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The effect of patent protection on firms' market value: The case of the renewable energy sector

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ABSTRACT

In the renewable energy industry, technology development requires a large initial investment by firms and takes a long time. Thus, protecting patents in this industry has become an increasingly important issue in maintaining a company's value. In this study, we examine how patent protection affects firms' market value by analyzing the listed companies in South Korea in the renewable energy sector over a 35-year period (from 1980 to 2014). We find that simple patent counts are not a strong measure for explaining a firm's financial success in this industry, whereas indices that represent a firm's ability to protect patents (backward citation and patent family) positively and significantly affect the firm's market value. This study suggests that patent protection is an important factor for companies in improving their economic value in the renewable energy sector.

1. Introduction

In the renewable energy industry, as in other high-tech industries, protection of a company's intellectual property substantially determines the company's success. In particular, developing technology in renewable energy requires a large investment by firms and takes a long time [1,2]. Thus if technology rights are nullified or other companies can easily imitate technology in the sector, the corresponding losses can be great, and firms would find it difficult to recover their investment in it [49].

In addition, recent patent litigation among renewable energy companies has increased, and companies whose patent lawsuits fail have suffered severe losses. For example, GE (General Electric) sued Mitsubishi Heavy Industries, alleging that it had infringed GE's wind turbine patent. The court ruled in favor of GE and ordered Mitsubishi to pay GE $170 million in penalties. Afterward, Mitsubishi Heavy Industries' stock price fell almost 7.3%. Thus protecting patents became an increasingly important issue in maintaining a company's value in the renewable energy industry.

However, little previous research examines the issue of patent protection and its effect on renewable energy firms. Rather, most of the previous literature on renewable energy focuses on technology transfer, network analysis, and public policy, using patent characteristics. For example, one research stream on renewable energy examines the relationship between the patent system and technology transfer in green energy [3]. Other literature uses patent network analysis to study organic photovoltaic cells in renewable energy [4].

In this study, we examine how patent protection affects firms' market value in renewable energy industry. In other words, we examine the effect of two important measures of patent protection—backward citation and the size of patent families—on firms' market value. Backward citation can be measured by the extent to which firms' patents are protected from invalidation suits because patents that do not cite previous knowledge are more likely to be subject to patent invalidation suits than those that do not [5]. Patent owners can file their patents in different countries to protect inventions via patent families [6]. Therefore, the number of patent families per company can be a proxy for the company's capacity to protect the patents it holds. We estimate an empirical model that captures the relationship between firms' patent protection and market value by using panel data on 197 firms in the South Korean renewable energy industry from 1980 to 2014. Our analysis shows that the number of backward citations and the size of patent families significantly affect a firm's market value in the renewable energy industry. In other words, a firm's degree of patent protection significantly enhances the financial fortunes of renewable energy.

The remainder of this paper is organized as follows. In Section 2, we focus on innovative activities related to the renewable energy sector and then study information about patent protection and its economic value. Section 3 explains the methodologies and econometric tools that we used. Section 4 elaborates on our results, and in Section 5, we conclude the paper.

2. Literature review

2.1. Patent studies in the renewable energy industry

Patents are usually regarded as a proxy measure for the level of innovation or technological knowledge [7,8,50-52]. This perspective is also reflected in patent studies about the renewable energy industry, and these studies can be divided into four research streams: technological changes and trends, technology transfer, network analysis, and government policy. Because patents imply technological knowledge [53,54], many prior studies use patents to examine innovation trends in renewable energy. Wong et al. [9] utilize patents to investigate innovation patterns in low-carbon energy systems in emerging Asian economies, and Wong et al. [10] use patents to illustrate patterns in technological accumulation. Furthermore, Tsai et al. [11] demonstrate the development of offshore wind technology in East Asian countries using patents granted. The effect of

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the patent system on technology transfer in renewable energy has also been explored [12,13], finding little impact.

In the case of network analysis, patent citation networks are considered as the knowledge flows between countries or organizations that have those renewable technologies [14]. In this case, a few nodes in the company, country, and technology fields have multiple links, and other nodes have very few links [4,15]. Other studies examine the relationship between government policy and the development of renewable energy using patent data. Zhao et al. [16] employ a patent analysis to indicate which policies promote advances in the use of solar power energy in China. Studies on the member countries of the Organization for Economic Cooperation and Development (OECD) show that government policies are applied more effectively in a country if it has a large number of patents with high innovation capability [13,17]. These perspectives indicate that patent is an important issue for the renewable energy industry.

However, although considerable literature shows the importance of patent [55,56], only a small proportion explores the relationship between patent protection and its effect on a firm's market performance, especially in the renewable energy industry. Renewable energy companies invest a considerable amount of capital in building the initial infrastructure and developing intellectual property, for which the initial investment has a long payback period [1,2,18]. Therefore, if the technology developed by the company is infringed or invalidated by other companies, it will lose its significant investment in the development of technology in terms of both monetary value and time. Thus the ability to protect their patents is an important issue for renewable energy companies as they try to maintain their value.

2.2. Patent protection and economic value of patent protection

Patent protection has received attention in previous studies, but mostly in other industries. These studies examine the issue from two different perspectives: how long patents can be protected (the patent renewal perspective) and the extent to which a patent should be protected (the patent scope perspective). Patent renewal perspective has been found to have a positive effect on R & D development. Schankerman [19] uses patent renewal data to measure patent protection and argues that higher patent protection positively affects incentives in R & D, depending on the technology [19]. In addition, an optimal patent policy for the patent length and patent scope is needed to properly reward innovators [20]. It has also been found that the scope of the patent protection serves as a catalyst for early announcement of innovative inventions [21]. In addition, it has been found that a broad scope and short-lived patents are the most efficient for social welfare [22].

