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Is Bail-in Debt Bail-inable?†

By SUNJOO HWANG*

The contingent convertible bond (or CoCo) is designed as a bail-in tool, which is written down or converted to equity if the issuing bank is seriously troubled and thus its trigger is activated. The trigger could either be rule-based or discretion-based. I show theoretically that the bail-in is less implementable and that the associated bail-in risk is lower if the trigger is discretion-based, as governments face greater political pressure from the act of letting creditors take losses. The political pressure is greater because governments have the sole authority to activate the trigger and hence can be accused of having 'blood on their hands'. Furthermore, the pressures could be augmented by investors' self-fulfilling expectations with regard to government bailouts. I support this theoretic prediction with empirical evidence showing that the bail-in risk premiums on CoCos with discretion-based triggers are on average 1.13 to 2.91%p lower than CoCos with rule-based triggers.

Key Word: Contingent Convertible Bonds, Bail-ins,
Discretion-based Triggers, Rule-based Triggers
JEL Code: G01, G12, G21, G28

I. Introduction

When systemically important banks fail, governments typically choose to bail out these banks. However, government bailouts can cause a number of serious problems. First, the government backing ends up encouraging large banks to take excessive risks.[1] Second, bailouts can initiate what is known as a 'diabolic loop.'[2] Banks typically have a large volume of sovereign bonds on their balance sheets. A large-scale taxpayer-bailout could increase sovereign credit risk and lower the value of sovereign bonds. Consequently, banks face a greater risk of balance sheet insolvency. Third, bailouts are unjust, as taxpayers should shoulder the burden of resolving failed banks even if they are not the stakeholders.

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After the global financial crisis and subsequent European sovereign debt crisis, G20 and EU countries and the Basel committee agreed on the adoption of a new bank resolution regime—the bail-in system.[3] Under this new regime, shareholders and creditors, but not taxpayers, are required to absorb losses if their banks fail. If the bail-in system can be properly implemented, it can prevent moral hazard at large banks and protect governments' fiscal positions as well as taxpayers. An important bail-in tool is the contingent convertible bond (CoCo). CoCos differ from straight bonds in that there are bail-in clauses in the bond contracts. According to these clauses, if the issuing bank is severely distressed and hence the conditions for a certain *trigger* are met, the principal and interest of a CoCo are written down or the CoCo is converted mandatorily to common equity of the issuing bank. In addition, some types of CoCos allow the issuer the option to cancel interest payments. Therefore, CoCo holders lose their claims and, unlike straight bond holders, they cannot force the issuing bank to file for bankruptcy even if the bank fails to meet its debt obligation. The troubled bank then can easily revive at the cost of its creditors (See Duffie (2009), McDonald (2013), and Flannery (2016) for this advantage of CoCos).

However, two recent events suggest that the implementability of the bail-in system is in doubt, particularly in cases where the government's political costs and financial shocks from bail-ins are sufficiently large. Firstly, in July of 2016, Italian banks confronted a serious non-performing loan problem. In response, the Italian government attempted to inject public funds into the distressed banks. This marked a remarkable event given that Italy had already adopted an EU-wide bail-in system. The Italian government wanted bailouts despite the fact that it is against the principle of a bail-in, as most of the creditors involved were ordinary citizens, and such a large number of citizens represented a huge political burden to the government.

Secondly, in February of 2016, news reports stated that Deutsche Bank's profitability had been greatly reduced and that it may be unable as a result to pay the promised interest to CoCo holders. Immediately, the stock price plummeted and CDS spreads soared amid worries about Deutsche Bank and the European banking system, which quickly became widespread.[4,5] These concerns could cause liquidity problems even in the absence of insolvency issues. Note that such shocks arise not due to a disorderly resolution because, due to CoCos, troubled banks can recover their financial soundness by transferring losses to creditors. Worries arise because investors were shocked that they will not be rescued by the government. Some commentators argued that CoCos are excessively complex instruments and that the loss-absorption mechanism could cause destabilizing effects (see Hart and Zingales, 2010; Admati *et al.*, 2013; Sundaresan and Wang, 2015).

This paper examines how the implementability of a bail-in depends on the types of triggers of CoCos. I do not analyze whether bail-ins are better or worse than

[1]See Allen *et al.* (2017) for a survey of studies that examine the moral hazard problem of government bailouts. See also Demirguc-Kunt and Detragiache (2002) and Ioannidou and Penas (2010) for empirical studies that find that government-oriented deposit insurance ends up increasing banks' risk-takings and the likelihood of financial crisis.

[2]See Acharya, Drechsler, and Schnabl (2014).

[3]In 2014, the Financial Stability Board (FSB) proposed an international standard on the bail-in system. See FSB (2014).

[4]*Bloomberg*, "Deutsche Bank's Woes Threaten CoCo Coupons, Credit Sights Says," February 8, 2016

[5]*Bloomberg*, "Deutsche Bank CoCo Holders See What Regulators Mean by Risk," February 8, 2016.

bailouts in this paper. Instead, I focus on the implementability of a bail-in because a welfare comparison is meaningful only after one can confirm that bail-ins are implementable. There are two bail-in mechanisms: a statutory bail-in and a contractual bail-in. The statutory bail-in applies in principle to all unsecured debt contracts, including senior unsecured bonds and some eligible deposits. Statutory bail-ins require significant amendments of existing laws pertaining to property rights, and concerns about depositors arise. This explains why many countries have struggled to enact laws on statutory bail-ins. In contrast, the contractual bail-in is based only on the bail-in clause in the bond contract; hence, significant changes in existing laws are not necessary. In this reason, CoCos—contractual bail-in debt—have been used in many countries.

The triggers of CoCos could be either rule-based or discretion-based. Typical rule-based triggers are based on accounting information, such as bank capital ratios. Theoretically, rule-based triggers could be based on market information such as stock prices and credit default swap spreads. However, almost all rule-based CoCos that have been issued since the global financial crisis are based on capital ratios. If the level of a chosen indicator falls short of a predetermined threshold, the rule-based trigger is activated and, hence, creditors absorb losses through either principal write-downs or mandatory conversions to equity. In contrast, discretion-based triggers rely on governments' judgments of whether the issuing bank is seriously distressed. If a competent authority declares that the issuing bank is at the point of non-viability (PONV), the trigger is activated and hence creditors take losses.

This paper consists of two parts. In the first part, I construct a theoretic model and show that CoCos with discretion-based triggers are less effective bail-in tools than CoCos with rule-based triggers, as the government's political burden is higher. If the trigger is discretion- based, a relevant authority must undertake the 'dirty job' of imposing losses on creditors. This is not the case with a rule-based trigger, which is activated mechanically if a predetermined condition is satisfied. Even if the mere effect of the type of trigger on the political cost is small, it could grow through the mechanism of the self-fulfillment of the expectation of a government bailout. If investors know that a government faces a somewhat greater political burden when they buy CoCos with discretion-based triggers as opposed to those with rule-based triggers, they may believe that the government would be more likely to rescue them in the case of a bank failure. Given this belief, they invest more in CoCos with discretion-based triggers than in CoCos with rule-based triggers, resulting in more participating investors. Because the government's political costs will most likely increase with the number of affected investors, the government will indeed choose to bail out CoCo holders when the issuing bank is in distress. That is, the investors' belief is fulfilled and therefore rationalized. In this sense, with regard to rational expectations equilibria, the bail-in risk and equilibrium interest rates of discretion-based CoCos are both lower if the trigger is discretion-based.

In the second part, I test the model prediction by conducting an empirical study. Figure 7 shows roughly the relationship between the bail-in risk and the type of trigger. As the ratio of discretion-based CoCos to all CoCos decreases across countries, the average interest rate of CoCos becomes higher. Using a dataset on CoCo issuance around the world during 2010-2016, I find that the interest rate at issuance of discretion-based trigger CoCos is lower by 1.13 to 2.91%p on average than that for rule-based trigger CoCos even after controlling for variables that are closely related to the likelihood of government bailouts and the financial soundness of the issuing bank. This finding suggests that triggers should be carefully designed in order to make CoCos effective as bail-in tools.

As triggers are the key features of CoCos, existing studies focus on the economic implications of various types of triggers. Among only a handful of related empirical studies, Avdjiev *et al*. (2017) examine the quantitative effects of CoCo issuance on the issuing banks' credit default swap (CDS) spreads. They show that the CoCo issuance announcement does not have significant effects on the issuing bank's CDS spreads if the trigger is discretion-based, whereas the announcement is associated with declines in the CDS spreads if the CoCo contains a rule-based trigger. Their findings appear to be consistent with the main result of the current paper. In the current paper, I show that the government is more likely to save troubled CoCo holders ex-post if the trigger is discretion-based. Then, ex-ante, the bank's stockholders' incentive to reduce risk is weak given that they can attract CoCo investors in any case. Due to this weak risk-reduction incentive, the bank's default risk as measured by the CDS spread for a senior unsecured bank bond (rather than the CDS on CoCos) does not decrease significantly. In contrast, if the trigger is rule-based, according to the current paper, the government is less likely to save troubled CoCo holders. Therefore, ex-ante, the bank faces a strong incentive to reduce its risk because otherwise it will not be able to attract CoCo investors. The CDS spreads on the bank's straight bonds then decline significantly due to the bank's strong risk-reduction incentives.

Sundaresan and Wang (2015) show in a theoretic model that CoCos with market triggers based on stock prices generally result in multiple equilibria. Although the multiple-equilibrium phenomenon also arises in this paper, the mechanism and focus are different. In their paper, investors' *expectations on market prices* endogenously determine the equilibrium in place.[6] In contrast, this paper shows that investors' *expectations on the likelihood of government assistance* endogenously determine the equilibrium in place. In general, comparative statics are not meaningful when there are multiple equilibria. However, even after considering the multiple-equilibrium phenomenon, the current paper could show that discretion-based CoCos end up more likely to receive government bailouts in equilibria as compared to CoCos with rule-based triggers.

Martynova and Perotti (2013) compare market triggers with accounting triggers in terms of informativeness. They show that market triggers are relatively more likely to cause the Type II error—triggers are activated even if issuing banks are sound and hence triggers should not be activated—when market prices are volatile. In contrast, it is shown that accounting triggers are more likely to cause the Type I error—triggers are not activated even if issuing banks are distressed—as accounting information must be confirmed by regulators, who are vulnerable to regulatory forbearance. Although informativeness is not the main focus, the current paper also

[6]Unlike Sundaresan and Wang (2015), Glasserman and Nouri (2016) consider a continuous-time framework in which market prices could be constantly adjusted. They show that the unique equilibrium condition could be obtained if the predetermined threshold for a trigger is sufficiently high. Calomiris and Herring (2013) argue that the multiple-equilibrium problem of Sundaresan and Wang (2015) does not arise if banks have the option to raise equity.

takes Type I and Type II errors into account when analyzing how discretion-based triggers are different from rule-based triggers with regard to their effects on the implementability of a bail-in.

Dewatripont (2014) discusses the implementability of a statutory bail-in system. He acknowledges that the creditor bail-in can impose severe shocks on the financial system. In order to prevent a bail-in-led financial crisis, he suggests retaining the option of a bailout, especially when it can be prefunded by banks. The work by Dewatripont (2014) is close to the present paper in that the current paper explicitly examines the financial shocks caused by bail-ins, though Dewatripont (2014) does not focus on CoCos but on statutory bail-ins.

This paper is organized in the following way. In Section 2, I construct a theoretic model that provides some predictions of the effectiveness of a CoCo as a bail-in tool. In Section 3, I conduct an empirical analysis in order to test the prediction that CoCos with discretion- based triggers work poorly as bail-in tools as compared to CoCos with rule-based triggers. Section 4 is the conclusion.

II. A Theoretical Analysis

There are three ‘active’ players in the model economy: investors holding contingent convertible bonds (hereafter, CoCos), a systemically important bank, and a government. Depositors and short-term funders are inactive players.

There are two points in time, $t=0,1$. At time 0, the bank issues a CoCo at (net) interest rate r with a rule-based or discretion-based trigger. After observing r, investors decide whether to purchase the CoCo. At time 1, if the bank is seriously troubled and, hence, the trigger is activated, the CoCo is converted to common equity or its principal and interest are written down depending on the loss-absorption mechanism. During the process of loss absorption, I assume that both the existing stockholders and CoCo holders bear losses.[7]

A key difference with CoCos as compared to straight bonds is that the former allows for the government to separate the bailout decision from the continuation decision. If the bank fails at time 1, the government has no choice but to continue the failed bank owing to its systemic importance.[8] In this regard, I assume in the following theoretic analysis that failed bank must be continued in any case. If the bond were a straight bond, the bond holders would take control over the bank from the stockholders. To continue the bank, the government would have to buy the control rights by repaying the straight bond holders. That is, the government is forced

[7]Suppose that the loss-absorption mechanism is a mandatory conversion to common equity. If the stock price of the bank is unchanged even after the mandatory conversion, existing stockholders and CoCo holders enter into a zero-sum game. If the conversion ratio is advantageous for the stockholders, they win while the bond holders lose. In contrast, if the conversion ratio is advantageous for the bond holders, they win while the stockholders lose. However, in actuality, the mandatory conversion is a severely adverse event. Hence, it is most likely that the stock price will fall dramatically. Therefore, both the stockholders and bond holders lose regardless of the conversion ratio. Suppose instead that the loss-absorption mechanism is a principal write-down. If the stock price does not change even after the trigger is activated, the CoCo holders lose their principal and interest, whereas the stockholders win as the bank’s liabilities are reduced for free. However, it is most likely that the stock price decreases greatly after the principal write-down and, hence, both the bond holders and the stockholders lose.

[8]‘Continuation’ refers to both an open-bank continuation and a closed-bank resolution with a going concern.

to bail out the bond holders. The situation differs with a CoCo. In this case, the CoCo holders' claims are canceled as the trigger is activated; hence, the government can continue the systemically important bank. That is, the government can choose whether to rescue the bond holders or not if the bond is a CoCo, whereas its only feasible option is to rescue the bond holders if the bond is a straight bond.

A. *Information Structure*

Rule-based triggers are based on imperfect signals of solvency, such as the common equity tier 1 (CET1) capital ratio, the stock price, or the CDS spread. None of these signals are perfect. For instance, a bank could be solvent (insolvent) even if its CET1 capital ratio is below (above) a certain threshold.

