure reasons from the latest report to discuss the results.

3.2. Research Model and Variable Descirptions

For the research model, we have conducted two estimation model: estimation I for measuring collaboration effect and estimation II for measuring leader effect. Then, each estimation model is constructed and compared through two sub-model: Ordinary Least Square (OLS Model) and General Tobit (GT Model). Each estimation and sub-model are applied on three dependent variables: academic publications, patent registrations, and economic outcomes. This study used multiple regression analysis because it is the most widely used analytical approach for studying the input–output relationships. For OLS model, we have used the subset of data where each quantitative performance of the project is greater than zero. Generalized Tobit model is also used when the range of the dependent variables is observed to be censored in some way (Tobin, 1958). By comparing the result among these models, we confirmed the validity of the regression result. The description of the variables is given in Table 1 and description and validation of each variables could be found in following section.

Table 1.
Descriptive Statistics and Data Usage of Variables

	Descriptive Statistics						Usage of Variables	
	Unit	**Obs.**	**Min**	**Max**	**Mean**	**SD**	**Estimation 1**	**Estimation 2**
Project Performance (Dependent)								
Academic publications	N	484	0.00	63.00	5.19	7.57	Yes	Yes
Patent registrations	N	484	0.00	69.00	2.78	5.27	Yes	Yes
Economic outcomes	₩B	484	0.00	1355.90	5.44	63.28	Yes	Yes
Project Control								
Government investment	₩B	484	0.04	27.90	2.11	3.20	Yes	Yes
Private investment (Cash, In-kind)	₩B	484	0.00	127.50	0.36	5.79	Yes	Yes
Researchers per investment	N/₩B	323	0.32	108.10	20.97	13.76	Yes	Yes
Project duration	YR	484	2.00	7.00	3.69	0.71	Yes	Yes
Academic publications (control)	N	484	0.00	63.00	5.19	7.57	Yes	Yes
Patent registrations (control)	N	484	0.00	69.00	2.78	5.27	Yes	Yes

Collaboration Effect									
Types of collaboration	Mixed	N	61					Yes	
	Non-profit	N	112					Yes	
	For-profit	N	119					Yes	
	All	N	29					Yes	
Collaboration Control									
Consortium size		N	484	1.00	14.00	1.90	2.40	Yes	
Consortium size (log)		N	484	0.00	1.14	0.27	0.28	Yes	
Participants from industry		%	484	0.00	1.00	0.57	0.42	Yes	
Leader Effect									
Types of leader	GRI	N	80						Yes
	SE	N	53						Yes
	ME	N	15						Yes
	LE	N	108						Yes
	UNIV	N	65						Yes
Leader Control									
Asset		₩B	480	0.20	21902.10	569.60	2149.6		Yes
Organization's age		YR	480	7.00	87.00	29.00	14.54		Yes
Total employments		N	482	1.00	22237.00	629.00	2718.36		Yes
Experience in renewable energy		N	484	0.00	33.00	3.40	5.72		Yes
Familiarity with participants		N	484	0.00	32.00	0.50	2.72		Yes

[1] Detail is given in *the Frame Act on Small and Medium Enterprises (Article 2)*

[2] Detail is given in *the Special Act on the Promotion of Growth and the Strengthening of Competitiveness of Middle-standing Enterprises (Article 2)*

3.2.1. Dependent Variables

As already mentioned, this study is analyzing intellectual outputs and economic outcomes with three dimensions: *academic publications*, *patent registrations*, and *economic outcomes*. These variables are known as key indicators in R&D performance measurement system, which had been included from the early literature of performance measurement such as the study of Brown & Svenson (1998). These variables were included in the survey of Energy R&D Result Analysis Reports, where respondents should provide the numerical value with proper evidence materials. In public R&D, both quantity and quality of journal publications reflect quantitative performance indicators for the purpose of comparison between different public R&D programs (Bonaccorsi & Daraio, 2003; Jiancheng & Junxia, 2004; Lee, Park, & Choi, 2009).

For academic publications, researchers provide the DOI number or article itself, KETEP checks the validity of the document by checking on the phrase of acknowledgements. If the funding source is more than one, the acknowledgement credit is divided by the number of funding sources. Patents contain standardized information related to new ideas and technological developments, which makes them one of the most important output indicators of innovative activities (Frietsch & Grupp, 2006; Pilkington, Dyerson, & Tissier, 2002).

