Green certificate price uncertainty and renewable energy investment: Evidence from an integration between solar and non-solar renewable energy certificate (REC) markets in Korea

Jeayoon Kim*

Korea Advanced Institute of Science and Technology (KAIST)

Abstract

A stable income flow from renewable energy certificate (REC) sales is crucial for ongoing business in renewable energy companies. This paper examines the relationship between REC price uncertainty and renewable energy investment. Using a REC market data in Korea, I find that a high level of uncertainty about REC prices discourages renewable energy investment. Given that the decision to invest in renewable projects is highly irreversible, it is optimal to postpone new renewable energy installations until REC price uncertainty is resolved. Solar photovoltaic (PV) is a prime example. Solar project developers significantly reduce new capacity investment in the periods with highly volatile REC prices, while they increase investment when the prices are expected to be stable. I further show that renewable energy firms require more debt and equity financing to proceed a project in the presence of severe uncertainty about REC revenues. This finding suggests that increased dependence on external financing contributes to deter investments in new capacity installations.

Keywords: Uncertainty about REC prices, renewable energy investment, integration of solar and non-solar REC markets.

JEL classification: D81, Q41, Q48

---

*Corresponding author: Jeayoon Kim, Ph.D. candidate, School of Management Engineering, College of Business, Korea Advanced Institute of Science and Technology (KAIST), 85 Hoegiro, Seoul 02455, Republic of Korea. Tel: (+) 822-958-3617, email: paradoxx44@kaist.ac.kr

This research has been supported by the Korean Ministry of Science and ICT through the Graduate School of Green Growth at KAIST College of Business in 2018. We appreciate valuable comments by seminar participants at KAIST.

Green certificate price uncertainty and renewable energy investment: Evidence from an integration between solar and non-solar renewable energy certificate (REC) markets in Korea

1. Introduction

As of January 2012, the Korean government begins to implement the renewable portfolio standards (RPS). Under the RPS policy, renewable power producers receive a renewable energy certificate (REC) for each MWh of their electricity generation. They sell RECs in a traded certificates market and earn additional revenue from the sales of RECs in addition to the sales of electricity.[1] Figure 1 shows the proportions of REC sales in the total revenue in renewable energy firms.[2] Fraction of total revenue associated with REC sales ranges from 20% to 70% with an average value of 48.6%. REC sales account for a substantial portion of the total income flow. Therefore, a stable cash flow from REC sales may be important for ongoing business in renewable energy companies. However, due to a short history of REC markets in Korea, REC prices were unstable and highly sensitive to supply and demand shocks. Although the tradable mechanism of RECs is initially designed to help renewable energy projects, it is questionable whether the RPS with volatile REC prices would effectively diffuse renewable energy technologies (RETs). Higher REC market volatility may discourage renewable energy investment since risk-averse investors feel uncertain about the future REC revenues. A natural question arises: will renewable energy investment sharply decrease in the presence of highly uncertain REC prices or will the investment increase in the presence of stable REC prices?[3]

[Insert Figure 1 here]

---

[1] Under the RPS program, utility companies should procure a specified fraction of their electricity as renewable energy. They usually buy RECs in the traded certificates market to meet their RPS target.

[2] Given that the income flow in renewable energy projects is mainly composed of electricity and REC sales, the fraction of total revenue associated with REC sales is estimated by the ratio of REC sales to the sum of the sales of the electricity and RECs

[3] Lee, Hong, Yoo, Koo, Kim, Jeong, Jeong, and Ji (2017) propose a case study on REC markets in North Carolina and Massachusetts in the U.S.. They find that solar REC prices in North Carolina are highly volatile while those in Massachusetts are less volatile. They further show that installed residential solar PV system is low in North Carolina whereas the installed capacity is high in Massachusetts.

This paper examines whether higher uncertainty about REC prices affects investment decisions in renewable energy. Using a REC market data in Korea, I find that renewable project developers decrease new capacity investment in the presence of highly volatile REC prices. In contrast, when REC prices become less volatile, they increase investments in renewable energy installations. Given that the decision to invest in renewable projects is highly irreversible and the sales of RECs account for a substantial portion of the total revenue, it is optimal to renounce new capacity installations under high REC price uncertainty. This negative influence of REC price uncertainty on investment decisions is pronounced for solar photovoltaic (PV) sector. Solar project developers significantly increase investments in solar PV installations when some of the uncertainty is resolved and REC prices are expected to be stable in the future.

Further, this study tries to investigate a potential channel through which REC price uncertainty affects investment decisions. It is possible that renewable energy firms decrease investment in the presence of highly uncertain REC prices because they need large amount of external capital in preparation for future risky revenues. When REC prices are volatile, it is more likely that the firms experience cash shortfalls in the future. Thus, they require relatively large amount of external financing to proceed a new project. However, this heavy use of debt and equity financing may discourage renewable energy firms from investing a new project. Consistent with this view, empirical analysis in this paper shows that the use of debt and equity financing for new plant build increases when REC prices are unstable. This suggests that the burdensome external capital contributes to deter renewable energy investment under high REC price uncertainty.

To capture the REC uncertainty influence on renewable energy investment, I exploit the exogenous variation in REC price volatility before and after the integration announcement of the two REC markets. Integration of solar and non-solar REC markets significantly curtails REC price volatility. Before the integration, solar and non-solar RECs were traded separately in Korea: RECs from solar energy generation are traded in a solar REC market while RECs from other renewable energy production (e.g., wind, hydro, and biomass) are traded in a non-solar REC market.[4] Interestingly, supply and demand shocks have dominated the price movements in solar and non-solar REC markets, respectively. Especially in the solar REC market, oversupply of RECs induces large fluctuations in the prices. In the initial stage of the RPS implementation, the government failed to expect a boom in solar industry and thus set a relatively small obligation level for solar RECs. In particular, the solar REC obligation level for utility companies was only 723 GWh (i.e., 723,000 RECs) in 2013. However, this demand for solar RECs was not sufficient to satisfy the steeply rising supply driven by the great boom in solar industry. Excess supply of solar RECs increases uncertainty about the possibility of future solar REC sales, and thereby inducing highly volatile prices. In the non-solar REC market, however, demand shocks driven by fears about future REC supply shortfalls lead to large fluctuations in the prices. Aggregate supply of non-solar RECs was not sufficient to meet the relatively large amount of demand. Uncertainty about the availability of future non-solar REC supplies triggers highly unstable prices as well.[5]

After the integration, solar and non-solar RECs are traded in a single market with a single price. Specified obligation levels for solar and non-solar RECs are abolished and thus both types of RECs are handled identically. Consequently, excess supply of solar RECs resolves the shortfalls of non-solar REC supplies. The integration of the two REC markets mitigates the demand shocks in non-solar REC market as well as the supply shocks in solar REC market. A stable equilibrium of supply and demand in REC transactions reduces the uncertainty about REC prices. I use this finding and then perform the 2SLS analysis of the effects of REC price uncertainty on renewable energy investment.

Main findings of this study contribute to the growing body of literature on the REC markets. I find that the integration of solar and non-solar REC markets lessens REC price volatility, and consequently this decrease in price volatility leads to active investments in renewable energy installations. Hustveit,

---

[4] The Korean government sets a solar carve-out, a regulation that utilities should meet a specified amount of electricity only with solar RECs. The solar carve-out and solar REC market were initially designed to compensate relatively high costs of solar PV system compared to other RETs.

[5] This is consistent with the view of Kilian (2009), who emphasize that precautionary demand shocks associated with market concerns about the availability of future oil supplies have made an immediate and sharp increase in the real price of oil.

Frogner, and Fleten (2017) analyze the Swedish-Norwegian REC market and argue that REC prices are highly sensitive to small supply and demand shocks. Zeng, Klabjan, and Arinez (2015) and Coulon, Khazaei, and Powell (2015) propose REC price forecasting models to clearly predict the behavior of participants in the REC markets. Coulon et al. (2015) further run simulations that analyze a sensitivity of solar generation growth to REC price levels. They assume that renewable energy firms are all risk-neutral to REC prices, and thus concentrate on how renewable energy developers react to REC price levels. However, my empirical analysis allows renewable energy firms to be risk averse to REC prices, and hence focuses on how REC price volatility affects investment decisions on renewable energy. On the other hand, Lee et al. (2017) provide a case study that higher volatility of solar REC prices in North Carolina is associated with low levels of installed solar PV, whereas less volatile solar REC prices in Massachusetts are related to high installed capacity of solar PV system. In line with this study, I extend the empirical analysis to include four renewable sectors and offer a panel data evidence of a link between REC price volatility and renewable energy investment.

This study also contributes to the literature that emphasizes financial sectors' role in renewable energy development. Levine (1997, 2005) presents that financial sector development ameliorates transaction frictions and facilitates trades on goods, services, and contracts. Consistent with this view, Brunnschweiler (2010) and Kim and Park (2016) find that developed financial markets provide easier access to debt and equity financing to renewable energy projects, and therefore financial development encourages the deployment of renewable energy. As an extension of these studies, my empirical analysis shows that well-functioning REC market reduces market price uncertainty and induces renewable energy firms to increase investments.