In addition, a few studies examine the relationship between patent protection and corporate value by measuring the ability to protect patent protection from patent litigation. Lerner [23] examines the impact of patent scope on the value of venture capital–backed biotechnology start-ups. He uses patent IPC (International Patent Classification) codes for calculating patent breadth, which he proxies as patent protection. He argues that the broader the patent protection scope is, more significant its effect will be on firm value [23]. However, the authors of this paper did not use patent protection as a concept to defend patent litigation or to protect technology rights.

In this study, we use backward citation of patents and patent family size as a measure of patent protection. This is because previous studies show that patents that do not cite prior articles are more likely to be invalidated, and patents with fewer backward citations are more likely to be subject to patent infringement litigation [5,24]. Therefore, the number of backward citations included in the patent plays an important role in protecting the patent from patent infringement lawsuits. The size of a patent family permits an inventor to apply for patents and protect the right to technology in several countries at once [25]. However, patent family size has not been seriously considered as a proxy for patent protection, although it is a good indicator of a firm's level of patent protection. Popp [26] uses patent family size as a measure of technological quality to estimate the relationship between increasing knowledge assets and renewable energy investment across 26 OECD countries from 1991 to 2004. This paper argues that the protective strategy, though registering more countries, increases per capita investment in the renewable energy sector at the national level [26]. In this paper, we define patent protection as the ability to defend against invalid patent litigation and to protect technology rights by using backward citation and patent family size. Using this concept, we examine the effect of patent protection on the market value of a company.

3. Model, data, and variables

3.1. Model

A model used by Griliches [27] is the predominant one employed for researching the market value and knowledge assets of companies. The following equation captures the value of knowledge assets using Tobin's Q.

$$V_{it} = q_{it}(A_{it} + bK_{it})^{\sigma} \tag{1}$$

V_{it} means the market value of a firm i at time t, A_{it} represents the current value of the firm's total assets, and K_{it} denotes the company's knowledge assets i at time t [28,29]. In this equation, the valuation coefficient is denoted as q_{it}. This valuation coefficient includes an individual effect, time differences, and industry- and firm-specific components [29–31]. By taking logarithms on both sides, the formula is simplified for calculating a firm's market value. According to Hall et al. [28], coefficient b estimates the shadow value of a firm's knowledge assets. Also, $\sigma = 1$ if the value estimation has a constant outcome [30].

$$\log Q_{it} = \log\frac{V_{it}}{A_{it}} = \log q_{it} + \log\left(1 + b\frac{K_{it}}{A_{it}}\right) + \epsilon_{it} \tag{2}$$

For estimating a firm's market value and related patent values, we follow the well-known equation developed by Hall et al. [28]

$$\log Q_{it} = \log q_{it} + \log\left(1 + b_1\frac{RDST_{it}}{Asset_{it}} + b_2\frac{PATST_{it}}{RDST_{it}} + b_3\frac{FCITST_{it}}{PATST_{it}}\right) + \epsilon_{it} \tag{3}$$

This equation explains the knowledge flow in a technology development process. R & D expenditure (*RDST*), patent count (*PATST*), and forward citation (*FCITST*) are regarded as different stages of knowledge flow. A company's knowledge assets are captured by R & D expenditure, patent stock, and patent citation, and each stage shows a company's knowledge stage [29–33]. First, firms seek to develop new technology, so they invest capital in R & D expenditure. So the ratio of stocks (*RDST*) to physical assets (*Asset*) indicates a firm's emphasis on R & D to achieve technological growth. Second, as a consequence of R & D expenditure, a technology is developed, and the inventor tries to protect this technology using a patent.

This patent stock value (*PATST*) indicates the consequence of R & D activities (*RDST*). Finally, forward citation of the patent (*FCITST*) is a proxy for the quality of a patent. If the technology that a company develops is valuable, forward citations of it are more numerous than those for another patent. Eq. (3) explains a firm's knowledge flow, and we can empirically see the impact of this knowledge asset on a company's market value.

However, we are interested in investigating the relationship between a firm's market value and patent protection. To detect the patent protection effect, we establish a backward citation stock (*BCITST*) and patent family stock (*PFAMST*) and divide these two variables into patent stock as follows:

$$\log Q_{it} = \log q_{it} + \log\left(1 + b_1\frac{RDST_{it}}{Asset_{it}} + b_2\frac{PATST_{it}}{RDST_{it}} + b_3\frac{FCITST_{it}}{PATST_{it}} + b_4\frac{BCITST_{it}}{PATST_{it}} + b_5\frac{NPRST_{it}}{PATST_{it}} + b_6\frac{PFAMST_{it}}{PATST_{it}}\right) + \epsilon_{it} \tag{4}$$

In addition, to capture the effect of backward citations more precisely, we construct nonpatent reference stock variables (*NPRST*). A patent contains nonpatent references if it uses science-based knowledge, such as journal articles or papers. Thus, the nonpatent reference stock per patent stock shows the monetary value of science knowledge spillover to a firm's market value. Thus, b_4 and b_6 represent the value of the patent protection effect in the dependent variable. Moreover, it is logical that a firm's knowledge assets and R & D activities will affect the firm's market value later. Thus, we make an assumption about the one-year lag between R & D expenditure, knowledge flow, patent protection, and financial returns on markets.