In order to model this imperfection of a rule-based trigger, let $X \in \{0,1\}$ denote the solvency of the bank, which is non-verifiable and hence non-contractible. $X = 1$ means that the bank becomes solvent at time 1, whereas $X = 0$ means it becomes insolvent at that time. That is, $p \equiv \Pr(X = 0)$ is the probability of failure.

Investors can observe an imperfect contractible signal $x \in (-\infty, \infty)$ of X. Let $F_x(\cdot)$ denote the distribution function of x conditional on X. The signal x and the underlying parameter X are positively related in the sense of first-order stochastic dominance; that is, $F_1(\underline{x}) < F_0(\underline{x})$ for any threshold $\underline{x} \in (-\infty, \infty)$. In other words, the probability of receiving bad news $\Pr(x < \underline{x} \mid X) = F_x(\underline{x})$ if the bank is solvent (i.e., $X = 1$) is smaller than that if the bank is insolvent (i.e., $X = 0$).

Rule-based trigger case: Without loss of generality, I consider the case where the trigger is activated if x is below a threshold $\underline{x}$. That is, the probability of the trigger being activated equals $\Pr(x < \underline{x}) = (1-p)F_1(\underline{x}) + pF_0(\underline{x})$. Note that this probability can also be expressed as

$$\text{(1)} \qquad \Pr(x < \underline{x}) = p + (1-p)F_1(\underline{x}) - p[1 - F_0(\underline{x})].$$

This expression implies that the signal x is associated with two possible errors. The trigger can be activated when the bank is solvent (i.e., $x < \underline{x}$ *and* $X = 1$) — *the error of false activation* — whose likelihood is $(1-p)F_1(\underline{x})$. It is also possible that the trigger is not activated even if the bank is insolvent (i.e., $x > \underline{x}$ *and* $X = 0$) — *the error of negligence* — whose likelihood is $p[1 - F_0(\underline{x})]$. Note that the error of false activation is increasing while the error of negligence is decreasing in the threshold $\underline{x}$. If the threshold is appropriately chosen, the rule-based trigger has no systematic error in the sense that the unconditional probability of the trigger being activated is equal to the probability of insolvency. That is, I define an 'unbiased' level of threshold $\underline{x}'$ as follows:

Definition 1. *A threshold* $\underline{x}$ *is unbiased if* $\Pr(x<\underline{x})=p$, *or equivalently,* $(1-p)F_1(\underline{x})=p[1-F_0(\underline{x})]$.[9]

Discretion-based trigger case: At its discretion, the government can consider a number of sources of information, including not only the signal x but also other non-contractible variables. The government can also require banks to report confidential information promptly and can conduct on-site examinations. For these reasons, I assume that the government can determine without any error whether a troubled bank is actually solvent or not; that is, it can observe the parameter X .

Some readers might believe that market participants know better than governments. I do not disagree with this belief and in fact it is not inconsistent with the current model. Rule- based decision making is valued for its quickness, but it must rely on a small set of verifiable indicators. In contrast, discretion-based decision making is valued because the decision maker can utilize not only verifiable but also non-verifiable (but highly informative) indicators when making decisions. That is, market participants compared to governments may observe more sources of information. However, only a handful of those sources can be used when designing a rule-based trigger due to the incompleteness of contracts.

B. *CoCo Market*

1. Supply

The bank chooses the size of an investment in assets and how to finance the assets. There are four ways to finance, deposits D, short-term debt S, (long-term) CoCo C, and equity E, though deposits and equity have limited roles in this model. Hahm, Shin, and Shin (2013) report that deposits and equity do not depend much on financial market conditions. This is presumably because depositors are usually protected by deposit insurance and depositor preference during insolvency proceedings. Moreover, depositors' primary motive for holding deposits is to use payment and settlement services; hence, they are less likely to change the balances of their deposit accounts simply because financial market conditions change. In this regard, I assume that depositors invest in the bank a fixed amount D at a zero net interest rate. When banks increase their investments in assets, they usually finance these investments with debt rather than equity, as equity issuance is often deemed the most expensive means of financing due to the associated risks, tax disadvantage, and dilution. In this reason, I assume that equity E is fixed. Below, I assume that $D=E=0$ without loss of generality.

The model is focused on CoCo and its relationship with short-term debt. Short-term debt is inexpensive given that it is demandable on short notice and collateral is posted against it, whereas CoCos are expensive due to their longer maturities, greater level of default risk, and the risk of bail-ins. However, the merit of a CoCo is that it

[9]Note that there exists a unique unbiased threshold $\underline{x}' \in (-\infty,\infty)$ since $(1-p)F_1(\underline{x})$ increasing from 0 to $(1-p)$ while $p[1-F_0(\underline{x})]$ is decreasing from p to 0 as $\underline{x}$ rises.

is recognized as regulatory capital according to the Basel III accord and other international regulations on capital adequacy.

The bank succeeds with probability $(1-p)$ and fails with probability p. If it fails, the bank earns nothing. By the limited liability, in this case, the bank pays nothing to creditors. If it succeeds, the bank earns $(1+\alpha)A$ from its investment in assets A. The return on investment $\alpha(A)A$ is assumed to be increasing and concave with regard to A. I also use the two regularity conditions $\lim_{A\to 0}\frac{d}{dA}\alpha(A)A=\infty$ and $\lim_{A\to\infty}\frac{d}{dA}\alpha(A)A=0$.

Below, I derive the CoCo supply function.

Discretion-based trigger: The bank (or its stockholders) solves the following problem.

(2)
$$\max_{A,C,S}(1-p)[(1+\alpha(A))A-S-(1+r)C]$$
$$\text{subject to } A=S+C,\ \frac{C}{A}\geq \underline{c}$$

where the first and second constraints are the accounting identity and capital adequacy requirement with the regulatory minimum capital ratio $\underline{c}$, respectively. Note that the (net) interest rate on short-term debt is assumed to be zero. As CoCos are more expensive than short-term funding, it is optimal to issue a CoCo only when the capital requirement is binding, that is, when the minimum capital ratio $\underline{c}$ is high enough. Since the global financial crisis and subsequent European sovereign debt crisis, regulations on international capital have been greatly strengthened. In this sense, I assume that $\underline{c}$ is sufficiently high that the capital adequacy requirement is binding. Then, by substituting $\underline{c}A$ for C, the optimal choice of assets $A^*(r)$ is determined by the following first-order condition.

(3)
$$\frac{d}{dA}\alpha(A)A=r\underline{c}\ \text{ at }\ A=A^*(r)$$

The equation above implies that the optimal size of investment $A^*(r)$ is decreasing in r because $\alpha(A)A$ is concave in A. Thus, the CoCo supply is equal to $C^s(r)\equiv \underline{c}A^*(r)$, which is also decreasing in r.

Rule-based trigger: Bank stockholders gain nothing if the CoCo trigger is activated.[10] In this case, the bank as an entity enjoys a reduction in its liabilities but

[10]If the bank is solvent but the trigger is activated, I assume that the stockholder value becomes zero for the following two reasons. If the rule-based trigger is activated, under the presence of incomplete information about the soundness of the bank, the financial market withdraws its trust in the bank and hence creditors may demand repayment or reject refinancing. Consequently, the bank faces a serious liquidity problem, which results in stockholder value going to zero even if the bank is solvent. In the 2016 Deutsche Bank case, even the rumor that the

the existing stockholders' value is assumed to be fully diluted. Therefore, they receive zero payoff regardless of whether the bank is solvent or not. If the loss-absorption mechanism of the CoCo is mandatory conversion, the existing stockholders' value is greatly diluted as the current international regulation pertaining to CoCos requires the conversion ratio to be disadvantageous for existing stockholders. If the loss-absorption mechanism calls for the write-down of principal and interest, existing stockholders are, in principle, intact, but in reality, they are wiped out as the stock price plummets. If the trigger is not activated but the bank is insolvent, the bank as an entity has nothing and hence its stockholders receive a zero payoff. Finally, the stockholders face a positive payoff only when the trigger is not activated and the bank is solvent. Therefore, they solve the following problem:

$$\max_{A,C,S}(1-p)(1-F_1(\underline{x})[(1+\alpha(A))A-S-(1+r)C] \quad \text{subject to } A=S+C,\ \frac{C}{A}\geq \underline{c} \tag{4}$$

Because the asset size and CoCo do not affect the probability of solvency or the probability of the trigger being activated, the CoCo supply is still equal to $C^s(r)=\underline{c}A^*(r)$.

2. Demand

There is a unit-measure of investors who choose whether to buy CoCos. These investors are risk-neutral. Each investor is endowed with one unit of money.[11] Investors may use the money to purchase one unit of the CoCo or to invest in an alternative project. The reservation utility from this alternative project is u, which follows distribution G on the support $[0,1]$.

Discretion-based trigger case: If the bank becomes insolvent, the government can choose whether to activate the trigger of the CoCo. If it chooses to activate it by declaring that the bank is at the point of non-viability, the CoCo holders' claims are canceled and they absorb losses. If the government does not activate the trigger, it has to repay the CoCo holders on behalf of the insolvent bank. Note that one cannot think of a situation in which the bank is insolvent, the government does not activate the trigger, but neither the bank nor the government repay the CoCo holders as, in this case, the CoCo holders can legitimately require repayment as their claims are still valid. If these valid claims are not satisfied, the bond holders can force the bank

bank was not able to pay interest as opposed to principal to CoCo holders caused a significant shock in the European financial market. Second, in reality, most rule-based triggers are based on the CET1 ratio. If this common-equity tier 1 capital ratio falls below the well-known threshold of 5.125%, most rule-based trigger CoCos become converted to equity or their principal is written down. According to Basel III, if the CET1 ratio is lower than 5.125%, the bank is deemed seriously troubled; accordingly, dividend payouts to stockholders are banned. In addition, many countries, including Korea, have domestic regulations under which prompt corrective action is taken if banks' CET1 ratios fall below the Basel III standard. That is, if the rule-based trigger is activated, it means a significant decrease in the stockholder value even if the bank is still solvent.

[11]In this paper, one unit of money is equal in value to one unit of consumption.

to enter into a bankruptcy process, resulting in the exposure of the financial market to a systemic crisis. Let $q^e \in \{0,1\}$ denote the investors' *expectation* of the probability that *the government does not activate the trigger but uses taxpayers' funds to repay CoCo holders*. That is, q^e can also be interpreted as the expected probability of regulatory forbearance. I assume that investors form a common expectation because they are identical in every aspect except for the reservation payoff. Then, the probability that CoCo holders lose is equal to $p(1-q^e)$; hence, the CoCo demand is given by

$$(5) \qquad C^D(r,q^e) \equiv G((1-p(1-q^e))(1+r))$$

Note that the CoCo demand is increasing in r.

Rule-based trigger: Note that the probability that the trigger is activated is $(1-p)F_1 + pF_0$, where $F_1 = F_1(\underline{x})$ and $F_0 = F_0(\underline{x})$. Recall that the government can observe and supervise the bank and is therefore able to detect whether the mechanical trigger is soon to be activated. If it realizes that the trigger condition is about to be satisfied, it may consider saving the CoCo holders for a reason to be explained momentarily. Thus, the investors form the belief $q^e \in \{0,1\}$ where $q^e = 1$ means that the government chooses to recapitalize the bank preemptively just before the trigger is activated, while $q^e = 0$ means that the government lets the bond holders take losses. Thus, CoCo holders lose with the probability of $((1-p)F_1 + pF_0)(1-q^e)$ and hence the CoCo demand is given by

$$(6) \qquad G([1-((1-p)F_1 + pF_0)(1-q^e)](1+r))$$

Note that the CoCo demand is increasing in r.

If the unbiased threshold $\underline{x}'$ is used, the probability of the trigger being activated is equal to the probability of insolvency. In this case, the CoCo demand is simplified to

$$(7) \qquad C^D(r,q^e) = G((1-p(1-q^e))(1+r))$$

3. Market-clearing Outcome

Discretion-based trigger: The CoCo demand $G((1-p(1-q^e))(1+r))$ depends on the investors' expectation on the likelihood of regulatory forbearance q^e in case the bank becomes insolvent. If investors believe that the government will activate the trigger $(q^e = 0)$, the CoCo demand is $G((1-p)(1+r))$ and hence the market-clearing interest rate and quantity r^0 and m^0, respectively, are given by

(8) $$C^D(r, q^e = 0) = G((1-p)(1+r)) = cA^*(r) = C^S(r) \text{ at } r = r^0$$

(9) $$m^0 = C^D(r^0, q^e = 0) = C^S(r^0).$$

m^0 can be understood as the mass of CoCo holders as each investor buys only one unit of the CoCo. See Figure 1. In contrast, if they believe that the government will not activate the trigger but will save CoCo holders using taxpayers' funds $(q^e = 1)$, the demand increases to $G(1+r)$. In this case, the market-clearing interest rate and quantity are correspondingly r^1 and m^1 such that

(10) $$C^D(r, q^e = 1) = G(1+r) = cA^*(r) = C^S(r) \text{ at } r = r^1$$

(11) $$m^1 = C^D(r^1, q^e = 1) = C^S(r^1).$$

Note that r^1 is lower than r^0 while m^1 is larger than m^0.

Rule-based trigger: Suppose that the threshold $\underline{x}'$ of the signal x is unbiased. In this case, the market-clearing outcome is identical to that under the discretion-based trigger. That is, the pair consisting of the market-clearing interest rate and quantity is (r^0, m^0) if $q^e = 0$, while it is (r^1, m^1) if $q^e = 1$.

Note that r^1 is the risk-free rate because it is the market-clearing interest rate when the probability that CoCo holders will lose is zero. Thus, the difference between the market-clearing interest rate and risk-free rate can be understood as the bail-in risk premium required by investors. If investors believe that the government will not save CoCo holders (i.e., $q^e = 0$), they require $(r^0 - r^1)$ as the bail-in risk premium. In contrast, if investors believe that the government will rescue CoCo holders (i.e., $q^e = 1$), they acknowledge that there is no bail-in risk. This result holds for both types of triggers.