This study complements the literature that analyzes firms' investment decisions under a wide range of uncertainty. Minton and Schrand (1999) show that firms with high cash flow uncertainty postpone investment in capital expenditures, R&D, and advertising. Bistline (2015) finds that in the presence of uncertainty about natural gas prices and climate policy, U.S. electric power sector delays capital-intensive investment, such as carbon capture storage (CCS), and waits until more information is revealed. Gulen and Ion (2016) document that higher policy uncertainty provides a strong incentive for managers to defer capital investment, and this effect is significantly stronger for firms with a higher degree of investment irreversibility. Major findings in this paper complement the previous studies by addressing the dynamics of renewable capacity planning under uncertainties in the REC markets.

The remainder of this paper is organized as follows. Section 2 hypothesizes links between REC price uncertainty, cash flow volatility, and investment in renewable energy projects. Section 3 documents data and variable descriptions. Section 4 presents empirical methodologies and results. Section 5 presents concluding remarks.

2. Uncertainty about renewable energy certificate prices, cash flow volatility and investment in renewable energy projects

In this section, I hypothesize about the relationship between price uncertainty in the REC market and renewable energy investment. To the extent that higher REC price volatility implies severe uncertainty about REC prices, I focus on how REC price volatility influences investment decisions in renewable energy projects.

Higher REC price volatility increases a cash flow volatility in renewable energy firms since the sales of RECs contribute to a significant portion of the total income flow.[6] The volatile cash flow in those companies raises a probability that firms experience a cash flow shortfall in the future. Due to the increased likelihood of realizations of cash shortfalls, firms have an incentive to forgo investment and increase precautionary savings in the presence of severe uncertainty (Minton and Schrand, 1999). Consistent with this view, Segal, Shaliastovich, and Yaron (2015) propose an empirical evidence that both aggregate capital and R&D investment significantly drop in response to a bad uncertainty on macroeconomic growth. In addition, Haushalter, Heron, and Lie (2002) focus on whether oil price

---

[6] Figure 1 and summary statistics in Table 1 confirm that the fraction of total revenue associated with REC sales accounts for 48.6% on average.

uncertainty affects equity values of oil producers. They find that the firm value of oil producers decreases in the presence of volatile oil prices. Because cash flow uncertainty driven by volatile oil prices increases a likelihood that the firm will not be able to fully fund all investment, market participants negatively value the oil producing companies. In line with these previous studies, renewable energy firms may worry about higher possibility of cash shortfalls when REC prices are uncertain in the near future. Consequently, they are likely to defer new renewable capacity investment in the periods with unstable REC prices.

In the presence of highly volatile REC prices, renewable energy companies further encounter difficulties in raising funds from outside investors. Debt and equity holders negatively value firm's credibility and growth potential when cash flows are expected to be volatile in the future (Minton and Schrand, 1999; Haushalter, Heron, and Lie, 2002; Rountree, Weston, and Allayannis, 2008; Huang, 2009; Tang and Yan, 2010). Rountree et al. (2008) and Huang (2009) provide an empirical evidence that cash flow volatility is negatively valued by equity investors due to a preference by the market for less volatile cash flows. Tang and Yan (2010) document that credit spread rises with cash flow volatility because firms with higher probability of cash shortfalls are likely to experience financial distress and even default. Furthermore, using S&P bond ratings, yield-to-maturity, and weighted average cost of capital (WACC) as proxies for financing costs, Minton and Schrand (1999) find a positive relationship between a firm's current cost of capital and its historical cash flow volatility. Given that the high cash flow volatility driven by volatile REC prices increases costs of raising external capital, renewable project developers may renounce new capacity investment under severe uncertainty about REC prices.

The negative effect of REC price uncertainty on investment decisions is likely to be strong due to a high degree of irreversibility of renewable energy investment. In particular, high upfront capital costs of power plants make renewable energy projects largely irreversible (IFC, 2011). Moreover, specialized physical facilities of renewable energy have a high asset specificity, and hence they are hard to resell and realize in cases of bankruptcy (Balakrishnan and Fox, 1993). This further increases the irreversibility of renewable energy investment. Due to the high investment irreversibility, it is optimal to delay renewable energy investment under higher REC price uncertainty and make a more careful decision afterward. Previous studies, such as Bistline (2015) and Gulen and Ion (2016), emphasize the link between uncertainties about investment opportunities, investment decision-making process, and irreversibility of the invested projects. In particular, Bistline (2015) shows that under high uncertainties about natural gas prices and climate policies, decision-makers in electric power sectors have compelling incentives to pursue quasi-reversible investment options that provide flexibility and avoid irreversible capital-intensive investments. Gulen and Ion (2016) provide an evidence that the negative relationship between firm-level capital investment and policy uncertainty is significantly stronger for companies with a higher degree of investment irreversibility. They argue that while a firm that can reverse its investment at no cost has no benefit from waiting and postponing current investments, a firm with completely irreversible investments have a lot more to gain from waiting until some of the uncertainty is reduced.

The above discussion leads to the main hypothesis of this study: uncertainty about REC prices negatively affects investment decisions on renewable energy. The volatile cash flow, which arises from unstable REC prices, will increase the likelihood that a renewable energy firm experiences cash flow shortfall in the future. It may also increase the costs of raising funds from institutional investors. Finally, fears about the cash flow shortfalls and limited availability of financing sources induce renewable energy companies to decrease investment in new projects. The higher irreversibility of renewable energy projects will further provide an incentive to deter new investment in renewable energy facilities when REC prices are uncertain. The main hypothesis is consistent with the economic mechanism motivated by real option theories, which suggest that benefits from delaying investment increases under a higher level of uncertainty.

3. Data and variable descriptions

This paper uses cross-industry monthly panel dataset from the 2012-2017 period to investigate the relationship between REC price uncertainty and renewable energy investment. The dataset includes four renewable industries in Korea: solar, wind, biomass, and small hydro.[7] To the extent that the Korean government begins to implement the RPS policy in January 2012, the sample period covers from January 2012 to February 2017. The remainder of this section outlines each variable description.

3.1 Measuring investment levels of renewable energy technologies

To measure the amount of investments in renewable energy, first, I employ installed renewable energy capacity. Installed renewable capacity is the direct outcome of renewable energy investments (Jenner, Groba, and Indvik, 2013). It can reflect renewable energy investments as purely as possible because installed capacity level is hard to be biased by forces that investors cannot control. For example, installed capacity level is less dependent on equipment performance, operation and maintenance issues, and other factors unrelated to the amount invested. Previous studies, such as Dong (2012), Jenner et al. (2013), and Kim and Park (2016), also use the capacity data to capture investment decisions in renewable energy. Second, I use electricity generation from renewable sources as another measurement for renewable energy investments. As suggested by Brunnschweiler (2010) and Pfeiffer and Mulder (2013), renewable electricity generation levels are used to indicate RET diffusion levels.[8] Higher degrees of renewable electricity production in a given month represent the large amount of available renewable energy to end users.

The Korean Electric Power Statistics Information System provides monthly installed capacity and electricity generation data for solar, wind, biomass, and small hydro energy. Panel A of Table 1 provides pooled averages and standard deviations of the installation and electricity generation level. Installed renewable capacity (renewable electricity generation) has a mean of 457.062 MW (69.730 GWh) with

---

[7] Solar industry samples cover solar PV projects. Wind industry samples include both onshore and offshore wind power projects. Biomass industry samples contain landfill gas projects. Small hydro samples cover hydroelectric power projects whose generating capacity is less than or equal to 10 MW.

[8] Although electricity generation from renewable sources is used to proxy the diffusion level of RETs, it is commonly affected by meteorological conditions, equipment performance and technical problems. These problems render electricity generation measurements to be biased by forces the investors cannot control or foresee (Müller, Brown and Ölz, 2011; Jenner et al., 2013). The installed renewable capacity data addressed in the above discussion complements the weaknesses of electricity generation measurements.

a standard deviation of 422.341 MW (50.097 GWh).

[Insert Table 1 here]

3.2 Measuring uncertainty levels of renewable energy certificate prices

As a main proxy for the uncertainty levels about REC prices, I concentrate on a historical volatility in REC prices. When highly volatile REC prices are observed in past days, REC buyers and sellers may have greater uncertainty about future REC prices and trades. In contrast, when stable REC prices are observed, participants in the REC market may anticipate stable REC prices in the future as well. Therefore, this paper assumes that a high level of historical REC price volatility is associated with greater uncertainty about REC prices. With this assumption, I use the historical REC price volatility as a key measurement for REC price uncertainty.

Specifically, I define the REC price volatility as the rolling standard deviation of REC prices over the past six months. For example, for the sample month January 2016, the REC price volatility variable is evaluated using six months of REC price data from the July 2015 to the December 2015. To normalize the variable, the rolling standard deviation of REC prices is scaled by the average REC prices over the same six months. Seminal studies such as those conducted by Minton and Schrand (1999), Huang (2009), and Tang and Yan (2010) also employ the rolling standard deviation to accurately measure a historical volatility and predict uncertainty about the future values of underlying assets. Time-series REC price data is available from the Korean Power Exchange database. Panel A of Table 1 reports the mean and standard deviation of REC price volatility. REC price volatility has a mean of 11.573% with a standard deviation of 8.883. It implies that on average, the standard deviation of REC prices over the past six months is 11.573% relative to the average REC prices over the same period.