For patent registrations, registered patents are managed by Korea Institute of Patent Information (KIPI) so KETEP could check the validity of patents through KIPI. For economic outcomes, respondent should provide the proof document for sales, cost reduction, technology transfer, or import substitutes. However, economic outcomes often created by more than R&D activity alone so that respondents must provide the "ratio of contribution" to their document with the confirmation from their organization. KETEP reviews the validity of information by checking tax invoice or other documents conforming to that standard. For analysis, we needed to moderate the effect on distribution shape for economic outcome, so we had to use square root values for economic outcomes to narrow the variance while minimizing the distortion of the data shape.

3.2.2. Independent Variables

Collaboration Effect. The dynamic interaction model of UIG relationship is originated from the Triple Helix model, which is a theory referenced frequently for measuring innovation in a knowledge-based economy (Leydesdorff & Etzkowitz, 1996). UIG relationships are composed of multiple combinations from *university (U), industry (I). and government research institutes (G).* This study re-categorized these combinations to distribute enough population and to distinguish the group with the level of pursuit in profitability: *for-profit, non-profit*, *mixed*, and *all*. *For-profit* contains the combination with enterprises only (*I) to (I)*. This is a collaboration type motivated mainly by cost economization, where companies seek to lower the cost of their R&D activities through sharing it with other companies (Hagedoorn, 2002). *Non-profit* contains combinations with university and government research institute, which indicates *(U) to (U), (U) to (G),* and *(G) to (G)*.

The collaboration between non-profit organizations arises mainly from the need to resolve complex problems (O'Regan & Oster, 2000). Many non-profit organizations are staffed by professional workers who are highly attached to their own professions and their flat hierarchy (Mintzberg, 1973), which is a good environment for sparking innovation but could cause problems in controlling human resources within the context of an increase in economies of scale. *Mixed* contains one entity from *non-profit* and another from *profit*, which indicate *(I) to (U)* and *(I) to (G)*. *All* contains all three entities of UIG relationship. *Mixed* and *All* type of collaboration is in demand when a project requires increases both in the scale of economies and the complexity of goals.

Leader Effect. In UIG relationship, research consortium is formed and one of participants must take a leader role. In this study, we took a step further and divide the type of leader organization concentrated on industry sector: *large enterprise (LE), medium enterprise (ME), small enterprise (SE), GRI, and university*. It is not only because in earlier section we established that size of enterprises can be directly related on R&D productivity (Chaney et al., 1991; Chang, 2010; Kelm et al., 1995; Tsai & Wang, 2005), but also renewable energy industry has favorable environment for small and medium enterprises which differentiated this industry from the rest of energy sector. One concern that we need to address is that *public enterprise* had to be categorized as large enterprises due to lack of samples. We thought that public enterprise leader would better be grouped with large enterprise because they both have the strongest purchase power in the industry.

Control Variables. This study controlled several factors in concern of *project control*, *collaboration control*, and *leader control*. These variables are collected through Energy R&D Result Analysis Reports, however, some of variables had to be calculated based on given information. Starting with project control, *government investment* and *private investment* had to be included since they are fundamental input of public research projects. *Private investment* is composed of not only cash but also in-kind, which is calculated by the number of equipment, facilities, or non-paid researchers [2]. Researchers per investment is calculated based on number of participated researchers divided by the amount of government investment. We also controlled project duration since the length of the time span for project participants working together could have a positive impact on project's performance (Gibson, 1999; Hoang & Rothaermel, 2005; Spanos, Vonortas, & Voudouris, 2015). *Academic publications* and *patent registrations* are also used as independent variables for the analysis of economic outcomes because Brown & Svenson (1988) study had emphasized that outputs are interim findings in the process of reaching outcomes, and both outputs and outcomes are constantly affected by feedbacks.

For *collaboration control*, we controlled few factors related to research consortium. *Consortium size* indicated number of participant organizations in the group, including leader organization. *Collaboration control(log)* was included because previous literature pointed out that it is natural to use a natural on the number of partners to compensate a skewness (Spanos et al., 2015). *Participants from industry* is also controlled since public renewable energy R&D is exceptionally reliable on experimental development stage projects with lots of players participated from the industry sector. We control this variable by calculating ratio of participant organizations from the industry sector divided by the consortium size of each project.