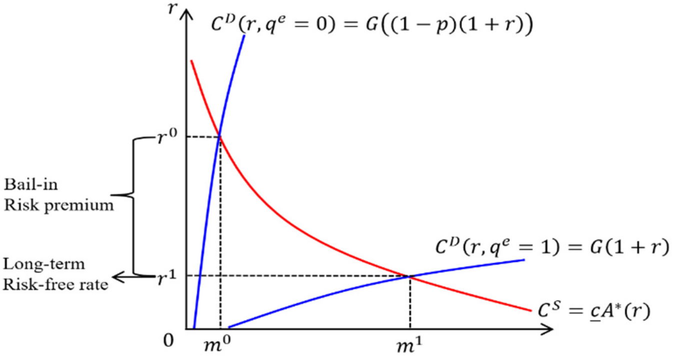


FIGURE 1. THE DEPENDENCE OF THE MARKET-CLEARING OUTCOME ON EXPECTATIONS

Lemma 1. (i) r^0, m^0, r^1 *and* m^1 *exist uniquely, and* $r^0 > r^1$ *but* $m^0 < m^1$. (ii) *If the trigger is discretion-based, the market-clearing interest rate and quantity are correspondingly* r^0 *and* m^0 *if* $q^e = 0$ *, whereas they are* r^1 *and* m^1 *if* $q^e = 1$. *The same is true if the trigger is rule-based and the threshold is unbiased (i.e.,* $\underline{x} = \underline{x}'$ *).*

Proof. (i) The existence and uniqueness follow from the fact that the CoCo demand is increasing while the CoCo supply is decreasing in r and the two regularity conditions $\lim_{A\to 0}\frac{d}{dA}\alpha(A)A = \infty$ and $\lim_{A\to\infty}\frac{d}{dA}\alpha(A)A = 0$. Given that $G(1+r) > G((1-p)(1+r))$ for all $r \geq 0$ and $A^*(r)$ is decreasing in r, equation (8) and (10) imply that $r^1 < r^0$. Because $r^1 < r^0$ and $A^*(r)$ is decreasing in r, equation (9) and (11) imply that $m^1 > m^0$. (ii) Equation (5), (8), (9), (10), (11), and the fact that the market-clearing outcome is invariant to the type of triggers immediately implies (ii). ■

The market-clearing outcome depends on the investors' expectation of regulatory forbearance and thus constitutes a rational expectations equilibrium if and only if the expectation is consistent with the government's actual choice. Below, I model the government's behavior and derive rational expectations equilibria.

C. *Government's Behavior and Equilibria*

1. Discretion-based trigger

When the bank becomes insolvent, the government decides whether to activate the trigger of the CoCo. During this decision process, the government considers three types of associated costs: fiscal, political, and shock costs.

If the government activates the trigger and lets the CoCo holders take losses, it is a shock to the investors, who may then withdraw their confidence in the banking system. Related to this, it was reported in February of 2016 that Deutsche Bank may be unable to pay the interest on its CoCos. Immediately, the stock price and CDS spreads decreased sharply and worries about Deutsche Bank and the European banking system spread quickly.[12,13] These worries could cause liquidity problems even when there are no insolvency issues. For instance, if a money market fund invests heavily in such a bank, not only the given fund but also other similar money market funds could suffer from fund runs. Let $\theta \geq 0$ denote the shock cost the government bears when it chooses not to save distressed CoCo holders.

If the government does not rescue the CoCo holders, certain political costs also arise. As the CoCo holders absorb losses, they withdraw their political support for

[12] *Bloomberg,* "Deutsche Bank's Woes Threaten CoCo Coupons, Credit Sights Says," February 8, 2016.
[13] *Bloomberg*, "Deutsche Bank CoCo Holders See What Regulators Mean by Risk," February 8, 2016.

the government and even protest against or sue it. Therefore, the government faces a political cost. This cost would be larger as more CoCo holders are forced to absorb losses. Similarly, during the 2016 banking turmoil, the Italian government was very reluctant to activate the trigger for bail-in debt, including senior and subordinated bonds, as most of the affected bond holders were ordinary citizens. It was reported that one third of senior bond holders and 46% of subordinated bond holders are retail investors.[14] Let $\pi_d c(m)$ denote such a political cost, where $\pi_d > 0$ is the intensity of the political cost and $c(m)$ is a nonnegative and increasing function of the number m of CoCo holders.

In contrast, suppose that the government decides not to activate the trigger but to recapitalize the bank at the expense of taxpayers. In this case, the shock cost is not a concern, whereas a fiscal cost arises because taxpayers' resources are used. The fiscal cost is $\delta(1+r)m$, where $\delta \in (0,1]$ reflects the possibility that bailout funds are repaid at least partially in the future by the rescued bank and $(1+r)m$ is the amount of money used in the bailout.[15]

For the following analysis, I use the assumption below pertaining to the political cost and the fiscal cost in order to focus on interesting and reasonable cases.

Assumption 1. (i) $\pi_d c(m^1) < \delta(1+r^1)m^1$.

(ii) $\pi_d[c(m^1) - c(m^0)] > \delta[(1+r^1)m^1 - (1+r^0)m^0]$.

The first part of Assumption 1 means that the political cost is lower than the fiscal cost if the shock cost is zero and, therefore, the government will never rescue the troubled CoCo holders. If CoCos are issued by small or medium-sized nonfinancial companies, the news that the government will not save troubled CoCo holders may not have any impact on the overall financial market. In this case, the shock cost is zero and hence the government never chooses a bailout. However, if the CoCos are issued by systemically important banks, the news will cause a panic in the financial market and will lead to financial instability. In this case, the shock cost is positive and large and the government therefore considers whether or not to save the bond holders.

The second part implies that the political cost rises more rapidly than the fiscal cost with the number of CoCo investors. A possible justification is as follows. The fiscal cost is a monetary cost and therefore increases linearly with the number of investors to be rescued. However, the political cost increases convexly with the number of investors because the cost is associated with the majority voting rule: if the number of troubled investors who are voters is smaller than a certain threshold number, the ruling party may not lose in forthcoming elections. However, if the number of troubled investors is only slightly larger than the threshold, the ruling party may lose in such elections. That is, the associated political cost of the ruling

[14]See Kinmonth (2016).

[15]The fiscal cost of repaying deposits *D* does not need to be considered, as it arises irrespective of whether the government rescues the CoCo holders

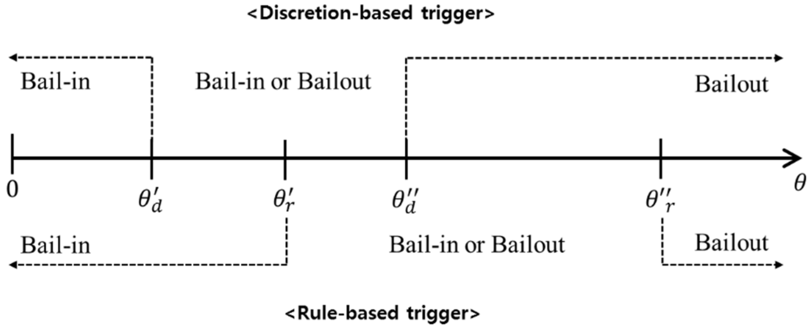


FIGURE 2. DISCRETION VS. RULE (IN CASE WHERE $\theta_r' < \theta_d''$)

party increases suddenly as the number of investors who purchased CoCos rises.

In sum, the government should compare the total cost of a bail-in and the total cost of a bailout when determining whether to activate a discretion-based trigger. If it chooses to activate the trigger, the government should bear the total cost of the bail-in, which is the sum of the shock cost θ and political cost $\pi_d c(m)$. Instead, if it decides not to activate the trigger but to help the failed bank repay the CoCo holders, the government should take the total cost of bailout, which is equal to the fiscal cost $\delta(1+r)m$.

Note that the political cost and fiscal cost depend on the expectations of investors regarding whether the government will rescue CoCo holders. If they believe this to be so (i.e., $q^e = 1$), the market-clearing number of CoCo holders and the interest rate are m^1 and r^1, respectively. Accordingly, the corresponding political cost and fiscal cost are $\pi_d c(m^1)$ and $\delta(1+r^1)(m^1)$. Similarly, if they do not believe a bailout will occur (i.e., $q^e = 0$), the political cost and fiscal cost change to $\pi_d c(m^0)$ and $\delta(1+r^0)(m^0)$, respectively.

Let $q \in \{0,1\}$ denote the government's choice. $q = 1$ indicates that the government chooses a bailout for troubled CoCo holders, while $q = 0$ means that the government decides to activate the trigger. If the expectation q^e is consistent with the actual choice q, then $q^* = q^e = q$ constitutes a rational expectations equilibrium.

The following proposition characterizes the rational expectations equilibria (see Figure 2).

Proposition 1. *(Discretion-based trigger case)*: Suppose that Assumption 1 holds. Then, there are θ_d' and θ_d'' such that $0 < \theta_d' < \theta_d''$,

(i) $(q^* = 0, r^0, m^0)$ *is the unique equilibrium if* $\theta \le \theta_d'$,

(ii) *both* $(q^* = 0, r^0, m^0)$ *and* $(q^* = 1, r^1, m^1)$ *are equilibria if* $\theta_d' < \theta < \theta_d''$, *and*

(iii) $(q^* = 1, r^1, m^1)$ *is the unique equilibrium if* $\theta \geq \theta_d''$.

Proof. According to Assumption 1, there exists a unique $\theta_d' > 0$ and $\theta_d'' > 0$ such that $\theta_d' = \delta(1+r^1)m^1 - \pi_d c(m^1) > 0$ and $\theta_d'' = \delta(1+r^0)m^0 - \pi_d c(m^0)$. Because $\delta(1+r^0)m^0 - \pi_d c(m^0) > \delta(1+r^1)m^1 - \pi_d c(m^1)$, I have $\theta_d'' > \theta_d'$.

(i) If $\theta \leq \theta_d'$, Assumption 1 (ii) implies that $\theta \leq \theta_d' = \delta(1+r^1)m^1 - \pi_d c(m^1) < \delta(1+r^0)m^0 - \pi_d c(m^0)$. It then follows that (A) $\delta(1+r^1)m^1 \geq \theta + \pi_d c(m^1)$ and (B) $\delta(1+r^0)m^0 \geq \theta + \pi_d c(m^0)$. (A) indicates that when investors believe that the government will save distressed CoCo holders (i.e., $q^e = 1$), the government will not save them (i.e., $q^e = 0$), as the total cost of a bail-in $\theta + \pi_d c(m^1)$ is lower than the total cost of a bailout $\delta(1+r^1)m^1$. That is, the expectation is not consistent with the actual choice. (B) means that when investors believe that the government will not rescue troubled CoCo holders (i.e., $q^e = 0$), the government will do so (i.e., $q = 0$). Therefore, $q^* = 0$ is the unique rational expectations equilibrium.

(iii) This can be proven analogously.

(ii) As $\theta > \theta_d'$, it follows that (C) $\delta(1+r^1)m^1 < \theta + \pi_d c(m^1)$. Also, $\theta < \theta_d''$ implies that (D) $\delta(1+r^0)m^0 > \theta + \pi_d c(m^0)$. (C) and (D) mean that the government chooses a bailout (bail-in) if investors believe a bailout (bail-in) will occur. ■

The intuition of Proposition 1 is as follows. In one extreme case in which financial turmoil due to the government's choice of a bail-in is sufficiently high (i.e., $\theta > \theta_d''$), the government has no choice but to save distressed CoCo holders for the sake of financial stability. In the other extreme, in which investors are fully aware of the possibility that the government could let them take losses and hence the action of a bail-in causes only a negligible shock on the financial system (i.e., $\theta < \theta'$), then regulatory forbearance does not arise regardless of how many investors have long positions in the CoCo. In an interesting case where the shock cost is moderate, the equilibrium depends on the expectation. If investors believe that the government will be lenient in treating troubled CoCo holders, then more investors choose to buy the CoCo and, hence, the government should bear a greater political burden when it chooses to activate the trigger. Consequently, it chooses to save the CoCo holders. However, if investors believe that the government will be tough on CoCo holders, the number of risk-exposed CoCo holders will be smaller, as will be the political pressure regarding a bail-in. Thus, the government chooses not to save the CoCo holders.

2. Rule-based Trigger

The type of trigger has an important implication with regard to the government's political cost of letting creditors take losses. A rule-based trigger is activated mechanically. Therefore, the government has no authority over or responsibility for trigger activation. Thus, the government does not get 'blood on its hands', even if CoCo holders lose money. Nevertheless, the government may feel some degree of political pressure because investors may blame the government for its failure of supervising the bank. In this sense, I assume that the political cost parameter π_r under the rule-based trigger case is positive but smaller than π_d.

Suppose that the realized level of the signal x is higher than the threshold (i.e., $x \geq \underline{x}$). In this case, the trigger is not activated. Even if the signal is good, the actual financial status of the bank could be poor. If the bank becomes insolvent (i.e., $X = 0$), the bank has nothing with which to repay the CoCo holders. Because their claims remain valid, the CoCo holders can demand repayment. In this case, the government must pay the CoCo holders back on behalf of the bank in order to prevent liquidation.

Suppose instead that the signal falls short of the threshold. Accordingly, trigger activation is imminent. In practice, the CET1 capital ratio is the most popular signal used in rule-based CoCos, and financial regulators monitor this capital ratio. Thus, a financial regulator could realize that the capital ratio is about to fall sharply in the near future and hence may consider recapitalizing the bank preemptively just before the activation of the trigger. In this sense, I consider the situation in which the government could enact a preemptive bailout on the brink of trigger activation. In doing so, the government bears the cost of the bailout, $\delta(1+r)m$. If the government does not choose the preemptive bailout option and lets the CoCo holders absorb losses, it incurs the bail-in cost, $\theta + \pi_r c(m)$. Note that the political cost parameter π_r is smaller than π_d and hence the political cost $\pi_r c(m)$ is not very sensitive to the number of CoCo holders. Thus, the following assumption may or may not hold:

Assumption 2. $\pi_r[c(m^1) - c(m^0)] > \delta[(1+r^1)m^1 - (1+r^0)m^0]$.