In addition to the REC price volatility variable, I employ a REC trading volume (as measured by thousand shares) as an alternative proxy for REC price uncertainty. When REC buyers and sellers have greater uncertainty about REC prices, trades of RECs may be inactive and a small number of trades will be observed. However, when there is low REC price uncertainty and the prices remain stable, trades of RECs may be active. I assume that a REC trading volume is negatively associated with REC price uncertainty, and use the REC trading volume as another measurement for REC price uncertainty. Particularly, REC trading volume is defined as a rolling average of the total number of traded RECs over the past six months. Before the integration of solar and non-solar REC markets, REC trading volume is the sum of the number of traded solar and non-solar RECs. After the integration, it is the total amount of traded RECs in the single REC market. Trading volume of RECs is drawn from the Korean Power Exchange database. The summary statistics in Panel A of Table 1 show that REC trading volume has a mean of 43.914 thousands with a standard deviation of 24.652.

3.3 Control variables

I include several controls to clearly capture the effect of REC price uncertainty on renewable energy investment. First, economic growth level should be regarded as a control variable since it may potentially affect both renewable sector development and price uncertainty in the REC market. In the presence of macroeconomic shocks, renewable project developers would delay new RET installations and wait until economic expansion comes. Additionally, uncertainty about REC prices could be severe during economic recessions. To control the macroeconomic influences, this paper includes quarterly growth rates of GDP (Gross domestic product) in the regression model. The quarterly growth rates of GDP are available from the Economic Statistics System in the Bank of Korea.

Second, as a control for government policy on renewable industries, this study uses RPS mandates. In addition to the economic situation, renewable energy investment is dependent on government policy. Particularly, the RPS policy forces utility companies to procure a specified fraction of their electricity production as renewable energy. For example, the obligation level on electricity supply companies is 3.5% in 2016, and thus electric utilities should either produce 3.5% of electricity from renewable sources or buy the equivalent amount of RECs. Therefore, higher RPS mandates (as measured by percentages of total electricity generation in utility firms) may induce large investment in renewable energy. This paper includes the RPS mandate level in main regression analysis. The data for RPS mandates is drawn from the Korea Energy Agency.

Third, this paper includes dependence on REC revenue in a renewable energy firm as an additional control. Dependence on REC revenue is defined as a fraction of total revenue associated with REC sales. To the extent that revenue of renewable energy projects mainly consists of electricity and REC sales, the proportions of REC sales in the total revenue is the ratio of REC sales to the sum of the sales of electricity and RECs. Figure 1 shows that REC revenue accounts for a substantial portion of the total revenue in renewable energy companies. Hence, it is important to control dependence on REC revenue to precisely identify the impact of REC price volatility. Prices of electricity and RECs are drawn from the Korean Power Exchange database.

Finally, to measure an investment opportunity of a renewable sector and its contribution on the following investments, I add growth rates of new capacity installations in the regression analysis. Higher growth rate in new capacity installations implies a great investment opportunity in a given period, and therefore it will lead to active investments in the near future. The growth of new capacity installations is defined as the ratio of newly added capacity to the average installed capacity level over the past 24 months.[9] It represents a growth rate in capacity installations relative to the past routine installation level. Given that a renewable sector with the fine investment opportunity may experience higher development in the future, this control variable further reflects a heterogeneous degree of growth potential across different renewable industries.

3.4 Mechanism variable: Dependence on external financing

In empirical analyses, I attempt to find a potential mechanism through which REC price uncertainty influences investment decisions in renewable energy. Among possible channels, this paper focuses on

---

[9] For some observations, the average installed capacity level over the past 2 years is negative or equals to zero. In this case, I adjust the growth of new capacity installations to the newly added capacity value in that given period.

whether renewable energy firm's dependence on external financing varies with uncertainty about REC prices. When REC prices are volatile, it is more likely that the firm experiences cash shortfalls in the future. Consequently, this renewable energy company needs more debt and equity financing to proceed a project. Heavy use and higher dependence on external financing would deter investment in new capacity installations since external financing itself is costly for companies (Myers and Majluf, 1984).

The term "dependence" is first coined by Rajan and Zingales (1998). Now, this term is widely used in the literature that examines the amount of debt and equity financing in manufacturing firms (e.g., Beck and Levine, 2002; Hsu, Tian and Xu, 2014; Kim and Park, 2016). Rajan and Zingales (1998) define *dependence* as a fraction of capital expenditures not financed by internal funds. Kim and Park (2016) adjust their variable of *dependence* to be suitable for renewable energy industry. Specifically, the modified variable of *dependence* is an aggregate of debt and equity financing per installed capacity level. Building on the seminal work of Kim and Park (2016), I define dependence on external financing as a ratio of funds raised for the construction of new renewable energy plants to the amount of constructed capacity. Those funds secured for new build include debt and equity financing, such as bonds, loans, and private equity. A renewable sector with a higher level of the dependence variable is more reliant on debt and equity financing to fund investments in renewable capacity installations. The values of debt and equity financing are available in the Bloomberg New Energy Finance (BNEF) database. According to Panel A of Table 1, dependence on external financing has a mean of 0.965 \$/W. It implies that on average, renewable energy firms require 965 thousand dollars to build a 1 MW renewable energy plant.

4. Empirical analysis

This section documents an empirical analysis examining whether investment decisions in renewable energy are dependent on REC price uncertainty. Figure 2 compares renewable capacity installations at varying levels of REC price volatility. Observations with low (high) REC price volatility are samples whose measure for the value of REC price volatility is below the 30th percentile (above the 70th percentile). Subsequent renewable energy installations are newly installed capacity over 12 months after the REC price volatility is observed. While the subsequent installation level is 145.540 MW in the periods with low REC price volatility, newly installed capacity in the periods with high REC volatility is only 77.223 MW. The difference is 68.317 MW and significant at the 1% level. It appears that renewable project developers increase their investment on new capacity after REC price uncertainty is resolved, and decrease the investment under a severe uncertainty about REC prices.

[Insert Figure 2 here]

In the following subsections, we conduct a multivariate analysis. We report our empirical design in detail and document results.

4.1 Empirical design

Identifying the effect of REC price uncertainty on renewable energy investment is challenging since renewable industries are typically reliant on various government policies and plans. Although we include the renewable electricity target level (i.e., RPS mandates) as a control variable for government policy, it is hard to measure and quantify all kinds of government policies on renewable industries. For example, at the Paris Agreement on December 2015, the Korean government has publicly announced that they will cut carbon emissions 37 percent below the business-as-usual (BAU) level by 2030. This plan may increase investments in renewable industries. It may simultaneously increase price uncertainty in the REC markets since the 37 percent cut below the BAU is an exceptionally stronger target than previous proposals and expectations. Such aggressive target raises a question of how the government achieves it until 2030.[10] In a multivariate analysis, it is difficult to quantify and control for this government action. Omitting government impacts on renewable sectors may generate biased and

---

[10] After the Paris Agreement, on July 2016, the Korean government changed RPS mandates more aggressive than previous one. While the government previously set the electric utility obligation level to 4.5, 5.0, and 6.0% in 2018, 2019, and 2020, respectively, the modified obligation level is the 5.0, 6.0, and 7.0% in 2018, 2019, and 2020, respectively.

inconsistent estimation results in OLS regressions.

In addition to the potential omitted variable problem, reverse causality concern is also present. Volatile REC prices may arise from low renewable energy investments in past days since supply shortfalls of RECs can result in unstable prices. Then, a negative correlation between REC price volatility and renewable energy investment may not stand for a causal effect of REC price volatility on renewable sectors. Finally, it is necessary to address the endogeneity issues driven by the potential omitted variable bias and reverse causality concerns.

This study controls for the endogeneity concerns by exploring the impact of the integration between solar and non-solar REC markets on REC price uncertainty. In particular, volatility of REC prices is relatively low after the integration, whereas it is comparatively high before the integration. It appears that the integration event makes REC prices less volatile. The integration between solar and non-solar REC markets is largely unanticipated event and thus using the integration announcement influence can potentially mitigate the endogeneity concerns. Specifically, I employ the integration announcement event as an instrument and run a 2SLS estimation that examines the relation between REC price uncertainty and renewable energy investment. Empirical results from the 2SLS may clearly capture the REC price uncertainty effect, which is robust to endogeneity concerns.

Before the integration of the two REC markets, REC prices are highly volatile. In the initial stage of the RPS implementation, the Korean government designs two separate REC markets, namely solar and non-solar REC markets. Since the solar PV system has a higher cost structure compared to other RETs, the government sets a solar carve-out and aims to compensate the comparative disadvantage of solar projects. Solar carve-out is a regulation that utility companies should meet a certain amount of electricity only with solar energy. It forces those utility firms to purchase the fixed amount of solar RECs. It also simultaneously guarantees solar industry a specified REC demand. The government expects that solar-carve out regulation provides stable REC revenue to solar energy firms, thereby promoting solar industry.