For *leader control*, we controlled several factors related to leader organization in perspective of both tangible and intangible asset. *Asset* indicates total asset of the organization such as cash, facilities, products, or trade accounts. It is common throughout business literature that investment in asset has to be related with the value of organization (McConnell & Muscarella, 1985). We also controlled o*rganization's age* since it is natural to expect older organization have more accumulated knowledge and marketing experiences so that they would have advantage in research performance as well. The organization's age was measured since date of establishment. *Total employments* variable is a part of intangible asset of the leader organization.

This is different from researchers participated in research projects that accounted in control variable of *researchers per investment* since this is only account for total number of employees in leader organization. Intangible resources are found to have impact on the performance of organization, including the performance on research activities (Cho, Park, & Kim, 2014; Del Canto & González, 1999). *Experience in renewable energy* was calculated by counting whether leader organization had previously involved in public renewable energy R&D program funded by KETEP as either leader or participant organization. *Familiarity with participants* is also calculated by counting whether the leader organization had previously conducted projects with participant organization in public renewable energy R&D program. The idea of *experience in renewable energy* and *familiarity with participants* was gained from Spanos et al. (2015) who have conducted similar analysis on publicly funded collaborative R&D projects.

4. Findings and Discussion

The descriptive statistics is demonstrated in Table 1. For the correlation test, this study used Pearson's correlations coefficient matrix and found all

[2] *Operation Guidelines for Projects for Innovation of Industrial Technology* states that payroll of researchers receiving salary from their institutions must be calculated in-kind to prevent duplication in payment.

variables are not significantly correlated to bias the result. For correlation, all correlation coefficients are clear except for *consortium size* and *consortium size (log)*. However, we are allowing this in our model as we discussed earlier that log variable is added to supplement skewness of original variable. To avoid the endogeneity problem, we also checked multicollinearity among variables. We have calculated the variance inflation factor (VIF), which came out as less than 10 in all analyses and average less than 4. The mean value of VIF for each regression model is given in Table 2. In a nutshell, neither correlation nor multicollinearity seem to be a concern for our analysis.

The estimation result is given on Table 2. From *estimation I*, which is the analysis of *collaboration effect*, we found that *all* type UIG relationship does not possess the highest advantage in performance of publications, patents, and economic outcomes. *All* type showed comparable advantage in creating academic publication but comparably less than *non-profit* type, shown in Table 2. All type even had less advantage creating in economic outcome compare to *mixed* type, which contains only part of entities in UIG. These findings disprove UIG relationship would have the highest advantage in creating intellectual and economic performance (hypothesis 1). *Non-profit* type of collaboration – indicating *(U) to (G)*, *(U) to (U)*, and *(G) to (G)* – found to have comparable advantage creating academic publication; none were found to have an advantage in patent; and *mixed* type – indicating *(I) to (U)* and *(I) to (G)* – found to have an advantage creating in economic outcome. Meanwhile, *for-profit* type of collaboration did not show any sign of significant relationships with all three kinds of performances.

Estimation II, which is the analyses of the *leader effect*, was made from the baseline on "GRI" leader. All enterprises showed relatively lower performance in academic publications, with medium enterprises showing the lowest performance. However, Medium enterprise leaders showed positive relationships with performance of patent registrations. This was reconfirmed in the actual statistical data as the average number of patent registrations were highest in medium enterprises and second highest in large enterprises. Also, out of the top five projects with patents output, four projects came from medium and large enterprise leaders. This shows medium enterprise-led collaboration is more effective for creating patent registrations than are other types of leader. All types of enterprises showed a positive relationship with the performance of project economic outcomes. The medium enterprises leader performs the best out of the three types of enterprises, with the large enterprise leader coming next, and the small enterprises leader coming last.