The following proposition characterizes the rational expectations equilibria in the rule-based trigger case (see Figures 3 and 4). If the difference in the political cost parameters ($\pi_d - \pi_r$) is moderate and hence Assumption 2 holds, the equilibrium structure is then similar to that of the discretion-based trigger case. However, if the difference is large and Assumption 2 therefore does not hold, there is no rational expectations equilibrium if the shock cost is at an intermediate level.

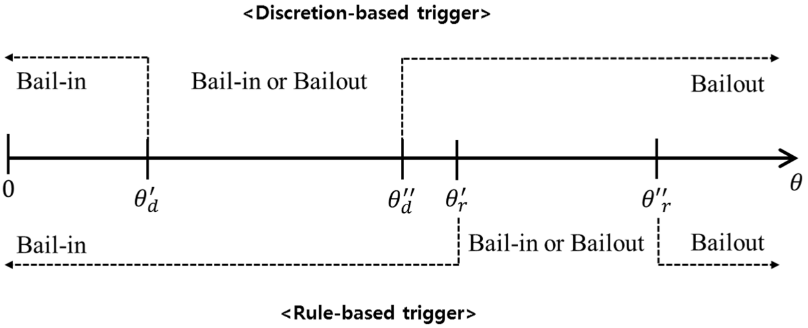


FIGURE 3. DISCRETION VS. RULE (IN CASE WHERE $\theta'_r \geq \theta''_d$)

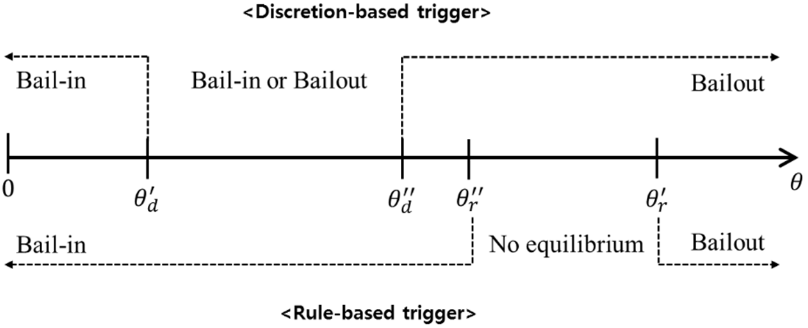


FIGURE 4. DISCRETION VS. RULE (IN CASE WHERE ASSUMPTION 2 DOES NOT HOLD)

Proposition 2. *(Rule-based trigger case)*: Suppose that Assumption 1 holds.

(Subcase 1) Suppose further that the Assumption 2 holds. Then, there are θ_r' and θ_r'' such that $0<\theta_r'<\theta_r''$,

(i) $(q^*=0,\, r^0,\, m^0)$ *is the unique equilibrium if* $\theta \leq \theta_r'$,

(ii) *both* $(q^*=0,\, r^0,\, m^0)$ *and* $(q^*=1,\, r^1,\, m^1)$ *are equilibria if* $\theta_r' < \theta < \theta_r''$, *and*

(iii) $(q^*=1,\, r^1,\, m^1)$ *is the unique equilibrium if* $\theta \geq \theta_r''$.

(Subcase 2) Suppose instead that the Assumption 2 does not hold. Then, there are θ_r' and θ_r'' such that $0<\theta_r'' \leq \theta_r'$,

(i) $(q^*=0,\, r^0,\, m^0)$ *is the unique equilibrium if* $\theta \leq \theta_r''$,

(ii) *There is no equilibrium if* $\theta_r'' < \theta < \theta_r'$, *and*

(iii) $(q^*=1,\, r^1,\, m^1)$ *is the unique equilibrium if* $\theta \geq \theta_r'$.

Proof. Via Assumption 1 and the fact that $\pi_r < \pi_d$, there exists unique $\theta_r' > 0$

and $\theta_r'' > 0$ such that $\theta_r' = \delta(1+r^1)m^1 - \pi_r c(m^1) > 0$ and $\theta_r'' = \delta(1+r^0)m^0 - \pi_r c(m^0) > 0$. The proof of subcase 1 is analogous to the proof of Proposition 1. Consider subcase 2. Because Assumption 2 does not hold, it follows that $\theta_r' = (1+r^1)m^1 - \pi_r c(m^1) \geq \delta(1+r^0)m^0 - \pi_r c(m^0) = \theta_r''$.

(i) If $\theta \leq \theta_r''$, I have $\delta(1+r^0)m^0 \geq \theta + \pi_r c(m^0)$ and $\delta(1+r^1)m^1 > \theta + \pi_r c(m^1)$. Thus, $q^* = 0$ is a unique equilibrium. (iii) If $\theta \geq \theta_r'$, it follows that $\delta(1+r^0)m^0 \leq \theta + \pi_r c(m^0)$ and $\delta(1+r^1)m^1 < \theta + \pi_r c(m^1)$. Then, $q^* = 1$ is a unique equilibrium. (ii) If $\theta_r'' < \theta < \theta_r'$, I have $\delta(1+r^0)m^0 < \theta + \pi_r c(m^0)$ and $\delta(1+r^1)m^1 > \theta + \pi_r c(m^1)$. Thus, the bailout cost exceeds the bail-in cost when investors expect a bailout. Moreover, the bail-in cost is larger than the bailout cost when investors believe a bail-in will occur. Thus, neither a bailout nor a bail-in constitutes an equilibrium. ■

3. Comparison

By comparing Propositions 1 and 2, one can assess the effectiveness of a CoCo as a bail-in tool. For both types of triggers, a bail-in constitutes the unique equilibrium if the shock cost θ is small enough while a bailout constitutes the unique equilibrium if the shock cost is large enough. If we focus on the unique equilibrium, it is clear that a rule-based trigger is better than a discretion-based trigger in terms of the implementability of a bail-in, as the following corollary shows.

Corollary 1. *Suppose that Assumption 1 holds. The region in which a bail-in constitutes the unique equilibrium is larger while the region in which a bailout constitutes the unique equilibrium is smaller if the trigger is rule-based rather than discretion-based.*

Proof. Note that $\theta_d' = \delta(1+r^1)m^1 - \pi_d c(m^1) < \delta(1+r^1)m^1 - \pi_r c(m^1) = \theta_r'$ and $\theta_d'' = \delta(1+r^0)m^0 - \pi_d c(m^0) < \delta(1+r^0)m^0 - \pi_r c(m^0) = \theta_r''$.

Suppose that Assumption 2 holds. Then, a bail-in constitutes the unique equilibrium if $\theta < \theta_k'$, $k = \{d, r\}$, while a bailout constitutes the unique equilibrium if $\theta > \theta''$ under both types of triggers. Because $\theta_d' < \theta_r'$ and $\theta_d'' < \theta_r''$, the proof is completed.

Suppose instead that Assumption 2 does not hold. Then, with a rule-based trigger, a bail-in constitutes the unique equilibrium if $\theta < \theta_r''$ while a bailout constitutes the unique equilibrium if $\theta > \theta_r'$. Because $\theta_d'' < \theta_r''$ and $\theta_d' < \theta_d''$, it follows that $\theta_d' < \theta_r''$. Also, $\theta_d'' < \theta_r'$ as $\theta_d'' < \theta_r''$ and $\theta_r'' < \theta_r'$ according to Proposition 2. ■

If the shock cost is at an intermediate level, the model does not make a definitive prediction, as there are either multiple or no equilibria. Nevertheless, one can determine that a bail-in arises more likely as an equilibrium if the trigger is rule-based rather than discretion-based in the following sense. Whenever there are multiple equilibria under the discretion-based trigger case, a bail-in constitutes the unique equilibrium or there are multiple equilibria under the rule-based trigger case (see Figures 2-4). Moreover, whenever there are multiple equilibria under the rule-based trigger case, a bailout constitutes the unique equilibrium or there are multiple equilibria under the discretion-based trigger case. Furthermore, whenever there are no equilibria under the rule-based trigger case, a bailout constitutes the unique equilibrium under the discretion-based trigger case.

4. Biased Threshold

Thus far, I have focused on the case where the threshold of the signal x is *unbiased* in the sense that the probability of the trigger being activated is equal to the probability of insolvency (see Definition 1).

However, in practice, thresholds appear to be biased upwardly. For instance, most CoCos with rule-based triggers in the real world are based on the CET1 capital ratio, and the threshold is around 5% (see Table 3). In principle, a bank is insolvent if its assets fall below its liabilities and, therefore, 0% appears to be an unbiased threshold level. Nevertheless, banks are encouraged or required by market or financial regulators to use a threshold higher than 0% when they issue CoCos based on the CET1 capital ratio.

Suppose that the threshold is higher than the unbiased level (i.e., $\underline{x} > \underline{x}'$). In this case, the probability that a rule-based trigger is activated is higher than the probability of insolvency p, as the error of false activation increases while the error of negligence decreases (see Equation (1)). As the bail-in risk increases, the CoCo demand shrinks. Thus, the equilibrium interest rate and bail-in risk premium rise (see Equation (6)). In contrast, the equilibrium interest rate and bail-in risk premium with a discretion-based trigger are unchanged.

Analogously, one can find that the equilibrium interest rate and bail-in risk premium for a CoCo with a rule-based trigger fall if the threshold is downwardly biased.

5. Unique Equilibrium

If the size of the shock cost parameter θ is moderate, there are multiple equilibria or no equilibria, as investors can perfectly observe the shock cost parameter. In such a case, all investors know whether the government chooses a bailout or a bail-in. However, if they can observe only an imperfect signal of the parameter, some investors believe that the government will choose a bailout while others expect a bail-in. Therefore, investors behave differently. In this case, the model can generate a unique equilibrium for all θ. In Appendix 1, I explore the possibility of having a unique equilibrium based on the global game approach suggested by Morris and Shin (1998). The main result is that the equilibrium is unique and the implementability of a bail-in is improved if the trigger is changed from discretion-based to rule-based.

III. Empirical Analysis

A. *Preliminaries*

1. Hypothesis

A main finding of the previous theoretic model is that the bail-in risk as measured by the interest rate at issuance—the coupon rate—is most likely lower under a discretion-based trigger than under a rule-based trigger with an unbiased level of threshold. In this section, this theoretical prediction is tested empirically. In particular, I consider the following hypothesis:

Hypothesis 1. The bail-in risk is lower (i.e., the likelihood of government assistance is higher) under a discretion-based trigger than under a rule-based trigger.

2. Measures of the Bail-in risk: Coupon Rate and Coupon Residual

The coupon rate is a measure of the bail-in risk. In theoretical model, I assume that the bank is never allowed to be liquidated due to its systemic importance and, hence, there is no default risk. The coupon rate r can then be decomposed into two parts: the risk-free benchmark rate and the bail-in risk premium (see Figure 1). Therefore, if the risk-free rate can be properly controlled, the coupon rate is a good measure of the bail-in risk. However, as the bankruptcy of Lehman brothers showed, even a systemically important bank can be liquidated, though it is very unlikely. This is why default indicators such as bank CDS premiums are positive. As the coupon rate in real-life reflects the default risk as well, it is an imperfect measure of the bail-in risk.

In addition, the validity of the coupon rate as a measure of the bail-in risk depends on whether CoCos are AT1 or T2 instruments. Tier 2 (T2) instruments are subordinated bonds for which a bail-in clause is added. Additional Tier 1 (AT1) instruments have more complicated structures. They are *de facto* perpetual bonds with bail-in clauses and two special options. First, with a call option, the issuer can opt to repay the bond before the maturity. Because this option is usually exercised, the market panics if the issuer does not exercise the option—*the call option risk*. Secondly, the issuer can choose to suspend or even default on the interest payment if business conditions are unfavorable—*the interest payment risk*.[16] The coupon rate of AT1 CoCo reflects the call option risk and interest payment risk as well as the default risk and bail-in risk.

An alternative measure of the bail-in risk is the coupon residual, which is obtained

[16] Also, regulators could mandate such a default on the interest payment if the bank's annual earnings are negative or its CET1 ratio decreases significantly.

TABLE 1—INTEREST STRUCTURE OF WOORI BANK'S T2 COCO

Premium	Measure	Value
Bail-in Risk	The coupon residual*	0.18%
Default Risk	CDS premium on 10-year subordinated bond	1.40%
Benchmark Rate	Interest rate on 10-year US Treasury bond	3.17%
Coupon Rate	Coupon rate	4.75%

Note: 1) The CoCo (ISIN: US98105FAC86) was issued in April 30, 2014. The maturity is ten years. The face value is $10 billion. 2) * The coupon residual = the coupon rate - the benchmark rate - the default risk premium.

TABLE 2—THE INTEREST STRUCTURE OF BARCLAYS'S AT1 COCO

Premium	Measure	Value
Bail-in Risk		
Call Option Risk	The coupon residual*	3.14%
Interest Payment Risk		
Default Risk	CDS premium on 30-year subordinated bond	2.27%
Benchmark Rate	Interest rate on 30-year US Treasury bond	2.45%
Coupon Rate	Coupon rate	7.86%

Note: 1) The CoCo (ISIN: XS1274156097) was issued in August 11, 2015. The maturity is 34 years. The face value is $15.6 billion. 2) * The coupon residual = the coupon rate - the benchmark rate - the default risk premium.

after subtracting a benchmark sovereign bond rate and a relevant CDS premium from the coupon rate.

For T2 instruments, this coupon residual is conceptually an ideal measure of the bail-in risk. Tables 1 and 2 describe how the coupon rates of CoCos are determined in real life.

Woori Bank (a Korean bank) issued a T2 CoCo (in USD) on April of 2014 at the coupon rate of 4.75%. The coupon rate can be decomposed into the benchmark country rate of 3.17% (measured by a similar-term US Treasury bond rate), the default risk premium of 1.40% (measured by the CDS premium on a similar-term Woori Bank subordinated bond), and a residual of 0.18%. Because it is a T2 instrument, investors are concerned only about the default risk and bail-in risk but not the call option risk or interest payment risk. As the CDS premium accounts for the default risk, the coupon residual could be construed as a good measure of the bail-in risk.