Contrary to the government aim of solar carve-out regulation, specified level of solar carve-out has strictly restricted solar REC demand. In recent years, there has been a great boom in solar industry due to a worldwide decline in solar PV module prices. As a consequence, supply of solar RECs has unexpectedly exceeded the solar carve-out level. For example, the solar carve-out in 2013 was 723 GWh (i.e., 723,000 RECs), and this demand level was not sufficient to satisfy the sharply rising supply of solar RECs. Oversupply of solar RECs increases uncertainty about the availability of future REC sales. Finally, solar REC prices become volatile. On the one hand, in the non-solar REC market, demand of non-solar RECs has exceeded the overall supply. Relatively large demand increases uncertainty about future REC supply shortfalls. Thus, non-solar REC prices become unstable as well.

After the integration of the two REC markets, however, REC prices become comparatively stable. In the integrated REC market, solar and non-solar RECs are traded together with a single price. The integration facilitates trades between solar and non-solar RECs, and therefore it resolves supply and demand shocks in each market. In particular, excess supply of solar RECs alleviates the short supply problem of non-solar RECs. Therefore, REC prices become less volatile after the integration.

Figure 3A shows trends of solar and non-solar REC price volatility around the integration event. Figure 3B shows patterns of REC trading volume. After the integration announcement, REC price volatility considerably decreases. In addition, REC trading volume steeply increases after the integration announcement. It appears that the market participants expect a stable equilibrium of supply and demand in REC transactions after the integration. This expectation is reflected in the prices and thus prices become stable after the announcement of the integration.[11]

[Insert Figure 3 here]

Further, Panel B in Table 1 documents a univariate analysis that compares REC price volatility between the periods before and after the integration announcement. The price volatility changes from 13.824% to 9.205% after the announcement. The difference is 4.619% and significant at the 1% level.

---

[11] It is possible that the REC price volatility decreases after the announcement of the integration because the market participants stop their trading after the announcement. However, this is not the case since the trading volume increases after the announcement.

Moreover, REC trading volume significantly increases. It changes from 26.337 thousands to 63.310 thousands. The difference is 36.973 thousands and significant at the 1% level. These univariate results are consistent with the view that the integration of REC markets resolves supply and demand shocks in the solar and non-solar REC market, respectively, thereby facilitating trades and diminishing price volatility.

Overall, using an indicator for the integration announcement as an instrumental variable, this paper performs a 2SLS estimation to identify the effects of REC price uncertainty on renewable energy investment. In the first stage, I regress REC price volatility (REC trading volume) on the indicator variable for the integration and a set of control variables. In the second stage, investment levels of renewable energy are regressed on the estimated REC price volatility (REC trading volume) and a set of control variables. Specifically, the identification strategy to account for REC price uncertainty influences is as follows:

(i) First stage: $\text{REC price uncertainty}_{\text{i,t}} = \alpha^1 + \beta^1 \times Integration\ announcement_t + \gamma^{1\prime} X_{i,t} + \delta_i + u_{i,t}$

(ii) Second stage: $\text{Renewable energy investment}_{\text{i,t+12}} = \alpha + \beta \times REC\ price\ uncertainty^*_{i,t} + \gamma' X_{i,t} +$

$\delta_i + \varepsilon_{i,t}$ (1)

i and *t* represent the industry and month, respectively. Solar, wind, biomass, and small hydro sectors are included. Sample period covers from January 2012 to February 2017. $Integration\ announcement_t$ is an indicator variable that equals 1 if the Korean government has announced the integration of solar and non-solar REC markets by month *t*. $REC\ price\ uncertainty_{i,t}$ is the rolling standard deviation of REC prices over the past six months preceding the month t. $REC\ price\ uncertainty_{i,t}$ is scaled by the average REC prices over the same period. As an alternative measure for $REC\ price\ uncertainty_{i,t}$, this study further uses a REC trading volume and check whether major findings are valid with this proxy. $REC\ price\ uncertainty^*_{i,t}$ is the REC price uncertainty estimated in the first stage regression. $Renewable\ capacity_{i,t+12}$ is either installed renewable capacity or renewable electricity generation. $X_{i,t}$ is a set of control variables described in section 3. δ_i is an industry fixed effect that absorbs technology-specific characteristics. $u_{i,t}$ and $\varepsilon_{i,t}$ are the error terms. I cluster standard errors by year level to allow error terms to be heteroskedastic and possibly auto-correlated within a given year.

With an instrumental variable (IV) estimation, it is important to check whether the instrumental variable satisfies (i) relevance condition and (ii) excludability condition. First, for the instrument to be valid, it must be sufficiently correlated with the key explanatory variable, REC price volatility (Relevance condition). Table 2 shows the first-stage estimation results. In column (1), the integration announcement is associated with 19.569% reduction in REC price volatility and the effect is significant at the 1% level. This result suggests that the integration facilitates trades and mitigates the uncertainty about the availability of REC transactions. Finally, this event contributes to form stable REC prices. In addition, the *F*-statistic equals 225.541 and exceeds the critical value of *F*=10. Thus, the instrument variable is not weak and the relevance condition is satisfied. In column (2) and (3), I limit the sample to solar industry and non-solar industries, respectively. The coefficients of the integration indicator remain highly statistically significant in both columns. These results further suggest that the integration announcement reduces price uncertainties of both solar and non-solar RECs.[12]

[Insert Table 2 here]

Second, to become a valid instrument, it must be uncorrelated with the error term (Excludability condition). That is, the integration indicator should not affect the renewable investment measures through any channel other than the REC uncertainty effect. Although it is impossible to directly test the excludability condition as with all IV based studies (Roberts and Whited, 2013), I attempt to partly alleviate concerns on the excludability. The integration event is a largely unexpected shock to renewable energy industries, and thus this event is unrelated to the fundamental value of energy assets (e.g., the value of power plants). Instead, the integration event is likely to affect renewable industries only via its effect on REC prices. One example of alternative explanations is that since the integration decision

---

[12] Consistent with the results in Table 2, column (1) in Table 5 further shows that the integration announcement is positively associated with REC trading volume and the effect is significant at the 1% level. This result confirms that the integration event reduces REC price uncertainty and encourages active trades in RECs.

itself is a government choice, it may be correlated with an omitted political channel that encourages renewable sector development. To rule out such alternative channel, Appendix 1 explore changes in government R&D spending on renewable energy industries around the integration announcement. If the integration decision is correlated with omitted government actions that promote renewable industry growth (i.e., the excludability condition is violated), then government R&D investments on renewable energy may considerably increase after the integration announcement. However, whereas the government R&D expenditure slightly increases in 2015, it substantially decreases in 2016.

4.2 REC price volatility and renewable energy investment

This section reports the central result of the paper. Panel B of Table 1 presents that both installed capacity and electricity generation from renewable sources significantly increase after the integration announcement. Interestingly, REC price volatility simultaneously declines after the integration. It seems that reduction in REC price volatility promotes renewable energy development. However, there can be an alternative explanation for the increase in renewable energy investments. For example, a rise in RPS mandates from 2.455% to 3.276% may contribute to the increase in installed renewable capacity and electricity generation. In a multivariate analysis, this paper controls for potential confounding effects and then identifies the influence of REC price volatility on renewable sectors.

Table 3 shows 2SLS estimation results examining the relation between historical REC price volatility and *ex post* renewable energy investment. The coefficient estimates of $REC\ price\ volatility_{i,t}$ capture the causal effect of REC price uncertainty on renewable capacity installations and electricity production. In column (1) of Table 3, the coefficient of $REC\ price\ volatility_{i,t}$ is significantly negative with a value of -5.940. This finding implies that in the presence of severe REC price uncertainty, renewable project developers decrease capacity investment. By contrast, when low REC price volatility is observed and the prices are expected to be stable in the future, renewable project developers increase renewable capacity installations. Specifically, a 5% decline in REC price volatility leads to 29.7 MW (= -5.940 * -5) increase in renewable capacity. This value is economically meaningful because it is equivalent to

6.498% of the average installed capacity level in the sample.

[Insert Table 3 here]

Column 2 in Table 3 addresses how REC price volatility influences renewable electricity generation. The coefficient of $REC\ price\ volatility_{i,t}$ is -0.512 and statistically significant at the 1% level. This suggests that low uncertainty about REC prices plays a key role in renewable energy deployment. In particular, a 5% reduction in REC price volatility is associated with an increase in renewable energy production of 3.671% (= -0.512 * -5 / 69.730) with respect to the sample mean. It appears that when renewable project developers anticipate a stable income from RECs, they begin to increase new capacity investment. This increase in new renewable capacity results in a rise in electricity generation from renewable sources and thus promotes renewable energy deployment.

In both columns (1) and (2) of Table 3, I report OLS estimates and find that each OLS coefficient overestimates the effect of REC price volatility on renewable energy investment, compared to the IV estimate. This is consistent with the expectation that omitted government actions and policies (e.g., The Korean government's declaration of unexpectedly strong emission-reduction target at the Paris Agreement) are positively correlated with both renewable sector development and REC market uncertainty, thereby inducing overestimated OLS results.