Why do medium enterprises show the most positive relationship with economic outcomes, while small enterprises show the least positive relationship with economic outcomes? We expect this result is caused by uniqueness of renewable energy industry, where medium enterprises can have as much investment capacity and technical competency in components and materials as large enterprises. Medium enterprises are mostly concentrating on improvements of preexisting technologies, where harvesting economic outcome is imminent. Also, they possess capacity on making follow-up investment. In South Korea, medium enterprises have been exhibiting strength in components and material parts markets in photovoltaic; they even have the competency to lead the large-scale wind farm projects.

To large enterprises, conducting public renewable energy R&D is one of tactics to diversify their business portfolio. When collecting data for the survey, this study also conducted short interview with principal investigators of several large enterprise-led projects and found that many of their projects were not majorly targeted for imminent deployment. Large enterprises in South Korea were executing publicly funded projects for technical areas where risks are high and long-term developments are needed. Some of the projects were pushed forward as pilot projects although the market was not even formed.

Major large enterprises, including public enterprises, in the renewable energy industry of South Korea were not concentrating their business portfolios on renewable energy. Large enterprises such as POSCO, KEPCO, and Doosan Heavy Industries are still heavily relying on business in traditional energy industries, such as power transmission and clean coal power plants.

Diversification of business and increases in debt ratio were found to increase potential risk of renewable energy companies (Lee & Heo, 2013), which led them to decline follow-up investments in public renewable R&D projects. Making investments in renewable energy constitutes diversifying business for most of the large enterprises. They also had experienced increases in debt ratio during last three financial years.

Small enterprises exhibit the lowest performance of economic outcomes in renewable energy due to the incapability to secure follow-up investments. Like medium enterprises, small enterprises are focusing on improvements of preexisting technologies as well. However, small enterprises do not have as much resources as medium enterprises.

This made the difference on the performance of economic outcomes between these two groups. This may be caused by the nature of small enterprises, since it was also noted in previous studies that stimulating follow-up investment is more likely in medium enterprises than small enterprises (Ahn, Kim, & Kim, 2017). But we also think that cost-reduction competitions in renewable energy industry aggravated the financial status of small enterprises. For instance, module costs for photovoltaics had dropped down severely due to the advance of enterprises in China. Enterprises in wind power are still struggling due to the increased shares in the domestic market. These problems were pointed out in "*The Enhancement Plan of Renewable Energy Industry*", announced by Ministry of Trade, Industry, and Energy in April 2020.

5. Conclusions

Renewable Energy R&D has different collaboration patterns from traditional power generation R&D, such as coal or nuclear. Because renewable energy sources are mostly distributed energy resources, the existence of various target markets made public research projects rely less on networking with public energy enterprises, which led to the growth in the market for small and medium enterprises. Because of these differences, R&D collaboration patterns are distinguished from those with a centralized power supply, and additional opportunities are given to small and medium enterprises to lead the publicly funded R&D projects.

This paper assessed the performance of South Korea's public renewable energy R&D program in terms of academic publications, patent registrations, and economic outcomes, as they are often considered as indicators of performance in public R&D. Using data of South Korea, this study has analyzed 484 projects of public renewable energy R&D programs to observe differences in types of collaboration and leading organization. This study found that UIG relationship was not the most effective way of improving intellectual and economic performances. Rather *non-profit* type of collaboration (combinations of university and government research institutes) found to have more effective in performance of academic publication, while *mixed* type (combinations of industry with university or industry with government research institutes) found to be more effective in creating economic outcomes. Also, medium enterprises found to have the most positive relationship with the performance of economic outcomes as a leader organization.

Small enterprises in renewable energy R&D have a positive impact on project commercialization, yet they are still under insufficient conditions to secure as much follow-up investment as medium or large enterprises. It is because small enterprises are relatively more affected by the global price competition in renewable energy, initiated by Chinese enterprises. Chinese enterprises have gained strong market powers with a competitive advantage in low production prices, especially in photovoltaics and wind power. Polycrystalline Silicon, which is a raw material used for solar panels, has been the subject of a price war. China became the biggest and cheapest supplier of polysilicon backed by major industry-specific advantages: it is the biggest metallic silicon exporter and has the lowest retail utility rates and labor costs (Mirae Asset, 2020). Wind power is also dominated by Chinese enterprises with their ability of high speed and low-cost production, so that Western suppliers have trouble matching them (Lema, Berger, & Schmitz, 2013). Such impacts have brought great cost reductions in terms of LCOE, yet created financial difficulties for enterprises in South Korea (Jung, 2019). To stabilize the renewable energy industry, governments would need to execute more policies to support small enterprises to gain technical competitiveness.