The coupon residual, however, is not an ideal measure of the bail-in risk of an AT1 CoCo. Table 2 illustrates this point. Barclays issued an AT1 CoCo in August of 2015 at the coupon rate of 7.86%. As it is an AT1 instrument, the coupon rate reflects not only the default risk and bail-in risk but also the call option risk and interest payment risk. However, it is difficult to find objective measures of the call option risk premium and interest payment risk premium.

Despite its drawbacks, the coupon rate could still be a good measure of the bail-in risk. Although the coupon residual is conceptually a better measure at least for T2 instruments, only a few samples are available, as many CoCos in real life have no counterpart sovereign bonds or subordinated bonds for which CDSs are traded. The maturity of CoCos is mostly ten years or thirty years, but many countries do not issue

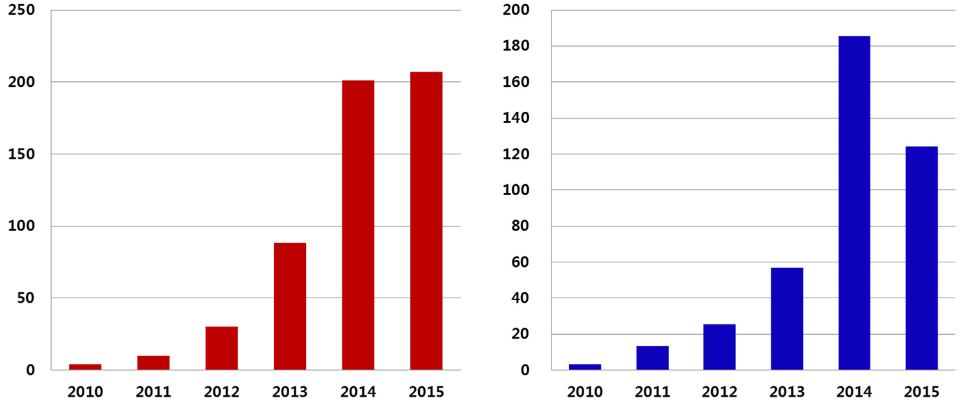
10-year or 30-year sovereign bonds. The problems are even worse with CDS contracts. For many banks, CDSs are not traded at all on any subordinated bond. In contrast, if the coupon rate is used as the bail-in risk measure, the available sample size triples in size.

In the following empirical analyses, I use two different approaches. Firstly, I use the coupon rate as the primary measure of the bail-in risk and attempt to control the default risk as much as possible. Various different specifications are considered, and robustness checks are conducted. Secondly, I choose the coupon residual as an alternative measure of the bail-in risk.

3. Data

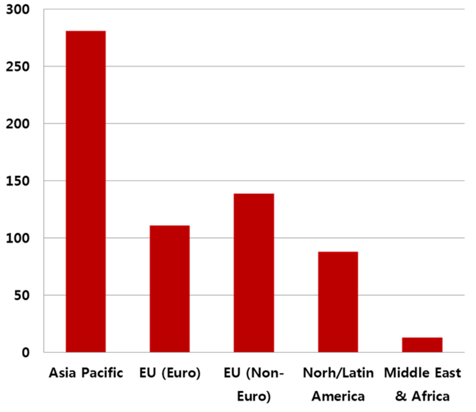
I utilize a dataset of CoCos issued by banks from January of 2010 to September of 2016. The sources of the dataset are Moody's Quarterly Rated and Tracked CoCo Monitor Database (2016 3Q) and a Bloomberg terminal. The data also contain information on issuing banks and their countries of domicile. The data cover 632 distinct CoCo instruments issued by 222 banks. The aggregate face value is $460 billion. (Short-term CoCos that mature within three years are excluded because CoCos are designed as a long-term debt.)

Figures 5 and 6 provide an overview of CoCo issuance. The number of issuance increases steadily during the sample period. The volume of CoCos increased to 185 billion US$ until 2014 and then decreased to $124 billion in 2015. According to the convention of international bond markets, I classify countries into five regions—Asia Pacific, EU Euro, EU non-Euro, North and Latin America, and Middle East and Africa. Asia-Pacific banks have been major issuers, accounting for 44% (281 issues) of all issues and 45% ($207 billion) of the total volume. European banks in the Euro area and in the non-Euro area issued 19% ($87 billion) and 24% ($112 billion) of the total volume, respectively. A country-level comparison shows that Chinese banks have been the largest issuers ($107 billion, 23% of the total volume). Then follows UK ($57 billion), Swiss ($41 billion), Australian ($40 billion), Canadian ($29 billion), French ($20 billion), Japanese ($18 billion), Spanish ($15

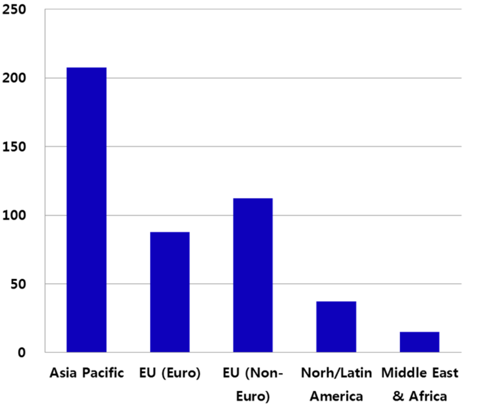


(A) NUMBER OF ISSUANCE (B) TOTAL VOLUME ($1 BILLION)

FIGURE 5. YEARLY COCOS ISSUANCE



(A) NUMBER OF ISSUANCE



(B) TOTAL VOLUME ($1 BILLION)

FIGURE 6. REGIONAL COCOS ISSUANCE

billion), Korean ($14 billion), Irish ($12 billion), and Brazilian ($11 billion) banks. The average country-wide volume is $10 billion.

4. Country-wide Comparison

Of many variables in the dataset, the coupon rate is a key variable. (A definition of each variable is given in Table A7) Table 3 shows that the coupon rate is 5.75% on average, with a standard deviation of 2.66%. Consider the aforementioned eleven major countries. Figure 7 shows that Japanese banks have been able to borrow at the world's lowest interest rate of 1.66% on average. Korean and Canadian banks have also borrowed at low interest rates of 3.57% and 4.02% on average, respectively. In contrast, French (7.34%), Brazilian (7.89%), Spanish (8.28%), and Irish banks (9.00%) borrowed at double or even higher interest rates.

Another key variable is the type of trigger. There are two types of triggers: CET1 and PONV. First, the CET1 trigger is a rule-based trigger based on the ratio of common-equity tier 1 (CET1) capital to the risk-weighted assets. The Basel III accord classifies capital into various groups according to the capacity of loss absorbency. Common-equity tier 1 capital has the greatest such capacity, as it mainly consists of common equity. Under the CET1 trigger, the write-down or conversion is activated if the CET1 ratio falls below a predetermined threshold. The threshold for most issues is 5.125%, as the Basel III accord deems 5.125% the minimum capital ratio that a going-concern bank should maintain. (Table 3 shows that the threshold is on average equal to 5.38% with a small standard deviation of 1.28%.) Second, the PONV trigger is a discretion-based trigger. Under this trigger, the government activates a write-down or conversion if it determines that the issuing bank is at the point of non-viability (PONV). See Table 4. The ratio of CoCos with a discretion-based trigger to all CoCos is 49.1% in terms of the number of issuances and 35.4% in terms of the total volume.

In fact, there is an additional type of trigger—the mixed trigger. Under the mixed trigger, write-down or conversion is activated if either the CET1 ratio falls short of

TABLE 3—SUMMARY STATISTICS: VARIABLES

	Unit	Obs.	Mean	S.D.	Min	Max
Coupon Rate	%	630	5.75	2.66	0.59	20.82
Coupon Residual (sub)	%	127	0.49	2.00	-4.35	5.10
Coupon Residual (senior)	%	167	0.80	2.23	-4.16	6.04
Discretion	Dummy	630	0.50	0.50	0	1
AT1	Dummy	632	0.55	0.49	0	1
Conversion	Dummy	618	0.34	0.47	0	1
CET1 Threshold*	%	315	5.38	1.28	2	9
Maturity**	Year	279	10.65	3.51	3.5	36.5
Face Value	USD bil.	632	0.72	0.93	0.002	7.2
Credit Score	21-scale	558	13.32	3.03	2	18
State Bank	Dummy	632	0.16	0.37	0	1
Total Assets	USD bil.	467	637.06	672.86	0.23	2,671.31
CET1	%	574	11.40	3.27	5.17	30.12
Country Rate	%	582	2.81	2.11	-0.21	12.44
Sovereign CDS	%p	476	0.91	1.19	0.11	9.92

Note: 1) * Only rule-based and mixed-trigger CoCos are considered. 2) ** Only T2 instruments considered as AT1 instruments are deemed perpetual.

TABLE 4—SUMMARY STATISTICS: COCO TYPES

	Number of Issuance		Total Volume	
	Obs.	Fraction	Volume*	Fraction
Total	632	100%	460	100%
Discretion	310	49.1%	163	35.4%
Rule-based	200	31.6%	168	36.5%
Mixed	120	19.0%	127	27.7%
Uncertain	2	0.3%	2	0.4%
Additional Tier 1	353	55.9%	289	62.8%
Tier 2	279	44.1%	171	37.2%
Conversion	213	33.7%	215	46.7%
Write-down	405	64.1%	241	52.4%
Uncertain	14	2.2%	4	1.0%

Note: * Face values are denominated in USD according to the exchange rate at the issue date. The unit is $1 billion.

the threshold or the government determines that the issuing bank is at the point of non-viability. Usually, the PONV condition is deemed more difficult to be met than the CET1 condition, as the point of non-viability corresponds to the case in which assets are less than liabilities (i.e., 0% of the CET1 ratio). In this sense, I regard the mixed trigger as a rule-based trigger. However, Japan is special. According to the Japanese Comprehensive Guidelines for the Supervision of Major Banks, such as III-2-1-1-3 (2), a bank that issued a CoCo with a mixed trigger can avoid the activation of write-down or conversion even when the CET1 condition is met (but the PONV condition is not yet met) if the bank submits a resolution plan to the supervision authority and gains approval of it (see Lee and Pang, 2014). For this reason, I regard the mixed trigger of Japanese banks as a discretion-based trigger in the following empirical analysis.

Figure 7 shows that the discretion-based trigger ratio varies across countries.[17] Japan, Korea and Canada represent one extreme case. The trigger of every CoCo is discretion-based. France, Brazil, and Ireland are at the other extreme. The trigger of every CoCo is rule-based. Australian, Swiss, Chinese, and UK banks use both types of triggers during CoCo issuances.

The country-level comparison of the discretion-based trigger ratio and that of the coupon rate suggest that there is a negative relationship between the two variables. See Figure 7. In Japan, Korea, and Canada, banks have issued only discretion-based trigger CoCos and the coupon rates are low. In France, Brazil, Spain, and Ireland, only rule-based trigger CoCos have been issued and the coupon rates are high. In other countries, both types of CoCos have been issued and the coupon rates are at an intermediate level.

One can argue that the negative relationship between the coupon rate and discretion- based trigger ratio is spurious, as the coupon rates are primarily explained by the low sovereign credit risk rather than the discretion-based trigger ratio. However, Figure 8 shows that the CDS premium on 5-year sovereign debt does not appear to be strongly related to the country-wide coupon rate.[18] French banks pay high interest rates despite the fact that the CDS premium on France is the lowest. In contrast, Japanese, Korean, and Chinese banks pay low interest rates even if the sovereign CDSs are relatively high. The correlation between the sovereign CDS and the coupon rate is as low as 0.33, while the correlation between the discretion-based trigger ratio and the coupon rate is as high (in magnitude) as -0.88. Although the country-wide comparison is consistent with Hypothesis 1, a more formal empirical analysis is required.

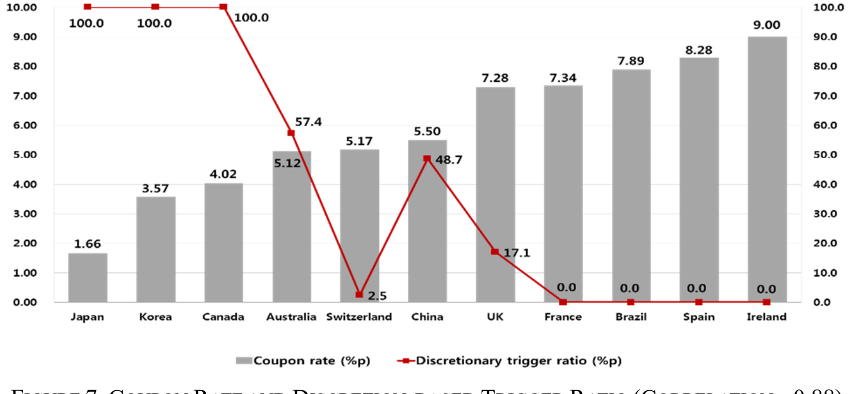


FIGURE 7. COUPON RATE AND DISCRETION-BASED TRIGGER RATIO (CORRELATION: -0.88)

[17]The coupon rate of a country is the average of the coupon rates of CoCos issued in the same country during 2010-2016. The discretion-based trigger ratio of a country is also obtained by a similar averaging process.

[18]To determine the CDS of a country, I initially consider CoCo issues made by banks in the same country during 2010-2016. Then, I take the average of the sovereign CDS premiums as evaluated at the CoCo issuance dates.

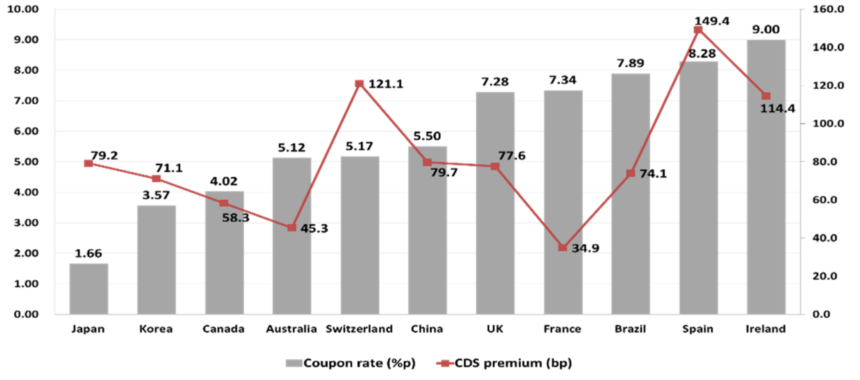


FIGURE 8. COUPON RATE AND 5-YEAR CDS PREMIUMS (CORRELATION: 0.33)

B. *Empirical Analysis 1: The Coupon Rate*

In this subsection, I examine the empirical relationship between the bail-in risk measured by the coupon rate and the type of trigger. To observe briefly how the coupon rate and type of trigger are related, see Table 5. The average coupon rate of discretion-based trigger CoCos is 4.60%, which is 2.33%p lower than the average coupon rate of rule-based trigger CoCos. This difference is significant at the 1% level.