Due to heterogeneous sensitivities to REC prices across renewable energy industries, the REC uncertainty effect may not be the same across sectors. To account for the heterogeneous influence of REC price volatility on renewable sectors, I divide the sample into solar, wind, biomass, and small hydro industries separately and run the 2SLS again in each subsample. Table 4 reports the subsample studies. Interestingly, the negative effect of REC price uncertainty on renewable energy investment is more pronounced for solar and wind industries. The coefficient values of solar and wind samples are -26.885 and -8.866, respectively, and significant at the 1% level. These estimates indicate that a 5% decrease in REC price volatility is associated with a rise in solar (wind) capacity installations in the next year equivalent to 14.491% (6.608%) of the sample mean. Since solar and wind industries are generally require large amount of financing to cover high upfront capital costs (Gillenwater and Seres, 2011; Kim and Park, 2016), they are highly dependent on the sales of RECs and sensitive to REC prices.[13] Moreover, given that many solar projects are small-scale and distributed power generation, the REC price uncertainty influence is exceptionally strong for solar sector.

[Insert Table 4 here]

Overall, empirical findings in Table 3 and 4 show that higher REC price volatility provides incentives for decreasing new capacity installations. Given that a decision to invest in renewable projects is highly irreversible, renewable project developers postpone new capacity investment when the income from REC sales is expected to be unstable. They begin to install new renewable capacity when some of the uncertainty about REC prices are resolved and the prices become stable. This finding is consistent with Bistline (2015), who documents that U.S. electric power sector strategically delays capital-intensive investment under a high uncertainty about natural gas prices. On the other hand, the effect of REC price volatility on renewable energy investment is particularly strong for solar and wind industries. This suggests that solar and wind projects are highly sensitive to the risks associated with REC prices.

4.3 REC trading volume and renewable energy investment

In this section, I employ a REC trading volume as an alternative proxy for REC price uncertainty, and check whether the major findings in Section 4.2 are valid with this measure. Specifically, this study expects that REC trading volume is negatively associated with REC price uncertainty, and use this conjecture to reexamine the relation between REC price uncertainty and renewable energy investment.[14] Table 5 reports the results. REC trading volume (as measured by thousands shares) is the rolling average of the total number of traded RECs over the past six months. Installed capacity (electricity generation) includes total installed capacity (electricity production) from solar, wind, biomass, and small hydro

---

[13] Appendix 2 confirms that solar and wind industries in Korea raise relatively large amount of debt and equity financing on average.

[14] When REC buyers and sellers have greater uncertainty about REC prices, low trades may occur in the market. By contrast, when there is low REC price uncertainty and the prices remain stable, trades of RECs may be active and the REC trading volume will be high.

industries. Column (1) exhibits the first stage estimation result. The coefficient estimate of the integration indicator is significantly positive with a value of 21.590. This result implies that the amount of traded RECs considerably increases after the integration of the two REC markets. It seems that stable equilibrium in REC prices in the integrated market leads to active trades of RECs.

[Insert Table 5 here]

Column (2) and (3) of Table 5 report the second stage regression results. The coefficients of REC trading volume are significantly positive in both columns and thus suggest that renewable energy investment increases with REC trading volume. Given that REC price uncertainty is likely to be negatively correlated with trading volume, the results in Table 5 strengthen the major findings in this paper: investment in renewable projects increases when uncertainty of REC prices is low. These findings are consistent with Aune, Dalen, and Hagem (2012), who conjecture that EU-wide free trade in green certificates will cut the overall cost of achieving the EU's renewable energy target.

4.4 Potential channel: REC price uncertainty and dependence on external financing

Thus far, this paper has covered empirical findings on REC price uncertainty and renewable energy investment: In response to a rise in REC price uncertainty, renewable project developers decrease investments. This section discusses a potential channel for the above empirical findings. In particular, I focus on how dependence on external financing in renewable energy companies varies with the levels of REC price uncertainty. Dependence on external financing is defined as the use of debt and equity financing for the construction of new renewable energy plants.[15]

In the presence of severe uncertainties about REC prices, REC prices become unstable and renewable energy firms have a volatile income stream. A firm with volatile cash flow needs to raise more external capital in order to operate business well, fully fund its investment and cover outstanding financial

---

[15] I illustrate this measure in detail in Section 3.4.

obligations. Given that raising more external funds itself is costly to companies (Myers and Majluf, 1984), increased dependence on external financing driven by REC price uncertainty may discourage renewable energy investment. To test the potential explanation, I use the dependence on external financing as a new dependent variable in the second stage regression of Equation 1 and run the 2SLS estimation.

Table 6 shows the results. In column (1), the coefficient estimate of REC price volatility is significantly positive with a value of 0.011. This implies that the use of debt and equity financing for new plant build increases when volatile REC prices are observed in past days. For example, a 5% rise in REC price volatility leads to an increase in the use of external financing equivalent to 5.699% (= 5 * 0.011 / 0.965) of the sample mean. On the contrary, dependence on external financing decreases when low price volatility is observed and stable REC income is expected in the future. This finding is in line with the view suggested by Minton and Schrand (1999) that higher cash flow volatility increases the costs of raising capital from debt and equity investors. Result in column (2) further confirms that renewable energy companies are highly dependent on debt and equity financing when REC trades are inactive due to severe price uncertainty. Finally, the evidence in Table 6 documents the potential channel through which severe REC price uncertainty discourages renewable energy investment.

[Insert Table 6 here]

5. Concluding remarks

To effectively promote renewable energy development, the RPS has been adopted in a number of countries, including the United Kingdom, Australia, Japan, as well as in 29 of 50 U.S. states, and Republic of Korea (REN21, 2016). The success of the RPS policy is likely to be dependent on low uncertainty about REC trades and prices. In Korea, the integration between solar and non-solar REC markets considerably reduces uncertainty about REC prices. Using this reduction in REC price uncertainty, this paper examines how changes in the risks associated with REC prices influence investment decisions in renewable energy projects. Specifically, I use the integration announcement of the REC markets as an instrument and run a 2SLS estimation to clearly identify the effects of REC price uncertainty on renewable energy investment.

Major findings in this paper show that investment in renewable energy projects decreases when REC prices are uncertain. However, the investment increases when REC prices are expected to be stable. The negative effect of REC price uncertainty on the investment is pronounced for solar and wind industries. I further investigate a potential explanation for the negative price uncertainty impact. In the presence of severe REC price uncertainty, renewable energy firms require more debt and equity financing to fund new capacity investment, and therefore this burdensome external financing discourages renewable energy investment.

My results suggest that promoting renewable energy requires a well-functioning REC market that provides stable REC prices and low uncertainty on trades. Renewable project developers feel comfortable investing in new renewable capacity under the well-functioning REC market. This finding has an important implication for policy makers in emerging markets, who newly design the RPS or have recently introduced the RPS: It is important to design the REC market so that RECs are actively traded in the market without supply and demand shocks to the prices.

References

Aune, F.R., Dalen, H.M., and Hagem, C., 2012. Implementing the EU renewable target through green certificate markets. *Energy Economics* 34 (4), 992-1000.

Balakrishnan, S. and Fox, I., 1993. Asset specificity, firm heterogeneity and capital structure. *Strategic Management Journal* 14 (1), 3-16.

Beck, T. and Levine, R., 2002. Industry growth and capital allocation: Does having a market-or bank-based system matter? *Journal of Financial Economics* 64 (2), 147-180.

Bistline, J.E., 2015. Electric sector capacity planning under uncertainty: Climate policy and natural gas in the US. *Energy Economics* 51, 236-251.

Brunnschweiler, C.N., 2010. Finance for renewable energy: an empirical analysis of developing and transition economies. *Environment and Development Economics* 15 (3), 241-274.

Coulon, M., Khazaei, J., and Powell, W.B., 2015. SMART-SREC: A stochastic model of the New Jersey solar renewable energy certificate market. *Journal of Environmental Economics and Management* 73, 13-31.

Dong, C., 2012. Feed-in tariff vs. renewable portfolio standard: An empirical test of their relative effectiveness in promoting wind capacity development. *Energy Policy* 42, 476-485.

Gillenwater, M., and Seres, S., 2011. The Clean Development Mechanism: a review of the first international offset programme. *Greenhouse Gas Measurement and Management* 1(3-4), 179-203.

Gulen, H., and Ion, M., 2016. Policy uncertainty and corporate investment. *The Review of Financial Studies* 29 (3), 523-564.

Haushalter, G.D., Heron, R.A., and Lie, E., 2002. Price uncertainty and corporate value. *Journal of Corporate Finance* 8 (3), 271-286.

Hsu, P., Tian, X., and Xu, Y., 2014. Financial development and innovation: Cross-country evidence. *Journal of Financial Economics* 112 (1), 116-135.

Huang, A.G., 2009. The cross section of cashflow volatility and expected stock returns. *Journal of Empirical Finance* 16 (3), 409-429.

Hustveit, M., Frogner, J.S., and Fleten, S.E., 2017. Tradable green certificates for renewable support: The role of expectations and uncertainty. *Energy* 141, 1717-1727.

IFC (International Finance Corporation), 2011. Climate finance: Engaging the private sector. IFC Publication.

Jenner, S., Groba, F. and Indvik, J., 2013. Assessing the strength and effectiveness of renewable electricity feed-in tariffs in European Union countries. *Energy Policy* 52, 385-401.

Kilian, L., 2009. Not all oil price shocks are alike: Disentangling demand and supply shocks in the crude oil market. *American Economic Review* 99 (3), 1053-69.

Kim, J., and Park, K., 2016. Financial development and deployment of renewable energy technologies. *Energy Economics* 59, 238-250.