To make more projects commercializable in public renewable energy R&D, medium enterprises can play a critical role as leading organizations. Medium enterprises have shown great capacity in generating economic outcomes. They have specialties in making parts and equipment in photovoltaic and wind power industries. They also are as capable of leading large projects as large enterprises. Therefore, it is important to implement policies to encourage more competitive medium-sized enterprises to lead projects. They have not received as much investments as large enterprises yet reaped remarkable amounts of economic benefits.

UIG collaboration seemed to be ineffective in terms of generating positive economic outcomes, although the Korean government has made many efforts to improve R&D performance through UIG collaboration. In our study, we could not find any sign that UIG collaboration has made better economic outcomes than other types of collaboration. This means that a revision on the UIG collaboration policy would be necessary in the future to promote more project commercialization in renewable energy.

Findings in this study are significant in illustrating the way to accelerate energy transition by stimulating commercialization of public renewable R&D projects. The improvement in economic outcomes indicates the increase in utility and potential of the project for the expansion of renewable energy generation and capacity. The economic outcomes of renewable energy R&D may send positive signals to both public and private investors and contribute to the continued development of renewable energy technology. Also, our findings could be helpful in securing public R&D budgets for renewable energy. For public R&D programs, especially in South Korea, the evaluation result on quantitative performances could directly affect the upcoming program budget.

There are a few limitations to this study. This study did not include interactive terms on collaboration types and leaders because some of these sub-categories created by interactive terms did not have enough observations for regression analysis. Another limitation is that this study did not focus our investigation on the collaboration size. It would be interesting to study whether performance increases constantly with increases in collaboration size and public investment.

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APPENDIX

Table 2.
Estimation Results on Academic Publications of Public Renewable Energy R&D

		Estimation I-1. Collaboration Effect on Academic Publication		**Estimation II-1. Leader Effect on Academic Publication**		**Estimation I-2. Collaboration Effect on Patent Registration**		**Estimation II-2. Leader Effect on Patent Registration**		**Estimation I-3. Collaboration Effect on Economic Outcome**		**Estimation II-3. Leader Effect on Economic Outcome**	
		OLS Model	**GT Model**	**OLS Model**	**GT Model**	**OLS Model**	**GT Model**	**OLS Model**	**GT Model**	**OLS Model**	**GT Model**	**OLS Model**	**GT Model**
Collaboration Effect													
Types of Collaboration	Non-profit	**8.24***** (1.37)	**10.72***** (1.62)			0.92 (1.20)	0.81 (1.58)			-17.35 (23.63)	**-16.35**** (4.40)		
	For-Profit	1.54 (1.31)	1.35 (1.58)			0.09 (1.09)	-0.19 (1.42)			20.08 (21.42)	0.97 (2.90)		
(Baseline: Mixed)	All	1.91 (1.61)	**4.00**** (1.85)			1.52 (1.34)	2.33 (1.71)			-16.18 (26.33)	**-5.55*** (3.37)		
Leader Effect													
Types of Leader	SE			**-6.88***** (1.68)	**-8.42***** (1.93)			-0.26 (1.46)	-0.80 (1.89)			26.90 (28.83)	**14.96***** (4.90)
	ME			**-7.64***** (2.11)	**-9.69***** (2.50)			**3.21*** (1.81)	**4.27*** (2.31)			**84.63**** (36.06)	**15.89***** (4.99)