3.2. Estimation method

To use the market value approach, nonlinear least squares (NLS) should be applied [28,29,31,34]. In previous studies, log (1 + x) is regarded as x, and the OLS method is applied [27,35,36]. However, this approach becomes inaccurate if x becomes large. As Hall [34] points out, the use of OLS is inaccurate if the ratio of knowledge assets to physical assets increases. And Hall [34] suggest that using NLS is appropriate for estimating the nonlinear function assumed above if the ratio of knowledge assets to physical assets is high.

The market value approach of this study has limitation on firm heterogeneity issue. Researchers are concerned about unobserved firm heterogeneity because it is hard to apply firm-fixed effects using a market value approach. However, unlike Tobin's Q, which measures market value, knowledge assets such as patent backward citations, patent families, and physical assets change very slowly over time, and thus they are highly correlated with firm-specific effects. Therefore, the firm-fixed effect on the model used in this paper makes accurate measurement somewhat difficult [29,31].

3.3. Data collection

This study is based on the listed companies in South Korea in renewable energy as defined by the Korean Energy Agency (KEA). According to the KEA, renewable energy is divided into 11 sectors (solar thermal, photovoltaic, biomass, wind power, geothermal, fuel cell, hydrogen energy, coal gasification, ocean energy, small hydro power, and waste energy). Thus, we consider renewable energy patents in these 11 sectors and collected listed companies which had these renewable energy patents.

One issue in processing the data is how to identify the renewable energy industry. A variety of industry sectors is related to the renewable energy industry by investing in advanced renewable energy technologies. So renewable energy has not been clearly defined in the Korean Standard Industrial Classification (KSIC). Thus, by looking at a firm database of the Renewable Energy Center of Korean Energy Management Corporations and renewable energy patent data from the Korean Institute for Energy Research, we can identify firms in the renewable energy industry. After eliminating a few companies with an extreme outlier from the patent data, our database of firms comprises 197 publicly traded companies from 1980 to 2014. By doing so, we match patent information and publicly traded firm-level financial information obtained from the Data-Guide, which has data for Korea's stock market.

3.4. Variables

We use Tobin's Q as a dependent variable, which contains information about the ratio of a firm's market value to its total assets. We define the value of a firm's assets as a company's total assets at the end of a fiscal year. A company's market value is recognized by aggregating the value of listed stocks. Compared with the dependent variable, the independent variables—the stock value of knowledge assets (R & D expenditure, patent-related variables)—are difficult to calculate. Thus, first, we collected R & D expenditure data from the financial database of the Data-Guide. This R & D expense information includes investment on a firm's R & D activities each year. However, when dealing with knowledge asset data, we have to consider knowledge assets a stock value. Thus, we constructed the R & D stock variable by using an R & D expense database. In doing so, we considered that R & D stock diminishes over time because of a firm's technological improvement and competition with rival companies. So we use the depreciation calculation used in previous studies, which considered the depreciation level of a stock the usual δ of 15% [30,33]. The R & D stock is calculated using the following equation.

$$R\,\&\,DSTOCK_T = R\,\&\,D_T + (1-\delta)R\,\&\,DSTOCK_{T-1} \tag{5}$$

Our research database starts in 1980, thus initial data for the R & D stock are unknown. We use Eq. (6) to calculate the initial values. This assumes that R & D expenditure is constantly growing at a specific rate. So we use the standardized g of 8% growth for calculating initial R & D stock [29–31,33].

$$R\,\&\,DSTOCK_{T0} = \frac{R\,\&\,D_{T0}}{(\delta + g)} \tag{6}$$

Patent-related variables (*PRV*)—such as the number of patents, forward citations, backward citations, and patent families—are constructed using the same method as R & D stock value, except for the initial value. We consider the depreciation level of the patent-related variable, such as

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the stock of R & D, the usual δ of 15%. This patent value is also an intangible asset of the stock of knowledge, so we can apply the same depreciation rate as that for stock of R & D here. However, we do not need to estimate the initial stock value of *PRV* because the first year of our database is 1980, and we can handle all the renewable patent data sources from 1980. Thus, we do not need to find the initial value of *PRV*.

$$PRVSTOCK_T = PRV_T + (1-\delta)PRVSTOCK_{T-1} \tag{7}$$

We use various patent protection indicators from the previous literature. We use the stock of backward citations (*BCITST*) and the stock of patent families (*PFAMST*) to measure the value of patent protection. First, the number of patent families has been recognized as a measure of patent protection. According to the European Patent Office [37], a patent family is defined as follows: "A patent family is a set of either patent applications or publications taken in multiple countries to protect a single invention by a common inventor(s) and then patented in more than one country." A firm can choose in which and how many countries to apply for a patent, and it can seek a patent grant in more than one jurisdiction [6,25,38]. This strategic action can be used as a way for firms to protect their patents from inventors in another country. To explain the impact of a patent family on a firm's market value, we use the number of patent families and divided it by the number of patents at each company. A company with a high proportion of patent families per patents has a great capacity to protect its patents from rival companies. Therefore, the number of patent families at each company conveys important clues about its capacity to protect its patents.