To examine the relationship formally, I conduct a regression analysis based on the following model.

$$\begin{aligned}(12)\qquad Coupon\ rate_i &= \alpha + \beta_1 Discretion_i + \beta_2 Country\ rate_i \\ &\quad + \beta_3 Credit\ score_i + \gamma X_i + \varepsilon_i\end{aligned}$$

The key independent variable is $Discretion_i$, which equals 1 if the trigger of CoCo i is discretion-based or 0 if it is rule-based. According to the theory presented in Section 2, the type of trigger is related to the political pressure borne by the government when it lets bail-ins take place.

$Country\ rate_i$ and $Credit\ score_i$ are used to control for the benchmark rate and default risk, respectively. $Country\ rate_i$ is the market interest rate on a sovereign bond whose remaining maturity is similar to the maturity of CoCo i. Although the sovereign bond rates may not be free of risk, I use them nonetheless as benchmark interest rates. This is done simply because in practice bond coupon rates are determined by summing the margins on sovereign bond rates. $Credit\ score_i$ reflects the baseline credit assessment (BCA) conducted by Moody's. The BCA represents the credit rating agency's assessment on the probability of default of the issuing bank's senior unsecured debt under the absence of external support. $Credit\ score_i$ is equal to 21 if the issuing bank's credit grade is Aaa (the highest grade) but is equal only to 1 if the grade is C (the lowest grade). One notch of credit rating corresponds to one point.

TABLE 5—T-TEST: COUPON RATES AND TRIGGER TYPES

	Obs.	Mean (%)	S.D.	S.E.
Discretion	317	4.60	2.23	0.12
Rule-based	311	6.93	2.55	0.14

X_i is a set of control variables. See the Table A7 and Table 3 for definitions and summary statistics, respectively. These control variables can be categorized into three groups.

The first group consists of variables that reflect the characteristics of CoCo instrument i. These variables are $Conversion_i$, $CET1\ threshold_i$, $Maturity_i$, and $Face\ value_i$. $Conversion_i$ is 1 if the bail-in mechanism is mandatory conversion or 0 if it is principal write-down. $CET1\ threshold_i$ is the minimum level of CET1 that the issuing bank of CoCo i should maintain in order to prevent a bail-in from taking place. If bond i has a CET1 trigger or a mixed trigger, such a minimum CET1 level is explicitly expressed in the bond contract. For a purely discretion-based CoCo that uses only a PONV trigger, the bond contract has no clause regarding a minimum CET1 level. However, the PONV usually corresponds to the case in which the bank's capital is close to zero. In practice, regulators and investors often deem 2% as the minimum capital ratio a healthy bank should maintain in order to avoid insolvency. This is why every CET1 trigger CoCo in my dataset has a threshold no less than 2% (see Table 3). For this reason, in the following analysis, I use 2% as $CET1\ threshold_i$ for discretion-based CoCos.

The second group is the set of variables that control for the issuing bank's characteristics. To control for financial soundness, size, and state ownership, I use $CET1_i$, $Total\ assets_i$, and $State\ bank_i$, where $State\ bank_i$ is 1 if the bank is a subsidiary of a sovereign or central bank, but 0 otherwise. Recall that the coupon rate is a good measure of the bail-in risk only if the default risk is properly controlled. $Total\ assets_i$ and $State\ bank_i$ are importantly related to the default risk because it is widely believed that governments choose bailouts more likely, the larger the bank or the closer the bank to governments.

The variables in the third group control for country effects. I use $Country\ rate_i$ and $Country\ CDS_i$ in order to control for the mean and variance of sovereign bond yield. $Country\ CDS_i$ is the CDS premium on a sovereign bond.

All flow variables are evaluated at the dates of CoCo issuance.

Table 6 shows the estimation result. I consider five different model specifications (1)-(5). As the number increases, more control variables are included.

The coefficient of $Discretion_i$ is negative and significant at the 1% level in all specifications. This result indicates that a change of a trigger from rule-based to discretion-based is associated with a decrease in the coupon rate. Depending on specifications, the coupon discount of a discretion-based trigger ranges approximately from 1.72 to 2.39%p. Given the low interest rate trend during the

TABLE 6—REGRESSION OF THE COUPON RATE

Specification	(1)	(2)	(3)	(4)	(5)
Discretion	-2.33*** (0.19)	-2.15*** (0.14)	-2.39*** (0.42)	-1.85*** (0.44)	-1.72*** (0.49)
Country Rate		0.52*** (0.06)	0.52*** (0.06)	0.73*** (0.08)	0.65*** (0.09)
Credit Score		-0.26*** (0.04)	-0.29*** (0.03)	-0.16*** (0.05)	-0.09 (0.05)
AT1			0.77 (1.05)	-0.25 (0.42)	0.00 (0.46)
Conversion			0.53* (0.29)	0.07 (0.23)	-0.18 (0.25)
CET1 Threshold			-0.13 (0.11)	0.02 (0.10)	-0.05 (0.10)
Maturity			-0.02 (0.03)	0.02 (0.01)	0.01 (0.01)
Face Value (in log)			0.11 (0.07)	0.34*** (0.08)	0.48*** (0.10)
State Bank				-1.02*** (0.32)	-0.91*** (0.30)
Total Assets (in log)				-0.13 (0.09)	-0.26*** (0.09)
CET1				0.10** (0.04)	0.00 (0.04)
Sovereign CDS (in %p)				0.12 (0.09)	0.02 (0.11)
Region	No	No	No	No	Yes
Year	No	No	No	No	Yes
Obs.	628	509	495	263	263
R-squared	0.19	0.57	0.58	0.69	0.75

Note: 1) The dependent variable is the coupon rate. 2) The Huber-White robust standard errors are in parentheses. *, **, and *** indicate significance at 10%, 5%, and 1%, respectively.

sample period of 2010-2016, a coupon discount of this size is meaningfully large.

There are several points that should be noted. First, the empirical model does not appear to face a serious endogeneity problem. Countries have regulations on the acceptable triggers of CoCos and, hence, selection problems are less likely to arise. In China, AT1 instruments should use CET1 triggers with a threshold of 5.125%, whereas T2 instruments should use the PONV trigger. All Chinese banks in my dataset have complied with these regulations. Similarly, the European version of Basel III (i.e., the CRRD4) requires banks to use CET1 triggers with thresholds of no less than 5.125% when they issue AT1 instruments. Although there are no clear regulations pertaining to T2 instruments, the PONV trigger is recommended. For this reason, European banks use CET1 triggers more frequently when they issue AT1 instruments but use PONV triggers more frequently when they issue T2 instruments. As the choice of trigger depends largely on the regulations, I use $Country\,rate_i$, $Country\,CDS_i$, and region dummies to control for this country

TABLE 7—REGRESSION FOR THE COUPON RATE: 0% TRIGGER LEVEL FOR DISCRETION-BASED TRIGGERS

Specification	(1)	(2)	(3)	(4)	(5)
Discretion	-2.33*** (0.19)	-2.15*** (0.14)	-2.60*** (0.46)	-2.09*** (0.41)	-1.90*** (0.48)
Country Rate		0.52*** (0.06)	0.52*** (0.06)	0.73*** (0.08)	0.65*** (0.09)
Credit Score		-0.26*** (0.04)	-0.29*** (0.03)	-0.16*** (0.05)	-0.09 (0.05)
AT1			0.78 (1.05)	-0.20 (0.43)	0.03 (0.46)
Conversion			0.52* (0.29)	0.06 (0.23)	-0.18 (0.25)
CET1 Threshold			-0.12 (0.08)	-0.03 (0.07)	-0.07 (0.06)
Maturity			-0.02 (0.03)	0.02 (0.01)	0.01 (0.01)
Face Value (in log)			0.11 (0.07)	0.34*** (0.08)	0.49*** (0.11)
State Bank				-1.03*** (0.32)	-0.93*** (0.30)
Total Assets (in log)				-0.12 (0.09)	-0.25*** (0.09)
CET1				0.10** (0.04)	0.00 (0.03)
Sovereign CDS (in %p)				0.12 (0.09)	0.02 (0.11)
Region	No	No	No	No	Yes
Year	No	No	No	No	Yes
Obs.	628	509	495	263	263
R-squared	0.19	0.57	0.58	0.69	0.75

Note: 1) The dependent variable is the coupon rate. 2) The Huber-White robust standard errors are in parentheses. *, **, and *** indicate significance at 10%, 5%, and 1%, respectively.

effect. Even after controlling for these country-related variables, the coefficient of $Discretion_i$ is still negative and significant.

Second, one can argue that a rule-based trigger CoCo has greater bail-in risk than a discretion-based trigger CoCo simply because the former uses a higher trigger threshold.

The CET1 trigger threshold is around 5.125%, whereas the PONV trigger usually corresponds to 2% of CET1. However, even after controlling for this difference in trigger levels using $CET1\ threshold_i$, the estimation results show that the measured bail-in risks are lower with discretion-based triggers. As a robustness check, I utilized 0% as the hypothetical $CET1\ threshold_i$ for discretion-based CoCos, as presented in Table 7. The estimation results do not show any remarkable change. The coefficient of $Discretion_i$ is still negative and significant at the 1% level in all five specifications.

A number of other robustness checks are provided in Appendix 2.

C. *Empirical Analysis 2: The Coupon Residual*

Here, I shall examine the empirical relationship between the coupon residual (= the coupon rate - the default risk premium as measured by a relevant CDS premium - the benchmark country rate) and the type of trigger. The coupon residual can be measured in two different ways depending on the choice of the relevant CDS premium. I use the CDS premium on bank subordinated debt in the first regression model and the CDS premium on senior unsecured debt in the second regression model. The former is conceptually better because CoCos are subordinated bonds with certain special clauses. However, the latter allows me to utilize more samples and avoid multi-collinearity problems with respect to $State\,bank_i$.

1. Coupon residual based on a CDS contract on subordinated debt

Initially, I conduct a simple T-test to illustrate the empirical relationship briefly, as shown in Table 8. The average coupon residual of discretion-based trigger CoCos is -0.40%, which is lower by 3.06%p than the average coupon residual of rule-based trigger CoCos. The difference in the coupon residual is significant at the 1% level.

It appears to be odd that the average coupon residual is negative in cases of CoCos with discretion-based triggers. In principle, the coupon residual cannot be negative as the bail-in risk is at least as much as zero. However, the 'measured' coupon residual could have a negative value if the bail-in risk is low and the measurement of the default risk (i.e., the CDS premium on the benchmark bond) is imperfect. The difference in the measured coupon residuals due to the difference in the trigger type is not significantly exposed to this measurement problem because errors can be canceled after taking the difference.

Next, I conduct a regression analysis. I exclude $Country\,rate_i$ and $Credit\,score_i$ from the set of control variables because $Country\,rate_i$ is a measure of the benchmark rate and $Credit\,score_i$ is a measure of the default risk premium. I also exclude $State\,bank_i$ because its inclusion causes a severe multi-collinearity problem.

Table 9 provides the estimation result. I consider four different model specifications. The coefficient of $Discretion_i$ is negative in all specifications and significant in all but specification 2. The size of the coefficient (in specifications (1), (3), and (4)) is meaningfully large.

TABLE 8—T-TEST: COUPON RESIDUAL (SUB) AND TRIGGER TYPE

	Obs.	Mean (%)	S.D.	S.E.
Discretion	88	-0.40	1.18	0.12
Rule-based	38	2.66	1.82	0.29

TABLE 9—REGRESSION FOR THE COUPON RESIDUAL (SUB)

Specification	(1)	(2)	(3)	(4)
Discretion	-3.07*** (0.32)	-1.27 (0.97)	-2.01** (0.87)	-3.22*** (0.86)
AT1		-0.60 (0.97)	-1.08 (0.68)	-0.92 (0.79)
Conversion		-0.88*** (0.24)	-1.13*** (0.31)	-1.11** (0.50)
CET1 Threshold		0.35* (0.18)	0.24 (0.18)	-0.08 (0.16)
Maturity		0.02 (0.03)	0.04 (0.02)	0.04 (0.04)
Face Value (in log)		0.41* (0.21)	0.41** (0.19)	0.47** (0.22)
Total Assets (in log)			-0.16 (0.10)	-0.11 (0.20)
CET1			-0.05 (0.07)	-0.06 (0.09)
Sovereign CDS (in %p)			-0.05 (0.22)	-0.05 (0.28)
Region	No	No	No	Yes
Year	No	No	No	Yes
Obs.	126	124	86	86
R-squared	0.50	0.61	0.65	0.71

Note: 1) The dependent variable is the coupon residual (= the coupon rate - the benchmark rate - the default premium). 2) The Huber-White robust standard errors are in parentheses. *, **, and *** indicate significance at 10%, 5%, and 1%, respectively.

2. Coupon residual based on a CDS contract on senior unsecured debt

Consider a simple t-test. See Table 10. The coupon residual is lower by 3.46%p if the trigger is discretion-based rather than rule-based. This difference is significant at the 1% level.

Next, I conduct a regression analysis. Unlike the case where the CDS on subordinated debt is used, $State\,bank_i$ can be included in the regression model. The estimation result is provided in Table 11. The coefficient of $Discretion_i$ is negative and significant in all four specifications. Except for specification 2, the measured discount is as high as 3.41-3.50%p.