Lee, M., Hong, T., Yoo, H., Koo, C., Kim, J., Jeong, K., Jeong, J., and Ji, C., 2017. Establishment of a base price for the Solar Renewable Energy Credit (SREC) from the perspective of residents and state governments in the United States. *Renewable and Sustainable Energy Reviews* 75, 1066-1080.

Levine, R., 1997. Financial development and economic growth: Views and agenda. *Journal of Economic Literature* 35 (2), 688-726.

Levine, R., 2005. Finance and growth: theory and evidence. Handbook of Economic Growth 1A, 865-934.

Minton, B.A., and Schrand, C., 1999. The impact of cash flow volatility on discretionary investment and the costs of debt and equity financing. *Journal of Financial Economics* 54 (3), 423-460.

Müller, S., Brown, A. and Ölz, S., 2011. Renewable energy: Policy considerations for deploying renewables. International Energy Agency.

Myers, S.C., and Majluf, N.S., 1984. Corporate financing and investment decisions when firms have information that investors do not have. *Journal of Financial Economics* 13 (2), 187-221.

Pfeiffer, B. and Mulder, P., 2013. Explaining the diffusion of renewable energy technology in developing countries. *Energy Economics* 40, 285-296.

Rajan, R.G. and Zingales, L., 1998. Financial dependence and growth. *American Economic Review* 88 (3), 559-586.

REN21 (Renewable Energy Policy Network for the 21st Century)., 2016. Renewables 2016 global status report.

Roberts, M.R. and Whited, T.M. 2013. Endogeneity in empirical corporate finance. *Handbook of the Economics of Finance* 2, 493-572.

Rountree, B., Weston, J.P., and Allayannis, G., 2008. Do investors value smooth performance?. *Journal of Financial Economics* 90 (3), 237-251.

Segal, G., Shaliastovich, I., and Yaron, A., 2015. Good and bad uncertainty: Macroeconomic and financial market implications. *Journal of Financial Economics* 117 (2), 369-397.

Tang, D.Y., and Yan, H., 2010. Market conditions, default risk and credit spreads. *Journal of Banking & Finance* 34 (4), 743-753.

Zeng, Y., Klabjan, D., and Arinez, J., 2015. Distributed solar renewable generation: Option contracts with renewable energy credit uncertainty. *Energy Economics* 48, 295-305.

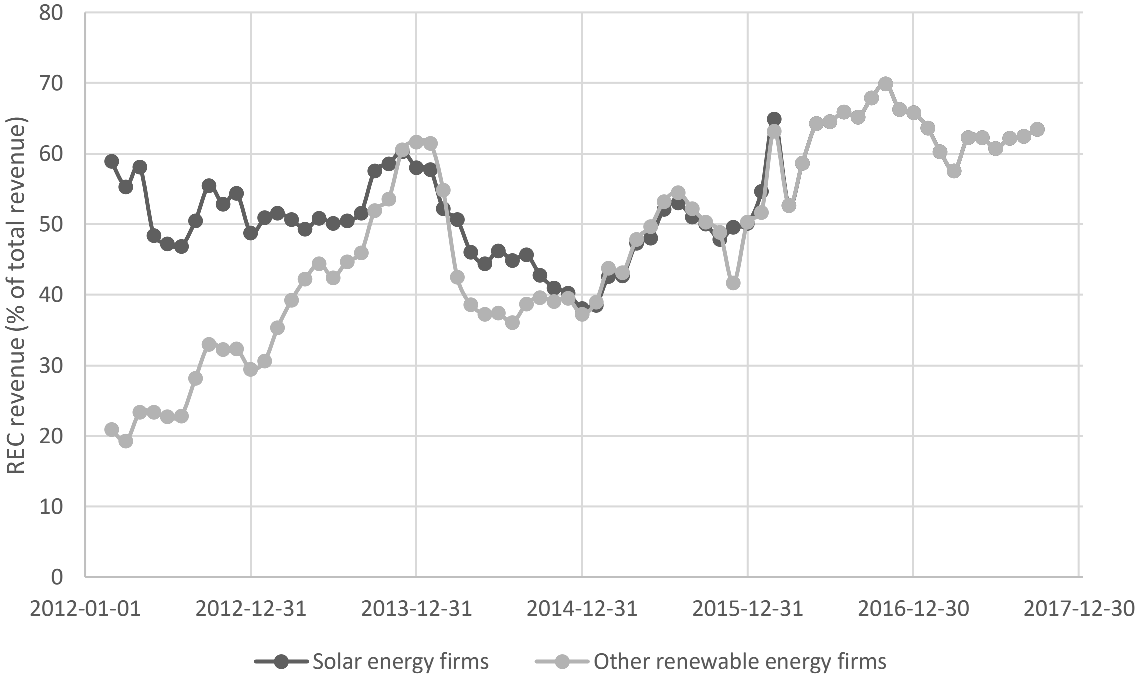


Figure 1 Fraction of total revenue associated with REC sales. Given that the main revenue streams of renewable energy projects come from electricity and REC sales, the REC revenue portion is measured by the ratio of REC sales to the sum of the sales of the electricity and RECs. Source: Authors' calculations based on the Korean Power Exchange database and the Korean Electric Power Statistics Information System.

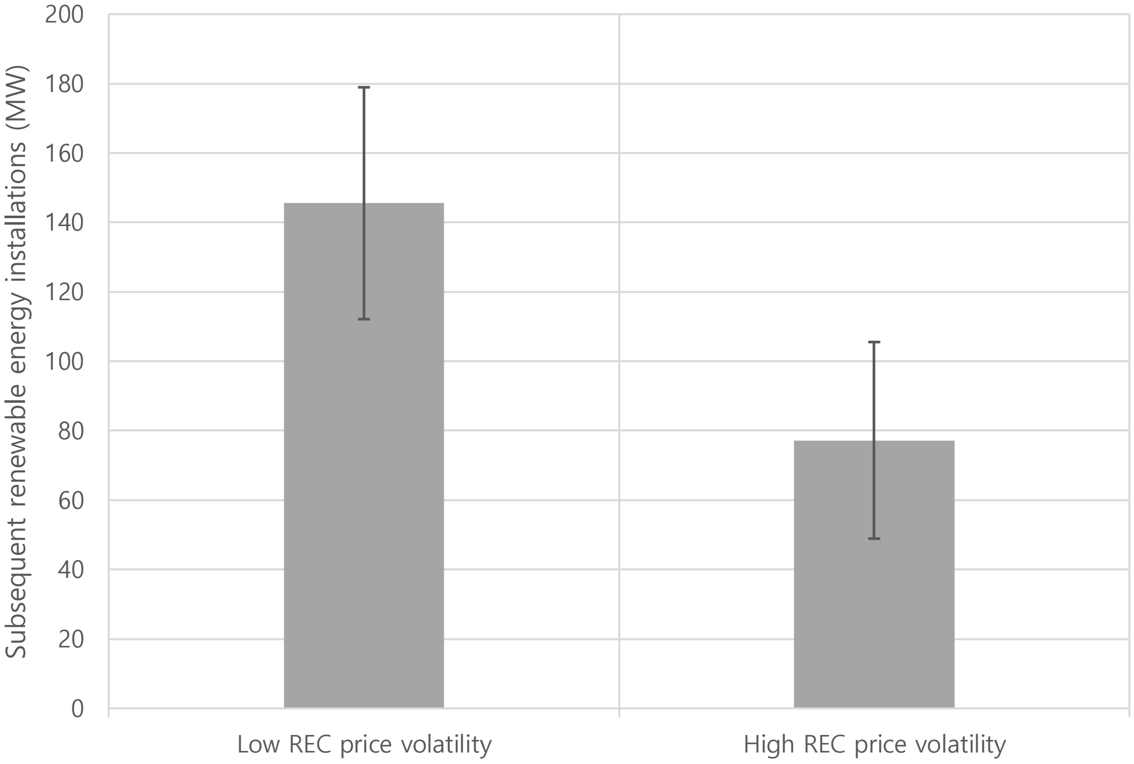


Figure 2 REC price volatility and subsequent 12-month renewable energy installations in Korea. Samples with low REC price volatility (high REC price volatility) indicate the periods when the price volatility lies below the 30th percentile (above the 70th percentile). Subsequent renewable energy installation (MW) is calculated as a sum of newly installed capacity over the 12 months after the REC price volatility is observed. Interval plots display 95% confidence intervals for the mean. Source: Authors' calculations based on the Korean Power Exchange database and the Korean Electric Power Statistics Information System.