Second, backward citations of patents (*BCIT*) show what kinds of existing knowledge this patent used, and these citations can delimit the scope of a patent [39]. Several scholars believe that a large number of backward citations have a low monetary value and do not indicate an innovative invention. However, patent lawyers and examiners argue that they add more relevant references to protect an invention [6]. According to Allison and Lernely et al. [5], patents that do not cite prior knowledge are more likely to be invalidated than ones that cite prior knowledge. If a patent does not cite relevant prior articles, it be challenged in a patent invalidation suit in the future [5,40]. Thus, a large number of backward citations can become proxies for the protection of patents from invalidation claims. Therefore, we use the stock of backward citations of patents (*BCITST*) per the stock of patents (*PATST*) as a measure of patent protection from patent invalidation suits.

Forward citation (*FCIT*) is considered a powerful tool for calculating the quality of patents [29,30]. This variable shows how valuable the patent is in the market. A patent that has a large number of forward citations contains high-quality technological information [41]. The stock of forward citations is calculated using the same method as that used for other knowledge assets. To correct for the potential problem of backward citation logic, we use the stock of non-patent references (*NPRST*) to capture knowledge spillover effects. In previous studies, backward citations are used as a proxy for spillover effects, and spillover effects have a positive effect on the market value of firms [32]. To deal with this effect, we add non-patent references to capture knowledge spillover effects. Patents contain nonpatent references if they use science-based knowledge such as journal articles or papers. Therefore, these indicators can capture knowledge spillover effects from science to technology. Finally, we include a year dummy and control for firm size by including the log of the number of employees at each firm. Also, we consider industry-fixed effects by adding industry dummy variables.

3.5. Descriptive statistics

Table 1 lists descriptive statistics on variables used in this study. As seen in this table, assets, Tobin's Q, R & D expenditure, and other knowledge stock values have means that are higher than their medians. In particular, knowledge stocks (*PATST, FCITST, BCITST, PFAMST,* and *NPRST*) are extremely right skewed. As in previous studies, R & D expenditure is not available for all firms in our dataset. To deal with this problem, we use a dummy variable for missing R & D data, which equals 1 if data are missing. This was the case for 14.01% of all observations. Similarly, total market values are not available for some observations. Because the financial data that we use do not have full data on the aggregate value of listed stocks, we dropped Tobin's Q, which is zero for market value.

Table 1
Descriptive statistics.

Variables	N	Mean	SD	Min.	Median	Max.
Tobin's Q	2806	0.60	0.63	0.0025	0.42	8.88
Asset	2806	3,956,615	1.32e+07	8134.71	306,992	2.30e+08
R & D	2806	55,829.72	554,937.3	0	1310.35	1.44e+07
R & D Stock	2806	194,224.8	1,881,471	0.018189	5951.88	5.47e+07
RDST/ASSET (R & D/Asset)	2806	0.04	0.06	0	0.01	0.58
Patent Stock	2806	8.78	42.89	0	0.32	603.62
PATST/RDST (Patent Stock/R & D Stock)	2806	0.0014	0.02	0	0	0.54
FWD Citation Stock	2806	9.22	49.30	0	0	857.16
FCITST/PATST(FWD Citation Stock/Patent Stock)	2806	0.55	1.24	0	0	10.00
BWD Citation Stock	2806	24.29	130.30	0	0	1874.40
BCITST/PATST(BWD Citation Stock/Patent Stock)	2806	1.02	1.51	0	0	7.00
Nonpatent reference Stock	2806	0.31	1.48	0	0	17.14
NPRST/PATST(Non patent reference Stock/Patent Stock)	2806	0.03	0.23	0	0	3.00
Patent family Stock	2806	3.41	23.58	0	0	429.19
PFST/PATST(Patent family Stock/Patent Stock)	2806	0.08	0.22	0	0	1.00
Employee	2806	3768.8	9690.8	8	661	101,970

Note: Monetary amount in KRW 1 million. < 1 USD = 1161 KRW > .

Table 2
Regression result (Market value as a function of R & D, patents, citations, and patent family).

	m1	m2	m3	m4	m5	m6	m7	m8	m9	m10	m11
Constant	− 1.0296***	− 1.0460***	− 1.0810***	− 1.1657***	− 1.1814***	− 1.1013***	− 1.2822***	− 1.2987***	− 1.0816***	− 1.2283***	− 1.3135***
	(0.0968)	(0.0970)	(0.0986)	(0.1072)	(0.1083)	(0.0975)	(0.1086)	(0.1099)	(0.0972)	(0.1085)	(0.1100)
RDST/ASSET	1.4491***	1.5695***	1.5939***	1.8117***	1.7987***	1.6334***	1.9923***	1.9907***	1.4810***	1.7412***	1.9300***
	(0.3817)	(0.3934)	(0.4038)	(0.4314)	(0.4358)	(0.3999)	(0.4543)	(0.4598)	(0.3988)	(0.4435)	(0.4619)
PATST/RDST		3.0604*	3.3049*	3.5462*	3.7140*	3.3823*	4.2211*	4.4225*	3.7414*	4.5631*	4.9110**
		(1.7870)	(1.8620)	(2.0434)	(2.0844)	(1.8724)	(2.2880)	(2.3387)	(1.9789)	(2.3443)	(2.4754)
FCITST/PATST			0.0437*		0.0382			0.0393		0.0269	0.0322
			(0.0223)		(0.0237)			(0.0251)		(0.0239)	(0.0251)
BCITST/PATST				0.0490**	0.0439**		0.0750***	0.0699***		0.0526**	0.0701***
				(0.0209)	(0.0213)		(0.0230)	(0.0235)		(0.0223)	(0.0238)
NPRST/PATST						0.5688***	0.7146***	0.7399***			0.6738***
						(0.1547)	(0.1847)	(0.1915)			(0.1927)
PFST/PATST									0.4183***	0.4836***	0.3328***
									(0.1089)	(0.1264)	(0.1273)
Firm-year observations	2806	2806	2806	2806	2806	2806	2806	2806	2806	2806	2806
Number of firms	197	197	197	197	197	197	197	197	197	197	197
Adj R-Squared	0.3668	0.3675	0.3683	0.3687	0.3692	0.3742	0.3769	0.3773	0.3717	0.3734	0.3788

Standard errors in parentheses. *$p < 0.1$, **$p < 0.05$, and ***$p < 0.01$.