LE					**-5.42*** **	(1.33)	**-7.82*** **	(1.55)					-0.08	(1.16)	-0.13	(1.51)					36.45	(22.90)	**13.27*** **	(4.06)
UNIV					**3.23** **	(1.42)	**3.02***	(1.61)					0.25	(1.21)	-0.15	(1.56)					13.08	(23.93)	-0.95	(4.59)
Project Control																								
Government investment	**0.66*** **	(0.25)	**0.76*** **	(0.29)	**1.16*** **	(0.24)	**1.36*** **	(0.27)	**0.54*** **	(0.21)	**0.58** **	(0.27)	**0.56*** **	(0.20)	**0.66** **	(0.26)	0.72	(4.09)	-0.01	(0.47)	0.68	(4.09)	0.05	(0.49)
Private investment(cash, in-kind)	0.31	(0.19)	0.34	(0.21)	0.17	(0.18)	0.18	(0.21)	0.07	(0.16)	0.13	(0.20)	0.07	(0.16)	0.16	(0.19)	-1.44	(3.09)	-1.25	(1.17)	-1.31	(3.08)	-1.17	(1.25)
Researchers per investment	**1.66*** **	(0.31)	**1.97*** **	(0.36)	**1.64*** **	(0.31)	**2.02*** **	(0.37)	**0.54** **	(0.27)	**0.63***	(0.34)	**0.57** **	(0.28)	**0.74** **	(0.35)	-6.52	(5.24)	-0.78	(0.71)	**-9.24***	(5.49)	-1.23	(0.76)
Project duration	**2.06*** **	(0.69)	**3.23*** **	(0.82)	**1.58** **	(0.67)	**2.53*** **	(0.80)	-0.76	(0.58)	-0.60	(0.76)	-0.77	(0.57)	-0.67	(0.75)	-6.2	(11.35)	-0.69	(1.38)	-2.11	(11.36)	-0.56	(1.43)
Academic publications (control)									**0.09** **	(0.05)	**0.14** **	(0.06)	**0.11** **	(0.05)	**0.16*** **	(0.06)	0.6	(0.93)	-0.03	(0.17)	0.70	(0.95)	0.08	(0.17)
Patent registrations (control)	0.14**	(0.07)	**0.16** **	(0.08)	**0.16** **	(0.07)	0.19**	(0.08)									1.27	(1.11)	**0.31*** **	(0.12)	1.05	(1.13)	**0.29** **	(0.12)
Collaboration Control																								
Consortium size	-0.14	(0.56)	-0.17	(0.64)					0.75	(0.46)	0.81	(0.59)					14.16	(9.12)	**2.39** **	(1.13)				
Consortium size (log)	2.61	(1.97)	2.93	(2.24)					-1.51	(1.64)	-1.74	(2.10)					-47.24	(32.16)	-6.55	(5.33)				

Participants from industry	-2.38	(1.54)	-1.36	(1.84)					0.26	(1.28)	0.66	(1.68)					24.38	(25.15)	1.16	(3.79)				
Leader Control																								
Asset					0.00	(0.00)	0.00	(0.00)					**0.0005****	(0.00)	**0.001***	(0.00)					0.00	(0.00)	0.00	(0.00)
Organization's age					-0.01	(0.03)	-0.02	(0.04)					-0.02	(0.03)	-0.03	(0.04)					0.58	(0.56)	0.01	(0.07)
Total employments					**0.0003***	(0.00)	0.00	(0.00)					0.00	(0.00)	0.00	(0.00)					0.00	(0.00)	0.00	(0.00)
Experience in renewable energy					0.00	(0.07)	-0.01	(0.08)					0.04	(0.06)	0.07	(0.08)					0.36	(1.19)	-0.06	(0.26)
Familiarity with participants					0.00	(0.12)	0.02	(0.14)					0.10	(0.10)	0.10	(0.13)					-0.50	(2.03)	0.24	(0.28)
Constant	**-12.51*****	(2.48)	**-20.90*****	(3.04)	**-5.56***	(2.87)	**-10.78*****	(3.39)	0.70	(2.14)	-2.21	(2.80)	1.76	(2.44)	-1.13	(3.17)	35.35	(42.07)	-2.95	(5.21)	-2.59	(48.29)	**-13.97****	(6.88)
Adj. R^2	0.35				0.38				0.12				0.13				0.06				0.05			
F statistic	14.93***				13.14***				3.71**				3.19**				1.55				1.11			
Mean VIF	3.46				1.78				3.54				1.84				3.36				1.81			
AIC			1877				1873				1708				1711		652						706	
Log-likelihood			-925				-920				-841				-839		-313						-336	

[1] Note 1: *, **, and *** denote significance at the 10%, 5%, and 1% levels, respectively [2] Note 2: Standard errors are indicated in parenthesis.