TABLE 10—T-TEST: COUPON RESIDUAL (SENIOR) AND TRIGGER TYPE

	Obs.	Mean (%)	S.D.	S.E.
Discretion	122	-0.05	1.31	0.11
Rule-based	43	3.42	2.19	0.33

TABLE 11—REGRESSION FOR THE COUPON RESIDUAL (SENIOR)

Specification	(1)	(2)	(3)	(4)
Discretion	-3.47*** (0.35)	-1.62** (0.71)	-3.50*** (0.88)	-3.41*** (0.77)
AT1		-1.31** (0.55)	-1.68*** (0.51)	-1.50*** (0.55)
Conversion		-0.35 (0.23)	-0.40 (0.32)	-0.46 (0.36)
CET1 Threshold		0.46*** (0.16)	0.10 (0.17)	-0.11 (0.15)
Maturity		0.06*** (0.01)	0.09*** (0.01)	0.07*** (0.02)
Face Value (in log)		0.31** (0.13)	0.30** (0.13)	0.38*** (0.11)
State Bank			-1.53*** (0.39)	-1.29*** (0.37)
Total Assets (in log)			-0.24* (0.13)	-0.15 (0.11)
CET1			-0.14 (0.10)	-0.09 (0.08)
Sovereign CDS (in %p)			0.06 (0.18)	0.04 (0.15)
Region	No	No	No	Yes
Year	No	No	No	Yes
Obs.	165	165	100	100
R-squared	0.48	0.58	0.69	0.81

Note: 1) The dependent variable is the coupon residual (= the coupon rate - the benchmark rate - the default premium). 2) The Huber-White robust standard errors are in parentheses. *, **, and *** indicate significance at 10%, 5%, and 1%, respectively.

IV. Conclusion

After the global financial crisis, G20 and EU countries agreed to adopt the bail-in system—a new bank resolution regime under which failed systemically important banks are reorganized at the expense of creditors and shareholders rather than taxpayers. A key instrument of the bail-in system is the contingent convertible bond (CoCo), which is mandatorily converted to equity or whose principal is written down if the bond issuing bank is seriously troubled and, hence, the trigger conditions of the bond are satisfied.

However, the implementability of the bail-in system is in doubt, particularly in cases where governments' political costs and financial shocks from bail-ins are sufficiently large. This paper examines how the implementability of a bail-in using CoCos depends on the type of trigger involved. In the first part of the paper, I construct a theoretical model and show that CoCos with discretion-based triggers are less effective bail-in tools than rule-based triggers CoCos because the government's political burden is higher. If the trigger is discretion-based, a relevant authority must undertake the 'dirty job' of imposing losses on creditors. This is not the case with a rule-based trigger, which is activated mechanically if a predetermined condition is satisfied. Even if the mere effect of the type of trigger on the political cost is small, it could grow through the mechanism of the self-fulfillment of expectations of government bailouts. In the second part of the paper, I test the model prediction by conducting an empirical study. Using a dataset of CoCo issuance around the world during 2010-2016, I find that the interest rate at the issuance of CoCos with discretion-based triggers is lower by 1.13 to 2.91%p on average than that of CoCos with rule-based triggers even after controlling for variables that are closely related to the likelihood of government bailouts and the financial soundness of the issuing bank. This finding suggests that triggers should be carefully designed in order to make CoCos effective as bail-in tools.

APPENDIX

1. Global Game and Unique Equilibrium

In order to focus on deriving a unique equilibrium, I simplify the previous model in the following manner. First, all investors have the same reservation payoff and, secondly, the gross interest rate R is fixed.

For the moment, suppose that the trigger is discretion-based.

Suppose that there is a unit-measure of investors, each of whom has one unit of money. They cannot observe the shock cost parameter θ, which follows the uniform distribution $U[0,1]$. However, the investors can personally observe a signal y, which is informative of θ in the sense that y follows $U[\theta-\varepsilon, \theta+\varepsilon]$, where ε is a small error. y is independent and identical across investors conditional on θ. In the first period, each investor forms an expectation of the likelihood of a government bailout and, based on this expectation, the investor decides whether to buy a CoCo.

In the second period, the government chooses whether to save troubled CoCo holders if the bank goes insolvent. As time passes from the first to second period, information on the bank's performance and the status of the financial system becomes known and, therefore, the government can predict relatively accurately how much the shock will be if it chooses not to bail out CoCo holders. That is, the government observes θ.

The government's cost of a bailout equals $mR+E$, where R is the gross interest rate and $E>(\pi_d-R)$ is a fixed cost.[19] The total cost of a bail-in is the sum of the shock cost θ and the political cost $\pi_d m$. The political cost is sufficiently sensitive to the number of CoCo holders. In this regard, I assume that $\pi_d>R$ so that the difference between the bailout cost and bail-in cost $D(m,\theta)\equiv mR+E-\theta-\pi_d m$ is thus decreasing in m. Note that the government

[19]This fixed cost does not play any economically important role in the model. I added this cost because the model then becomes tractable.

would choose a bailout if $D(m,\theta)$ is negative but otherwise would choose a bail-in. Given that $D(m,\theta)$ is decreasing in m, the government is more likely to choose a bailout as the number of CoCo holders increases.

There are two polar cases in which the number of CoCo holders is irrelevant with regard to the government's decision making. If $\theta > E$, I have $D(m,\theta) < 0$ for all m. Thus, the government always chooses to rescue distressed CoCo holders. If $\theta < E - (\pi_d - R)$, it follows that $D(m,\theta) > 0$ for all m. Thus, the government never chooses a bailout. Thus, $E - (\pi_d - R)$ and E correspond to the two critical levels of the shock cost $\theta_d^{'}$ and $\theta_d^{''}$ of the previous model.

However, if θ is at an intermediate level (i.e., $E - (\pi_d - R) < \theta < E$), and if investors observe θ perfectly, there are multiple equilibria. Below, I focus on this case and solve for a unique equilibrium when investors cannot observe θ but can observe y. Let m^* denote the critical mass of CoCo holders such that the government chooses a bailout if and only if $m \geq m^*$. Then, $m^* = m^*(\theta)$ is characterized by $D(m^*,\theta) = 0$, or equivalently,

(A1) $$m^*(\theta) = \frac{E - \theta}{\pi_d - R}$$

Note that $m^*(\theta)$ is decreasing in θ. That is, the government is more eager to save distressed CoCo holders upon a higher shock cost of the bail-in, θ.

At this stage, I consider the optimal choices of investors. If an investor buys one unit of the CoCo by paying one unit of money and if the government is generous, the investor is then always repaid in full. Thus, her payoff is $R - 1$. However, if the government is tough on her, she can be repaid only if the bank is solvent and, therefore, her payoff equals $(1-p)R - 1$.

Suppose that $(1-p)R < 1 < R$. Then, investors buy a unit of CoCo if and only if they expect government assistance. Note that the government is more likely to assist CoCo holders with a higher shock cost θ of the bail-in. As θ and the signal y are statistically positively related, investors reasonably believe that the government will be generous if the realization of the signal y is sufficiently high. Thus, investors buy the CoCo if the signal received is higher than a certain cutoff k. In fact, it can be shown that such a cutoff strategy is the unique equilibrium strategy by applying Lemma 3 of Morris and Shin (1998).

All investors choose this cutoff strategy with the same cutoff k, though the realizations of the signal may differ across investors. Therefore, the number m of investors who buy a CoCo is given by

(A2) $$m = \int_{\theta-\varepsilon}^{\theta+\varepsilon} 1(y \geq k)\frac{1}{2\varepsilon}dy = \frac{\theta + \varepsilon - k}{2\varepsilon}$$

where $1(A)$ is an indicator function whose value equals 1 if event A is occurred but otherwise equals 0. Recall that the government would choose a bailout if and only if m is greater than the critical mass $m^*(\theta)$. Equation (A1) and (A2) then imply that the government would choose a bailout if the shock cost exceeds a critical level $\theta^*(k)$ such that

(A3) $$\theta^*(k) \equiv \frac{(\pi_d - R)(k-\varepsilon)+2\varepsilon E}{(\pi_d - R)+2\varepsilon}$$

Note that the critical level of the shock cost $\theta^*(k)$ is increasing in the cutoff k. As k rises, fewer investors are exposed to the bail-in risk and, hence, the government is less likely to choose a bailout.

Given $\theta^*(k)$, an investor who receives a signal y has the following expected utility:

(A4) $$\begin{aligned} u(y,\theta^*(k)) &\equiv R\int_{y-\varepsilon}^{y+\varepsilon}[(1-p)+p1(\theta \geq \theta^*(k))]\frac{1}{2\varepsilon}d\theta - 1 \\ &= (1-p)R + pR\left(\frac{y+\varepsilon-\theta^*(k)}{2\varepsilon}\right)-1 \end{aligned}$$

The equilibrium cutoff level $k^* = k^*(\varepsilon)$ of the signal y is characterized by $u(k^*,\theta^*(k^*))=0$. From Equation (A3) and (A4), it follows that

(A5) $$k^*(\varepsilon) \equiv E - \left(\frac{R-1}{pR}\right)(\pi - R) + \left(\frac{1-(1-p)R}{pR} - \frac{1}{2}\right)2\varepsilon$$

Finally, I consider the limit case in which the error ε of signal y tends toward zero. Equation (A3) implies that θ^* and k^* are equivalent in this case. Thus, it follows that

(A6) $$\theta^* \to E - \left(\frac{R-1}{pR}\right)(\pi - R) \;\; as \;\; \varepsilon \to 0$$

Note that θ^* lies between the two critical levels $E-(\pi - R)$ and E. If θ is lower than θ^*, a bail-in is the unique equilibrium. Otherwise, a bailout is the unique equilibrium.

Thus far, I have focused on the discretion-based trigger case. However, if the threshold $\underline{x}$ is unbiased, the analysis above directly applies to the rule-based trigger case as well. The only change is that the political cost parameter should be replaced with π_r, which is smaller than π_d. Note from Equation (A6) that the critical level of the shock cost θ^* in the limit case is decreasing in π. Thus, if the trigger is rule-based, θ^* is higher and, hence, the government would more likely choose a bail-in in comparison with the case where the trigger is discretion-based.

Comparative statics provides implications with regard to how the implementability of a bail-in depends on the type of trigger. Equation (A6) implies that the magnitude of the negative effect of π on θ^* (i.e., $(R-1)/pR$) is decreasing in p while it is increasing in R. Investors are more willing to invest in CoCos with a lower probability of failure p or a higher interest rate R. More investors then participate in the CoCo market and, hence, the change of the trigger type and the resulting change in the political cost parameter have a greater impact on the implementability of a bail-in. Therefore, whether the trigger of CoCos is rule-based or discretion-based is important in a country whose financial system is stable despite the fact that the interest rate is relatively high.

2. Robustness Check

(1) Control variables of the default risk

In order to separate the default risk from the coupon rate, I used $Credit\ score_i$ as a control variable. $Credit\ score_i$ is based on the baseline credit assessment (BCA) conducted by Moody's. The BCA does not reflect the possibility that the parent company or the government provides the issuing bank with financial assistance. If this possibility of external support is not considered, the coefficient of $Discretion_i$ may not properly represent the effect of a discretion-based trigger on the implementability of a bail-in. In order to measure the effect properly, factors that are related to the likelihood of government bailouts but unrelated to the characteristics of CoCos should be controlled. For this reason, I also consider the $Adjusted\ BCA$, which reflects the possibility of receiving external support.

I estimate the regression model by replacing $Credit\ score_i$ with $Adjusted\ credit\ score_i$, which is a monotone transformation of the $Adjusted\ BCA$.[20] Table A1 shows the estimation result of the regression model in which $Credit\ score_i$ is replaced with $Adjusted\ credit\ score_i$ The coefficient of $Discretion_i$ is negative and significant at the 1% level in all specifications. Remarkably, the size of the coefficient is more or less the same as before. This is presumably due to the fact that bank characteristics that increase the probability of government bailouts are already properly controlled by existing control variables such as $State\ bank_i$ or $Total\ assets_i$.

Neither $Credit\ score_i$ nor $Adjusted\ credit\ score_i$ is based on market information. Thus, information updating may not be instantaneous, and information

[20] $Adjusted\ credit\ score_i$ is 21 if the credit grade from the adjusted baseline credit assessment is Aaa (the highest grade) and 1 if the grade is C (the lowest grade). One notch of credit rating corresponds to one point.

TABLE A1—REGRESSION FOR THE COUPON RATE: ADJUSTED BASELINE CREDIT ASSESSMENT

Specification	(1)	(2)	(3)	(4)	(5)
Discretion	-2.33*** (0.19)	-2.20*** (0.14)	-2.38*** (0.41)	-1.90*** (0.45)	-1.69*** (0.49)
Country Rate		0.52*** (0.06)	0.51*** (0.06)	0.74*** (0.08)	0.67*** (0.09)
Adjusted Credit Score		-0.27*** (0.04)	-0.29*** (0.04)	-0.14*** (0.05)	-0.06 (0.05)
AT1			0.77 (1.03)	-0.20 (0.44)	0.00 (0.46)
Conversion			0.51* (0.29)	0.01 (0.23)	-0.25 (0.24)
CET1 Threshold			-0.10 (0.11)	0.04 (0.10)	-0.04 (0.10)
Maturity			-0.02 (0.03)	0.01 (0.01)	0.00 (0.01)
Face Value (in log)			0.08 (0.08)	0.33*** (0.08)	0.48*** (0.11)
State Bank				-1.00*** (0.32)	-0.89*** (0.30)
Total Assets (in log)				-0.13 (0.10)	-0.27*** (0.10)
CET1				0.09** (0.04)	-0.00 (0.04)
Sovereign CDS (in %p)				0.11 (0.10)	0.04 (0.11)
Region	No	No	No	No	Yes
Year	No	No	No	No	Yes
Obs.	628	508	494	263	263
R-squared	0.19	0.57	0.58	0.69	0.75

Note: 1) The dependent variable is the coupon rate. 2) The Huber-White robust standard errors are in parentheses. *, **, and *** indicate significance at 10%, 5%, and 1%, respectively.

gathering from a large group of informed investors may be limited. As an alternative, I use the bank CDS premium, as it is one of the leading market indicators of default risk. In particular, I use $CDS\,senior_i$, which is the CDS premium on the bank's senior unsecured bonds whose maturities are close to the maturity of the given CoCo. Table A2 shows the estimation result of the regression model in which $Credit\,score_i$ is replaced by $CDS\,senior_i$. The coupon discounting effect of a discretion-based trigger is still observed in all specifications. Moreover, the size of the coupon discount as measured by the coefficient of $Discretion_i$ does not change much.