4. Results

4.1. Full model estimation

Table 2 shows the results of our estimation. The results present estimated regression coefficients, which imply the effects of R & D, patents, forward citations, backward citations, non-patent references, and patent families on the market valuation of firms. We construct models 1–11 and show the economic value of knowledge assets.

First, we examine the relationship between R & D activities and innovation outputs and firms' market values. The ratio of the stock of R & D to total assets (*RDST*/*ASSET*) has a positive relationship with market value and is statistically significant across all models. This suggests that research activities are an important factor in renewable energy for increasing firms' market value. Similarly, the patent stock per R & D stock (*PATST*/*RDST*) is also positively associated with the market value of firms, and it is at least marginally statistically significant (at the 10% level) in models 2–11. This shows that firms with higher innovation productivity are well regarded in the stock market.

We further analyze the relationship among citations, the patent protection strategy, and the firms' market value, and these results are shown in models 3–11. Models 3, 4, and 9 are designed to show each effect of the stock of forward citations (*FCITST*/*PATST*), backward citations (*BCITST*/*PATST*), and patent family (*PFST*/*PATST*) per the stock of patents on market value, and the rest of the models are designed to show their effects, controlling for other factors. The forward citation of patents does not have any impact on market value, showing no statistical significance except in model 3. Model 3 shows that the forward citation of patents has marginal statistical significance at the 10% level. This model is the one that is least controlled, so omitted variable bias may cause the statistical significance. Furthermore, a forward citation may not be informative enough to be valuable in the market because the Korean patent system is not required to provide all relevant prior articles as a forward citation. Thus we conclude that forward citation is insignificant to the market value of firms. The effect of backward citations is the opposite of that of forward citations. This patent protection indicator has a positive relationship with the market value of firms. This relationship is fairly consistent and statistically significant across the models. Interestingly, a patent family is also positively related to firms' market value and statistically significant in all the models.

Although this study regards the number of backward citations per patent as a patent protection strategy to prevent invalidation of the patent, one could also consider it knowledge spillover, as can be seen in nonpatent citation. Unlike citation of patents, the citation of non-patent references tends to indicate fundamental ideas in, for example, scientific journal articles. In other words, when a patent cites a scientific journal or commercial literature, a link is created between science and technology. Thus, citing non-patent references could be considered a knowledge flow from science to technology [42]. The ratio of the stock of nonpatent citations to patent citations (*NPRST*/*PATST*) was added to examine such spillover effects from science to technology. The stock of non-patent references per patents is positively related to firms' market value and is statistically significant in all the models.

In summary, we show that knowledge assets are positively associated with firms' financial performance and that patent protection strategy is well regarded in the market. These findings suggest the important role of a patent protection strategy in the renewable energy industry.

4.2. Robustness check

We consider different assumptions and settings to validate our results. First, we consider the effect of a firm's size. If a firm is large, it may have more resources to invest in financially intensive projects, which could affect the knowledge assets or the value of the firm. To avoid this possible size effect, we control for the number of employees at each firm. In other words, we assume that a firm with more employees is larger and has more resources to invest in knowledge assets. We add the logarithmic value of employees in the models to control for the size effect, and corresponding results are shown in Table 3. The results in Table 3 are more or less similar to those in Table 2 with small variations, and the findings are consistent even after controlling for the effect of firm size. Therefore, a firm's ability to protect patents significantly affects the market value of a firm.

Second, we employed a different estimation method to ensure that our findings do not arise from a specific estimation method. We approximated our estimation from $log(1 + x)$ by x [29]. We used the ordinary least squares (OLS) method, as it is linearly approximated, and the

Table 3
Robustness check (Include employee numbers).