Figure 3A Solar and non-solar REC price volatility

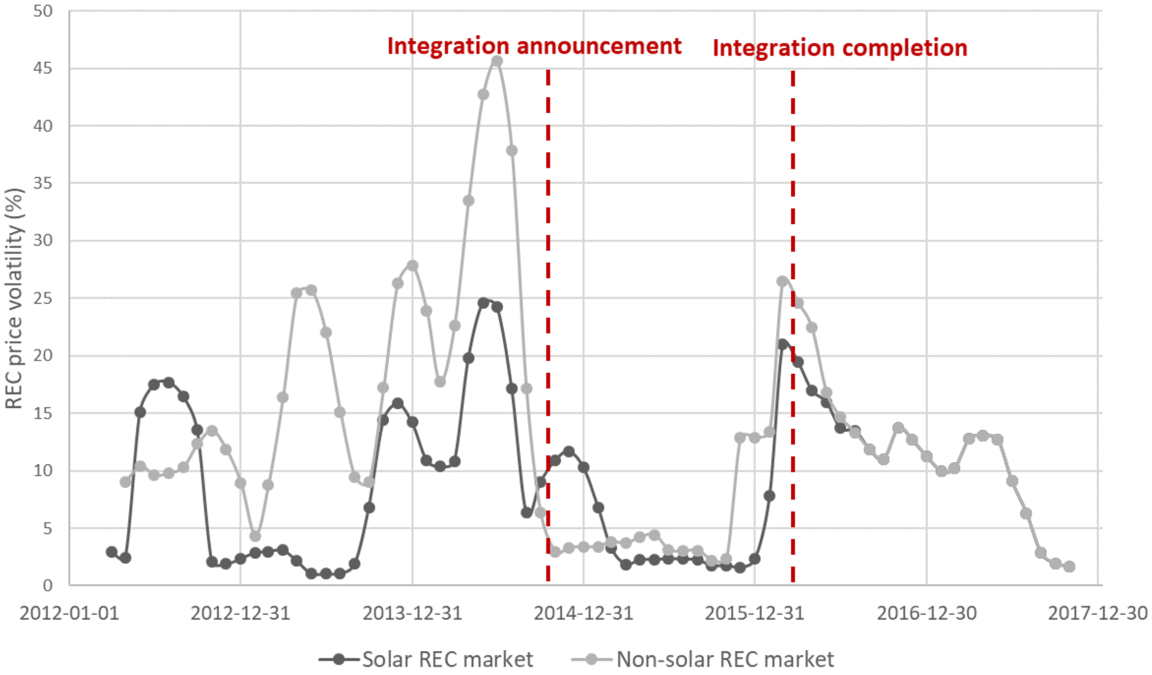


Figure 3B REC trading volume

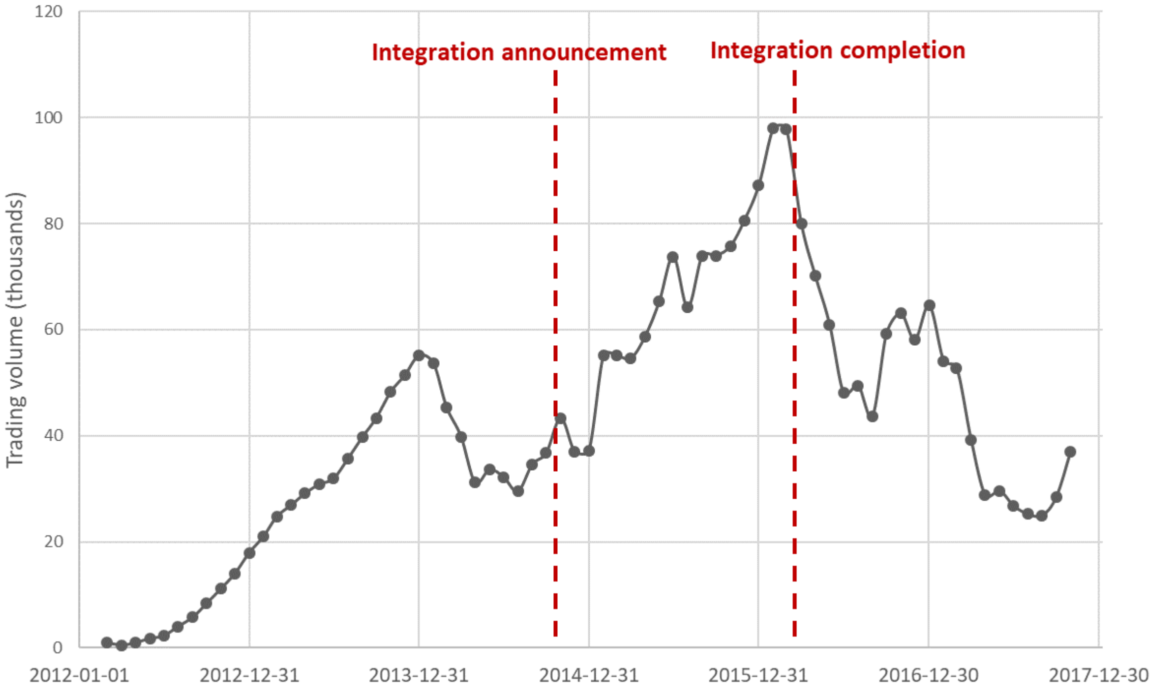


Figure 3 Trends of REC price volatility and trading volume around the integration announcement between solar and non-solar REC markets. REC price volatility is computed as a rolling standard deviation of REC prices over the past six months. REC trading volume is evaluated as a rolling average of the total number of traded RECs over the past six months. Source: Authors' calculations based on the Korean Power Exchange database.

Table 1 Summary statistics

Panel A	Mean	Standard deviation	25%	Median	75%
Installed capacity (MW)	457.062	422.341	100.955	273.007	668.766
Electricity generation (GWh)	69.730	50.097	33.950	55.286	96.334
Dependence on external financing ($/W)	0.965	1.471	0.000	0.000	1.600
REC price volatility (% of average REC price)	11.573	8.883	3.297	10.821	15.986
REC trading volume (in thousands)	43.914	24.652	29.499	43.726	59.231
Integration announcement	0.468	0.503	0.000	0.000	1.000
GDP growth (%)	0.708	0.246	0.500	0.700	0.900
RPS mandates (%)	2.839	0.549	2.500	3.000	3.000
Dependence on REC revenue (% of total revenue)	48.573	13.071	41.955	50.208	58.109
Growth of new capacity installations (%)	81.452	624.970	0.000	16.794	122.813

Panel B	Before integration announcement (1)	After integration announcement (2)	Differences (2)-(1)
Installed capacity (MW)	331.857	599.536	267.679*** (0.000)
Electricity generation (GWh)	56.005	85.348	29.343*** (0.000)
Dependence on external financing ($/W)	1.073	0.841	-0.232 (0.216)
REC price volatility (% of average REC price)	13.824	9.205	-4.619 *** (0.004)
REC trading volume (in thousands)	26.337	63.310	36.973*** (0.000)
GDP growth (%)	0.718	0.697	-0.022 (0.733)
RPS mandates (%)	2.455	3.276	0.821*** (0.000)
Dependence on REC revenue (% of total revenue)	43.564	54.273	10.709*** (0.000)
Growth of new capacity installations (%)	67.607	97.206	29.599 (0.711)

Notes: This table shows summary statistics. P-values are reported in parentheses. ***, **, and * denote statistical significance at 1%, 5%, and 10% levels, respectively.

Table 2 First-stage estimation

	REC price volatility$_{i,t}$		
Sample	(1) Full	(2) Solar REC market	(3) Non-solar REC market
Integration announcement$_t$	-19.569*** (0.000)	-9.585*** (0.006)	-22.993*** (0.000)
GDP growth$_t$	-7.696 (0.187)	-12.805 (0.166)	-6.188 (0.174)
RPS mandates$_t$	0.156*** (0.003)	0.094* (0.064)	0.173*** (0.003)
Dependence on REC revenue$_{i,t}$	0.107 (0.546)	0.050 (0.860)	0.127 (0.462)
Growth of new capacity installations$_{i,t}$	0.001** (0.013)	0.000 (0.985)	0.001*** (0.002)
Industry fixed effect	Yes	No	Yes
R^2	0.532	0.364	0.587
Observations	189	48	141
F-statistic	225.541*** (0.000)	29.212*** (0.006)	316.933*** (0.000)

Notes: This table shows first-stage estimation results, which examine the relationship between the integration of solar and non-solar REC markets and REC price volatility. We cluster standard errors by year level. P-values are reported in parentheses. ***, **, and * denote statistical significance at 1%, 5%, and 10% levels, respectively. The coefficient of RPS mandates is divided by 100.

Table 3 REC price volatility and renewable energy investment

	Installed capacity$_{i,t+12}$ (1)	Electricity generation$_{i,t+12}$ (2)
REC price volatility$_{i,t}$	-5.940*** (0.000)	-0.512*** (0.000)
GDP growth$_t$	72.982 (0.139)	-5.011 (0.604)
RPS mandates$_t$	3.524*** (0.000)	0.359*** (0.000)
Dependence on REC revenue$_{i,t}$	-6.106 (0.149)	-0.253 (0.667)
Growth of new capacity installations$_{i,t}$	-0.004 (0.696)	-0.001 (0.246)
Industry fixed effect	Yes	Yes
Observations	189	189
Robust regression-based Hausman test	18.10** (0.013)	3.603 (0.131)
OLS estimates: REC price volatility$_{i,t}$	-1.701 (0.432)	-0.089 (0.724)

Notes: This table shows 2SLS estimation results that investigate the effect of REC price volatility on renewable capacity installations. We cluster standard errors by year level. P-values are reported in parentheses. ***, **, and * denote statistical significance at 1%, 5%, and 10% levels, respectively. The coefficient of RPS mandates is divided by 100.

Table 4 Subsample studies: REC price volatility and renewable energy investment

	Installed capacity$_{i,t+12}$			
	(1)	(2)	(3)	(4)
Sector	Solar	Wind	Biomass	Small hydro
REC price volatility$_{i,t}$	-26.885***	-8.866***	0.005	-0.281***
	(0.000)	(0.000)	(0.230)	(0.000)
Control variables	Yes	Yes	Yes	Yes
Observations	48	47	47	47
Robust regression-based Hausman test	18.45**	24.02***	0.747	9.942**
	(0.013)	(0.008)	(0.436)	(0.034)
OLS estimates: REC price volatility$_{i,t}$	-6.644	-4.020*	0.002	-0.086**
	(0.357)	(0.060)	(0.480)	(0.043)

Notes: This table shows subsample studies on the relationship between REC price volatility and renewable capacity installations. Subsamples are solar, wind, biomass and waste, and hydro industries. We cluster standard errors by year level. P-values are reported in parentheses. ***, **, and * denote statistical significance at 1%, 5%, and 10% levels, respectively.

Table 5 REC trading volume and renewable energy investment

	REC trading volume$_t$	Installed capacity$_{t+12}$	Electricity generation$_{t+12}$
	(1)	(2)	(3)
Model	First stage	Second stage	Second stage
Integration announcement$_t$	21.590*** (0.000)		
REC trading volume$_t$		20.570*** (0.000)	1.793*** (0.000)
GDP growth$_t$	7.871 (0.442)	-100.205 (0.512)	-55.984** (0.022)
RPS mandates$_t$	0.210** (0.026)	3.420** (0.036)	0.437** (0.018)
Dependence on REC revenue$_{i,t}$	1.014* (0.075)	-18.412*** (0.003)	-0.413 (0.594)
Growth of new capacity installations$_{i,t}$	-0.000 (0.740)	0.077*** (0.005)	0.005 (0.496)
Observations	49	49	49
F-statistic	201.878*** (0.000)	-	-
Robust regression-based Hausman test	-	12.67** (0.024)	0.105 (0.762)
OLS estimates: REC trading volume$_t$	-	14.415*** (0.005)	1.520** (0.016)

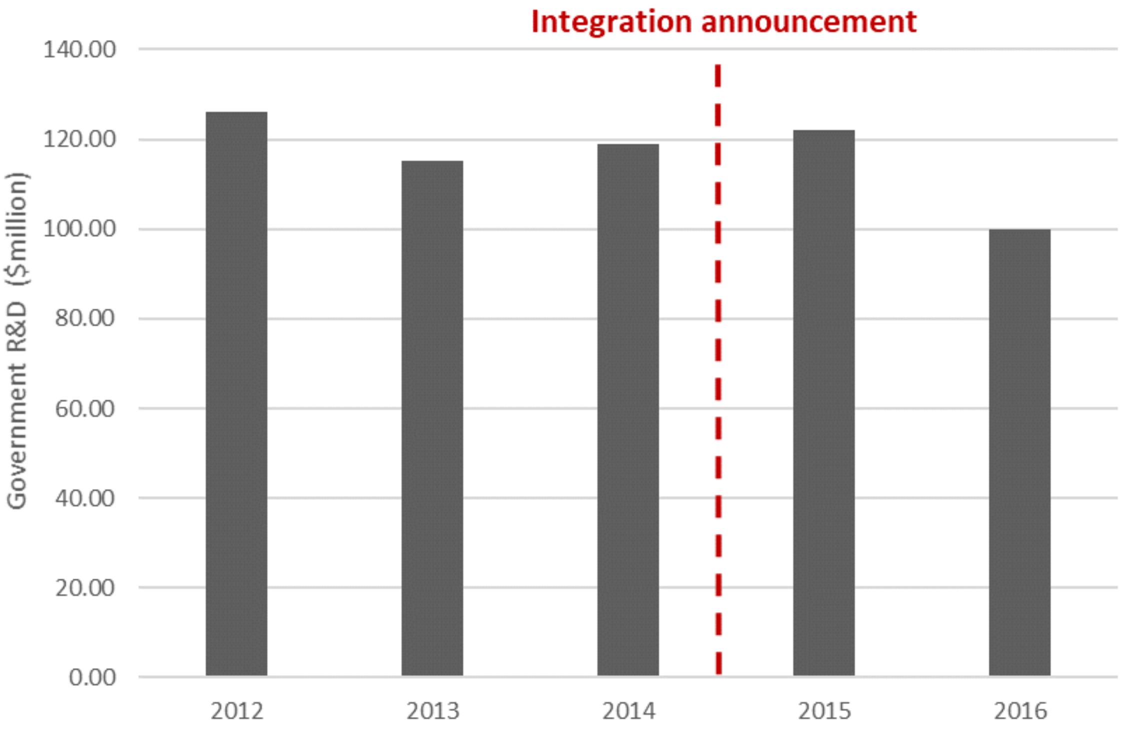
Notes: This table shows 2SLS estimation results that examine the impact of REC trading volume on renewable energy investment. We cluster standard errors by year level. P-values are reported in parentheses. ***, **, and * denote statistical significance at 1%, 5%, and 10% levels, respectively. The coefficient of RPS mandates is divided by 100.

Table 6 REC price uncertainty and dependence on external financing

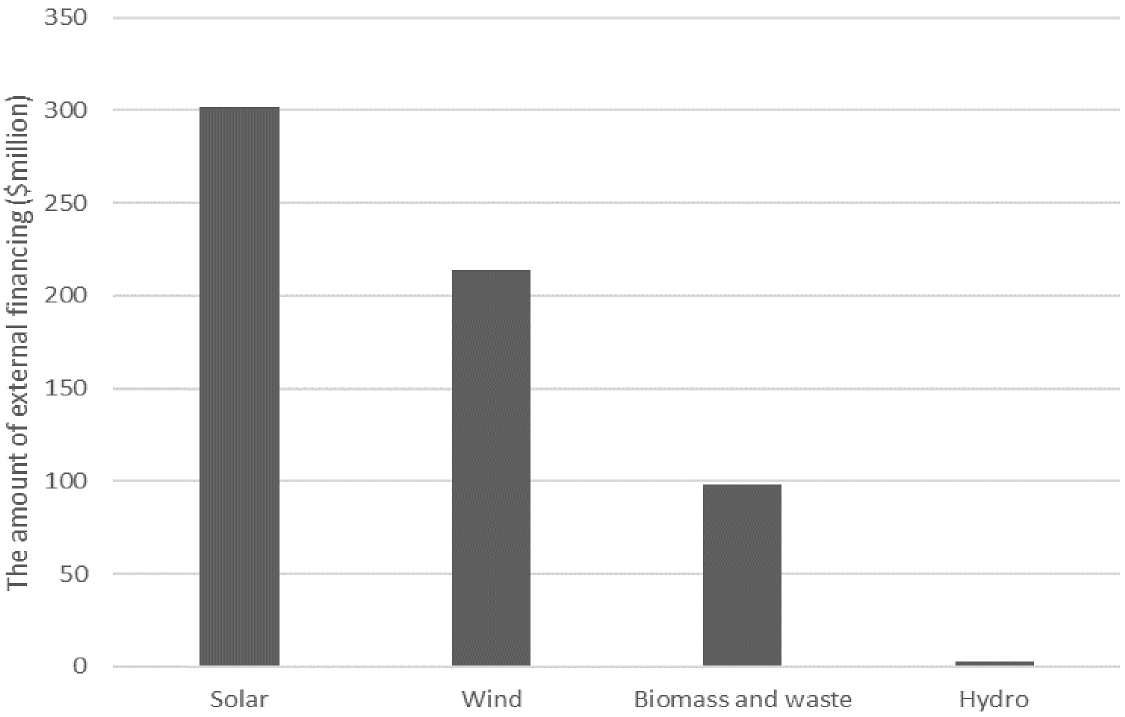
	Dependence on external financing$_{i,t+12}$	
	(1)	(2)
REC price volatility$_{i,t}$	0.011*** (0.000)	
REC trading volume$_{t}$		-0.011*** (0.009)
GDP growth$_{t}$	0.430*** (0.001)	0.180 (0.320)
RPS mandates$_{t}$	-0.003*** (0.000)	-0.001 (0.680)
Dependence on REC revenue$_{i,t}$	0.006 (0.376)	0.009 (0.222)
Growth of new capacity installations$_{i,t}$	-0.000 (0.953)	0.000*** (0.000)
Industry fixed effect	Yes	No
Observations	189	49
Robust regression-based Hausman test	0.347 (0.587)	5.840* (0.073)
OLS estimates: REC price volatility$_{i,t}$ and REC trading volume$_{t}$	0.013** (0.041)	-0.003 (0.577)

Notes: This table shows 2SLS estimation results that analyze the association between REC price volatility and dependence on external financing. We cluster standard errors by year level. P-values are reported in parentheses. ***, **, and * denote statistical significance at 1%, 5%, and 10% levels, respectively. The coefficient of RPS mandates is divided by 100.

Appendix



Appendix 1 Government R&D spending on renewable energy industries around the integration announcement of solar and non-solar REC markets. Source: Authors' calculations based on the Bloomberg New Energy Finance (BNEF) database.



Appendix 2 Annual average amount of debt and equity financing across renewable industries in Korea. Source: Authors' calculations based on the Bloomberg New Energy Finance (BNEF) database.