	m1	m2	m3	m4	m5	m6	m7	m8	m9	m10	m11
Constant	− 0.7807***	− 0.8047***	− 0.8402***	− 0.9246***	− 0.9406***	− 0.8351***	− 1.0158***	− 1.0328***	− 0.7469***	− 0.8947***	− 0.9830***
	(0.1216)	(0.1222)	(0.1235)	(0.1304)	(0.1314)	(0.1219)	(0.1307)	(0.1318)	(0.1224)	(0.1316)	(0.1323)
RDST/ASSET	1.3168***	1.4231***	1.4417***	1.6444***	1.6291***	1.4651***	1.7911***	1.7873***	1.2228***	1.4522***	1.6308***
	(0.3735)	(0.3844)	(0.3944)	(0.4205)	(0.4246)	(0.3892)	(0.4410)	(0.4463)	(0.3847)	(0.4264)	(0.4439)
PATST/RDST		2.5941	2.8197	3.0088	3.1668	2.8510	3.5688*	3.7586*	3.1891*	3.9109*	4.2239*
		(1.6743)	(1.7451)	(1.9108)	(1.9498)	(1.7460)	(2.1319)	(2.1803)	(1.8516)	(2.1955)	(2.3168)
FCITST/PATST			0.0436**		0.0380			0.0392		0.0244	0.0298
			(0.0221)		(0.0235)			(0.0249)		(0.0235)	(0.0247)
BCITST/PATST				0.0480**	0.0429**		0.0745***	0.0694***		0.0531**	0.0697***
				(0.0206)	(0.0211)		(0.0228)	(0.0233)		(0.0222)	(0.0236)
NPRST/PATST						0.6005***	0.7485***	0.7754***			0.6918***
						(0.1581)	(0.1883)	(0.1953)			(0.1973)
PFST/PATST									0.5434***	0.6270***	0.4779***
									(0.1184)	(0.1381)	(0.1385)
Log (Employee)	− 0.0372***	− 0.0358***	− 0.0357***	− 0.0354***	− 0.0354***	− 0.0398***	− 0.0397***	− 0.0396***	− 0.0509***	− 0.0506***	− 0.0501***
	(0.0111)	(0.0111)	(0.0111)	(0.0111)	(0.0111)	(0.0111)	(0.0111)	(0.0111)	(0.0115)	(0.0115)	(0.0114)
Firm-year observations	2806	2806	2806	2806	2806	2806	2806	2806	2806	2806	2806
Number of firms	197	197	197	197	197	197	197	197	197	197	197
Adj R-Squared	0.3691	0.3696	0.3704	0.3708	0.3712	0.3768	0.3796	0.3800	0.3759	0.3776	0.3829

Standard errors in parentheses. *$p < 0.1$, **$p < 0.05$, and ***$p < 0.01$.

results are presented in Table 4. Our findings are also robust to the different estimation methods but with some changes in statistical significance. Therefore, we can conclude that our findings are robust, showing that knowledge assets and patent protection ability are positively related to the market value of a firm in the renewable energy sector.

Finally, our database includes companies that concentrate on renewable energy and develop it as part of their business portfolio. Therefore, analyzing firms with the classification approach applied above can cause an industry classification problem. Thus, in order to overcome this issue, we reclassified the companies using stricter rules. We used two criteria to identify renewable energy companies. First, we reclassified firms based on the Standard Classification of Renewable Energy suggested in "Policy for Job Creation in Energy Industry," a research report conducted by the Legislative Policy Research Association in 2012 [43]. The classification is shown in Table 5.

Second, we also identified companies that are members of the Korean Renewable Energy Association. Then, based on these two strict classification rules, we further identified 32 renewable energy companies among the 197 companies in the original data. Using information on these 32 companies, we further checked the robustness of our results as shown in Table 6. Our results are similar to those in the full sample in Table 2. In particular, backward citations and patent families, which measure patent protection, can be interpreted as having a significant effect on the market value of a company.

To checking the validity of previous results, we further applied the OLS method to this data set, and the results are presented in Table 7. The results from using OLS method are also consistent with previous results. Thus, we can conclude that patent protection ability and a firm's knowledge assets positively affect the market value of firms in the renewable energy industry.

Table 4
Robustness check (Ordinary Least squares).

	m1	m2	m3	m4	m5	m6	m7	m8	m9	m10	m11
Constant	− 0.7631***	− 0.7791***	− 0.8119***	− 0.8663***	− 0.8837***	− 0.8015***	− 0.9406***	− 0.9585***	− 0.7274***	− 0.8309***	− 0.9082***
	(0.1174)	(0.1177)	(0.1198)	(0.1229)	(0.1246)	(0.1188)	(0.1244)	(0.1261)	(0.1186)	(0.1260)	(0.1271)
RDST/ASSET	0.9772***	1.0188***	1.0138***	1.0476***	1.0394***	1.0496***	1.0977***	1.0894***	0.8950***	0.9199***	0.9898***
	(0.2524)	(0.2537)	(0.2515)	(0.2525)	(0.2507)	(0.2559)	(0.2548)	(0.2531)	(0.2486)	(0.2465)	(0.2494)
PATST/RDST		1.4804**	1.5813**	1.4670**	1.5574**	1.5677**	1.5544**	1.6468**	1.5962**	1.6519**	1.7100**
		(0.6786)	(0.6921)	(0.6785)	(0.6900)	(0.6899)	(0.6907)	(0.7027)	(0.7156)	(0.7230)	(0.7233)
FCITST/PATST			0.0368**		0.0324*			0.0330*		0.0255	0.0276
			(0.0179)		(0.0179)			(0.0177)		(0.0177)	(0.0177)
BCITST/PATST				0.0333**	0.0290*		0.0524***	0.0480***		0.0305*	0.0469***
				(0.0163)	(0.0162)		(0.0157)	(0.0154)		(0.0158)	(0.0154)
NPRST/PATST						0.4380***	0.4777***	0.4784***			0.4207***
						(0.0657)	(0.0673)	(0.0662)			(0.0602)
PFST/PATST									0.4174***	0.4103***	0.3212***
									(0.0773)	(0.0778)	(0.0703)
Firm-year observations	2806	2806	2806	2806	2806	2806	2806	2806	2806	2806	2806
Number of firms	197	197	197	197	197	197	197	197	197	197	197
Adj R-Squared	0.3687	0.3690	0.3698	0.3697	0.3703	0.3777	0.3798	0.3804	0.3754	0.3765	0.3839

Standard errors in parentheses. *$p < 0.1$, **$p < 0.05$, and ***$p < 0.01$.

Table 5
Renewable energy industry classification table.

Classification		Korea Standard Industry Classification	
1	Renewable Energy		
1.1	Solar cell	20129	Other Basic Inorganic Chemicals Manufacturing
		2612	Manufacture of diodes, transistors and similar semiconductor devices
		28111	Manufacture of electric motors and generators
		42499	Other construction finishing work
		29272	Manufacture of machinery for manufacturing flat panel displays
1.2	Fuel cell	28111	Manufacture of electric motors and generators
1.3	Ocean	20119	Other basic organic chemicals manufacturing
	biotechnology	20499	Other non-classified chemical products manufacturing
1.4	Ocean	2811	Manufacture of electric motors, generators and electric converters
	Energy	2911	Internal combustion engine and turbine manufacturing: Excluding aircraft and vehicles
		2912	Hydraulic equipment manufacturing
		2913	Pump and compressor manufacturing: including tap, valve and similar device manufacturing
		2511	Manufacture of structural metal products for rescue
		3111	Crude drying up
		3530	Steam, hot and cold water and air conditioning supply business
		4122	Civil engineering facility construction business
		4213	Professional construction work related to facility construction
		4220	Building Equipment Installation Work
		4231	Electric work
1.5	waste resource energy	20121	Industrial gas manufacturing
		33999	Manufacture of other non-classified products
		3701	Sewage and wastewater treatment
		3702	Manure and Livestock Manure Treatment
		38210	Non-designated waste treatment business
		38230	Construction waste disposal business
		41224	Waste treatment and pollution prevention facility construction business
		72122	Environmental consulting and related engineering services
1.6	Agricultural biomass energy	01110	Grain and other food crops business
		01140	Other grain cultivation business
		20119	Other basic organic chemicals manufacturing
		20499	Other non-classified chemical products manufacturing
		3702	Manure and livestock feed processing business
		41225	Industrial plant construction business
1.7	Forest biomass resource reclamation	02040	Inbound service
		16299	Other wood products manufacturing
		25121	Central heating boiler and radiator manufacturing
1.8	Clean coal energy	20119	Other basic organic chemicals manufacturing

5. Conclusion

This study examines how a firm's patent protection ability is associated with the firm's market value in renewable energy. To conduct an empirical analysis, we examine patent data in the Korean renewable energy industry and its relationship to the market value of firms. Our results indicate that simple patent counts are not a strong indicator of financial success, whereas indices showing a firm's patent protection ability (backward citation and patent family) have a positive and significant effect on the firm's market value. This result means that backward citations and patent families, as signs of a firm's ability to protect patents, are important factors in the financial success of firms in renewable energy and therefore is an important factor in improving the firms' economic and financial value.

This study makes valuable theoretical contributions to the literature on renewable energy. This research is the first to analyze the effect of patent protection on a renewable energy company's market value. Previous literature focuses on investigating technology transfer, a network analysis of patents, and related public policy utilizing patent information. However, while patent litigation among renewable energy companies has continuously increased and caused those companies severe losses, almost no study other than this one has examined this important issue. Therefore, this study contributes to the literature not only by suggesting that a renewable energy firm's patent protection ability is important for its financial performance but also reveals that the backward citation of patents and the size of patent families are important measures of the ability of firms in this industry to protect their patents. Considering the large initial investment in technology development as well as the long time needed to develop new technologies in renewable energy, our study also emphasizes the need for further investigation of patent protection.

Our study also provides managers with meaningful insights. Our results indicate that it is important for managers to consider backward citations an important factor in protecting patents against patent invalidation suits. In addition, company managers can use patent families to protect their patents in various countries. From the point of view of investors, knowing about firms' ability to protect patents can help to determine the market value of the firms. Because renewable energy involves a long-term return on investment, knowing this information, which can initially determine the value of a company's investment, is important for investors so that they can improve the efficiency of their investments and ensure the healthy growth of the industry. Many countries, such as China and countries in Europe and South America, have emphasized and invested heavily in renewable energy technology to address global environmental problems [44,45]. Thus, these countries have established policies to help companies develop innovative technology. These governments have suggested and implemented several plans for the companies to participate in this newly emerging industry. Our study suggests that a government can stimulate the growth of the renewable energy sector by subsidizing the registration of patents for companies' product families in foreign

Table 6
Robustness check (Non-linear least squares with classified renewable energy company).

	m1	m2	m3	m4	m5	m6	m7	m8	m9	m10	m11
Constant	0.4034**	0.3618*	0.2011	0.0293	− 0.0677	0.3401*	0.0294	− 0.0658	− 0.2893	− 0.1177	− 0.1192
	(0.1776)	(0.1854)	(0.2053)	(0.2074)	(0.2184)	(0.1864)	(0.2077)	(0.2184)	(0.1848)	(0.2195)	(0.2197)
RDST/ASSET	8.8991***	9.4275***	9.9418***	11.1067***	11.3077***	10.2084***	11.7473***	11.9122***	9.5582***	11.6329***	12.0985***
	(2.6595)	(2.8022)	(2.8784)	(3.1184)	(3.1375)	(2.9412)	(3.2162)	(3.2242)	(2.8221)	(3.1884)	(3.2533)
PATST/RDST		1.2477*	1.9554**	1.3775*	2.0406*	1.3835*	1.5044*	2.1625**	1.6636**	2.7186**	2.7690**
		(0.6518)	(0.9557)	(0.7711)	(1.0680)	(0.6831)	(0.7930)	(1.0921)	(0.7946)	(1.3193)	(1.3247)
FCITST/PATST			0.1131*		0.1072			0.1043		0.1154	0.1126
			(0.0644)		(0.0759)			(0.0754)		(0.0784)	(0.0781)
BCITST/PATST				0.1469**	0.1406**		0.1412**	0.1359**		0.1261*	0.1284*
				(0.0640)	(0.0682)		(0.0637)	(0.0680)		(0.0701)	(0.0704)
NPRST/PATST						1.6700*	1.6819*	1.7592*			1.4648
						(0.9434)	(0.9749)	(1.0134)			(0.9097)
PFST/PATST									1.0344**	1.2983**	1.1880**
									(0.4397)	(0.6006)	(0.5852)
Log(Employee)	− 0.1926***	− 0.1891***	− 0.1862***	− 0.1786***	− 0.1782***	0.1937***	− 0.1832***	− 0.1826***	− 0.1920***	− 0.1816***	− 0.1847***
	(0.0216)	(0.0221)	(0.0220)	(0.0111)	(0.0217)	(0.0222)	(0.0220)	(0.0218)	(0.0219)	(0.0215)	(0.0217)
Firm-year observations	528	528	528	528	528	528	528	528	528	528	528
Number of firms	32	32	32	32	32	32	32	32	32	32	32
Adj R-Squared	0.2095	0.2088	0.2133	0.2163	0.2186	0.2141	0.2208	0.2229	0.2163	0.2245	0.2275

Standard errors in parentheses. *$p < 0.1$, **$p < 0.05$, and ***$p < 0.01$.

Table 7
Robustness check (Ordinary least squares with classified renewable energy company).

	m1	m2	m3	m4	m5	m6	m7	m8	m9	m10	m11
Constant	0.5951***	0.5800***	0.4192**	0.3141	0.1668	0.5794***	0.3106	0.1587	0.5195***	0.1557	0.1486
	(0.1709)	(0.1763)	(0.1952)	(0.2024)	(0.2109)	(0.1769)	(0.2024)	(0.2110)	(0.1785)	(0.2099)	(0.2100)
RDST/ASSET	3.6487***	3.7121***	3.9217***	3.9161***	4.1125***	3.8135***	4.0212***	4.2276***	3.5272***	3.9178***	4.0362***
	(1.2243)	(1.2445)	(1.2092)	(1.2247)	(1.1920)	(1.2474)	(1.2273)	(1.1938)	(1.2215)	(1.1751)	(1.1772)
PATST/RDST		0.5024	0.8276**	0.4640	0.7798**	0.5314*	0.4930	0.8194**	0.6779*	0.9722**	1.0008**
		(0.3151)	(0.3885)	(0.3065)	(0.3834)	(0.3182)	(0.3092)	(0.3877)	(0.3462)	(0.4254)	(0.4281)
FCITST/PATST			0.0708**		0.0685**			0.0705**		0.0739**	0.0756**
			(0.0337)		(0.0338)			(0.0337)		(0.0337)	(0.0336)
BCITST/PATST				0.0818**	0.0793**		0.0827**	0.0801**		0.0620*	0.0636*
				(0.0362)	(0.0368)		(0.0359)	(0.0365)		(0.0375)	(0.0373)
NPRST/PATST						0.6178***	0.6276***	0.6519***			0.6189***
						(0.2158)	(0.2140)	(0.2191)			(0.2169)
PFST/PATST									0.5234**	0.4746**	0.4525**
									(0.2113)	(0.2128)	(0.2115)
Log(Employee)	− 0.2060***	− 0.2046***	− 0.1987***	− 0.1945***	− 0.1891***	− 0.2079***	− 0.1978***	− 0.1924***	− 0.2050***	− 0.1912***	− 0.1942***
	(0.0215)	(0.0219)	(0.0222)	(0.0218)	(0.0221)	(0.0220)	(0.0219)	(0.0221)	(0.0218)	(0.0220)	(0.0221)
Firm-year observations	528	528	528	528	528	528	528	528	528	528	528
Number of firms	32	32	32	32	32	32	32	32	32	32	32
R-Squared	0.2063	0.2065	0.2128	0.2131	0.2190	0.2109	0.2176	0.2239	0.2133	0.2243	0.2286

Standard errors in parentheses. $^{*}p < 0.1$, $^{**}p < 0.05$, and $^{***}p < 0.01$.

countries. The companies thereby can reduce their cost of registering a patent family in various countries and can protect their technology, increasing their value.

Although this paper has some novel findings, it also has some limitations. First, while we classify renewable energy companies using strict rules, industry classifications can be limited. Thus, it will be meaningful to conduct a similar analysis after the SIC introduces renewable energy industry in its classification. Second, the stock market is volatile and sometimes does not behave rationally. Market value model assumes that the market is efficient and that investors are rational [46]. However, these assumptions are often controversial in modern society [47,57]. In particular, financial markets often behave irrationally and violate the transparency and technical trading rules for market participants [48]. Therefore, the results should be interpreted carefully.

In renewable energy industry, patent protection research needs future studies. First, patent protection systems vary across countries. Therefore, future studies should analyze the relationship between patent protection and firm value in across countries that have different patent protection systems. This will enable us to understand the relationship more fundamentally. Second, the renewable energy industry has various subdivisions. Therefore, it will be meaningful to explore the heterogeneity of the relationship between patent protection and firm value across these different subdivisions, which will have valuable implications for patent protection policy in this industry.

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