$CDS\,senior_i$ controls for the default risk of a senior unsecured bond rather than a subordinated bond. Because the CoCo is a subordinated bond, the CDS premium on a subordinated bond could account for the default risk of the CoCo better than $CDS\,senior_i$. In this sense, I replace $CDS\,senior_i$ with $CDS\,sub_i$, which is the

TABLE A2—REGRESSION FOR THE COUPON RATE: CDS ON SENIOR DEBT

Specification	(1)	(2)	(3)	(4)	(5)
Discretion	-2.33*** (0.19)	-2.67*** (0.15)	-1.93*** (0.38)	-1.90*** (0.45)	-1.69*** (0.49)
Country Rate		0.61*** (0.05)	0.65*** (0.05)	0.74*** (0.08)	0.67*** (0.09)
CDS Senior (in %p)		0.49*** (0.15)	0.51*** (0.16)	-0.14*** (0.05)	-0.06 (0.05)
AT1			-0.21 (0.41)	-0.15 (0.51)	-0.49 (0.48)
Conversion			-0.25 (0.15)	-0.27 (0.23)	0.01 (0.23)
CET1 Threshold			0.23*** (0.08)	0.13 (0.10)	-0.03 (0.10)
Maturity			-0.00 (0.01)	0.00 (0.02)	0.03* (0.01)
Face Value (in log)			0.15 (0.06)	0.33*** (0.08)	0.31*** (0.09)
State Bank				-0.88** (0.37)	-0.96*** (0.32)
Total Assets (in log)				-0.38** (0.14)	-0.40*** (0.13)
CET1				0.01 (0.05)	-0.06 (0.06)
Sovereign CDS (in %p)				0.10 (0.10)	0.07 (0.09)
Region	No	No	No	No	Yes
Year	No	No	No	No	Yes
Obs.	628	346	342	194	194
R-squared	0.19	0.67	0.69	0.73	0.80

Note: 1) The dependent variable is the coupon rate. 2) The Huber-White robust standard errors are in parentheses. *, **, and *** indicate significance at 10%, 5%, and 1%, respectively.

CDS premium on the subordinated bank bond whose maturity is close to the maturity of the given CoCo. A drawback of $CDS\,sub_i$ is that the available sample size is smaller, as the trading volume of CDSs on subordinated bonds is much smaller than that on senior bonds. Furthermore, $State\,bank_i$ should be dropped as it causes a severe multi-collinearity problem. This problem appears to arise because the sample size is small. Table A3 shows the estimation result. The coefficient of $Discretion_i$ is still negative and significant at the 1% level in all specifications. There is no meaningful change in the size of the coefficient.

TABLE A3—REGRESSION FOR THE COUPON RATE: CDS ON SUBORDINATED DEBT

Specification	(1)	(2)	(3)	(4)	(5)
Discretion	-2.33*** (0.19)	-2.91*** (0.18)	-1.79*** (0.45)	-1.90*** (0.45)	-1.45*** (0.53)
Country Rate		0.56*** (0.10)	0.65*** (0.10)	0.74*** (0.08)	0.38*** (0.14)
CDS Sub (in %p)		0.35*** (0.11)	0.40*** (0.13)	-0.14*** (0.05)	0.22 (0.19)
AT1			0.45 (0.61)	-0.05 (0.72)	-1.09* (0.62)
Conversion			-0.54*** (0.20)	-0.68*** (0.22)	-0.16 (0.24)
CET1 Threshold			0.32*** (0.09)	0.24*** (0.09)	0.05 (0.09)
Maturity			-0.02 (0.02)	-0.00 (0.02)	0.05** (0.02)
Face Value (in log)			0.14 (0.10)	0.21** (0.10)	0.18* (0.09)
Total Assets (in log)				-0.36** (0.14)	-0.53*** (0.15)
CET1				0.03 (0.05)	-0.03 (0.05)
Sovereign CDS (in %p)				0.00 (0.09)	-0.01 (0.10)
Region	No	No	No	No	Yes
Year	No	No	No	No	Yes
Obs.	628	247	245	166	166
R-squared	0.19	0.63	0.66	0.75	0.81

Note: 1) The dependent variable is the coupon rate. 2) The Huber-White robust standard errors are in parentheses. *, **, and *** indicate significance at 10%, 5%, and 1%, respectively.

(2) Mixed triggers

In the baseline empirical model (12), I classify all but Japanese mixed-trigger CoCos as rule-based trigger CoCos. This is done because the CET1 condition is deemed easier to be met than the PONV condition. However, the reverse is not impossible. The CET1 is a lagged indicator of a given bank's viability, as it is usually reported quarterly. Suppose that a bank faces a serious insolvency shock and therefore has to shed liabilities immediately. Although the CET1 level is not yet updated and is accordingly still good, the government may choose to declare that the given bank is at the point of non-viability in order to shed bank liabilities. If such a preemptive move is anticipated, mixed-trigger CoCos should be classified as discretion-based trigger CoCos. However, concerns over regulatory forbearance suggest that the government is less likely to move preemptively. Due to this complexity, I drop mixed-trigger CoCos for the moment and consider only purely discretion-based or purely rule-based trigger CoCos. See Table A4. The estimation result shows that the coefficient of $Discretion_i$ is negative in all five specifications

TABLE A4—REGRESSION FOR THE COUPON RATE: MIXED TRIGGERS ARE OMITTED

Specification	(1)	(2)	(3)	(4)	(5)
Discretion	-2.04*** (0.21)	-2.29*** (0.17)	-1.13* (0.58)	-1.38*** (0.64)	-0.64 (0.82)
Country Rate		0.64*** (0.07)	0.65*** (0.06)	0.85*** (0.08)	0.67*** (0.10)
Credit Score		-0.17*** (0.05)	-0.21*** (0.04)	-0.09 (0.06)	-0.07 (0.06)
AT1			1.23 (1.48)	-0.37 (0.35)	0.17 (0.45)
Conversion			0.45 (0.34)	-0.06 (0.23)	-0.28 (0.26)
CET1 Threshold			0.19 (0.13)	0.18 (0.14)	0.20 (0.16)
Maturity			-0.03 (0.05)	0.02** (0.01)	0.01 (0.01)
Face Value (in log)			0.19** (0.08)	0.39*** (0.09)	0.61*** (0.11)
State Bank				-1.04*** (0.30)	-0.98*** (0.31)
Total Assets (in log)				-0.14 (0.09)	-0.28*** (0.09)
CET1				0.05 (0.10)	-0.02 (0.04)
Sovereign CDS (in %p)				0.10 (0.10)	0.03 (0.11)
Region	No	No	No	No	Yes
Year	No	No	No	No	Yes
Obs.	509	418	405	230	230
R-squared	0.15	0.56	0.59	0.71	0.75

Note: 1) The dependent variable is the coupon rate. 2) The Huber-White robust standard errors are in parentheses. *, **, and *** indicate significance at 10%, 5%, and 1%, respectively.

and significant in all but specification (5). Although the significance is weaker, the estimation result remains consistent with Hypothesis 1. If significant, the estimated size of the coupon discount is around 1.13 to 2.29%p, which is slightly lower than the estimated size under the baseline empirical model.

Another concern with $Discretion_i$ is related to the treatment of Japanese mixed-trigger CoCos. Although I believe Japanese mixed-trigger CoCos should be classified as discretion-based CoCos due to Japan's creditor-friendly regulations, I classify them for the moment as rule-based trigger CoCos in order to check the robustness. Table A5 shows the estimation result. The coefficient of $Discretion_i$ is negative in all five specifications and significant at the 1% level in specifications (1)-(3). The estimated sizes of the coupon discount in specifications (1)-(3) are slightly higher than 2%p.

TABLE A5—REGRESSION FOR THE COUPON RATE: JAPANESE MIXED TRIGGERS ARE CLASSIFIED AS RULE-BASED

Specification	(1)	(2)	(3)	(4)	(5)
Discretion	-2.17*** (0.19)	-2.02*** (0.14)	-2.06*** (0.53)	-0.28 (0.77)	-0.15 (0.69)
Country Rate		0.53*** (0.06)	0.51*** (0.05)	0.73*** (0.08)	0.61*** (0.10)
Credit Score		-0.27*** (0.04)	-0.32*** (0.03)	-0.21*** (0.05)	-0.07 (0.05)
AT1			0.62 (1.04)	-0.47 (0.38)	-0.32 (0.41)
Conversion			0.63** (0.30)	0.27 (0.23)	-0.01 (0.24)
CET1 Threshold			-0.06 (0.13)	0.33* (0.17)	0.15 (0.16)
Maturity			-0.02 (0.03)	0.03** (0.01)	0.03** (0.01)
Face Value (in log)			0.10 (0.07)	0.33*** (0.09)	0.46*** (0.11)
State Bank				-1.13*** (0.32)	-0.95*** (0.28)
Total Assets (in log)				-0.15 (0.10)	-0.30*** (0.09)
CET1				0.11** (0.04)	-0.00 (0.04)
Sovereign CDS (in %p)				0.14 (0.11)	0.07 (0.11)
Region	No	No	No	No	Yes
Year	No	No	No	No	Yes
Obs.	628	509	495	263	263
R-squared	0.16	0.55	0.56	0.67	0.74

Note: 1) The dependent variable is the coupon rate. 2) The Huber-White robust standard errors are in parentheses. *, **, and *** indicate significance at 10%, 5%, and 1%, respectively.

(3) Within Country Variation

The regression analysis thus far relies heavily on the cross-country variation of CoCo returns given that many countries use only discretion-based triggers or only rule-based triggers, but not both. More reliable empirical results could be obtained if within-country variation is utilized because country specific factors can then be better controlled. To this end, I conduct the same regression analysis based on the empirical model (12) but with country-fixed effects included. See Table A6. I find that the coupon discounting effect of a discretion-based trigger still exists and that the size of the effect is 1.14%p in model specification 1, 1.26%p in model specification (2), and 0.91%p in model specification (3). The coupon discounting effect is statistically significant in the first two models at the 1% level and is statistically significant in the third model at the 10% level.

I also conduct the original regression analysis reported in Table A6 but with the

TABLE A6—REGRESSION FOR THE COUPON RATE: COUNTRY FIXED EFFECT

Specification	(1)	(2)	(3)	(4)	(5)
Discretion	-1.14*** (0.19)	-1.26*** (0.19)	-0.91* (0.51)	-0.19 (0.42)	-0.05 (0.69)
Country Rate		0.14 (0.14)	0.10 (0.13)	-0.07 (0.12)	0.17 (0.15)
Credit Score		-0.28*** (0.05)	-0.31*** (0.05)	-0.15** (0.07)	-0.15** (0.06)
AT1			0.74 (1.04)	-0.15 (0.37)	-0.02 (0.43)
Conversion			0.15 (0.51)	-0.73*** (0.27)	-0.50* (0.28)
CET1 Threshold			-0.03 (0.13)	0.21** (0.08)	0.17* (0.09)
Maturity			-0.00 (0.04)	0.04*** (0.01)	0.04*** (0.01)
Face Value (in log)			0.13 (0.09)	0.29*** (0.08)	0.30*** (0.09)
State Bank				-1.04*** (0.27)	-1.01*** (0.27)
Total Assets (in log)				-0.07 (0.07)	-0.08 (0.07)
CET1				0.01 (0.03)	0.02 (0.04)
Sovereign CDS (in %p)				0.16** (0.07)	0.10 (0.08)
Region	No	No	No	No	Yes
Year	No	No	No	No	Yes
Obs.	628	509	495	263	263
R-squared	0.64	0.70	0.71	0.87	0.87

Note: 1) The dependent variable is the coupon rate. 2) The Huber-White robust standard errors are in parentheses. *, **, and *** indicate significance at 10%, 5%, and 1%, respectively.

standard error clustered at the country level. The coupon discounting effect is significant at all five model specifications at the 1% level except for model specification (4), where the effect is significant at the 5% level.

3. Definition of Variables

TABLE A7—DEFINITION OF VARIABLES

Variable	Unit	Definition
Coupon Rate	%	The interest rate at issuance.
Coupon Residual (sub)	%	Coupon rate - Benchmark country rate* - CDS on benchmark subordinated bond**
Coupon Residual (senior)	%	Coupon rate - Benchmark country rate* - CDS on benchmark senior bond***
Discretion	Dummy	1 if the trigger is discretion-based but 0 if it is rule-based or mixed. For Japanese banks, mixed triggers are regarded as discretion-based.
AT1	Dummy	1 if the capital type is AT1 but 0 if it is T2.
Conversion	Dummy	1 if the bail-in mechanism is conversion to equity but 0 if it is principal write-down
CET1 Threshold	%	Numerical trigger. For discretion-based trigger instruments, I use 0%.
Maturity	Year	The nominal maturity. The longest finite maturity in the dataset is 42.5. I use 42.5 if the nominal maturity is infinite.
Face Value	USD bil.	The principal amount denominated in USD by the exchange rate at issuance.
Credit Score	21-scale	21 if the issuing bank's credit grade rated by Moody's is Aaa (the highest grade). One notch corresponds to one point. It is 1 if the grade is C (the lowest grade).
State Bank	Dummy	1 if the ultimate parent company is a sovereign or central bank.
Total Assets	USD bil.	Calculated based on the Basel standard.
CET1	%	The CET1 to risk-weighted assets ratio at issuance.
Country Rate	%	Market interest rate on the benchmark government bond. Among all government bonds, the benchmark bond is the one whose remaining maturity is closest to the maturity of the given CoCo instrument.
Sovereign CDS	%p	Market premium on the CDS contract on the 5-year government bond.

Note: 1) Coupon residual (sub), coupon residual (senior), credit score, total assets, CET1, country rate, and sovereign CDS are evaluated at the issue date of the given CoCo instrument. 2) * Market interest rate on the benchmark government bond whose remaining maturity is within the five-year window of the maturity of the given CoCo instrument. 3) ** Market premium on the CDS contract on the benchmark subordinated bond whose remaining maturity is within the five-year window of the maturity of the given CoCo instrument. 4) *** Market premium on the CDS contract on the benchmark senior unsecured bond whose remaining maturity is within the five -year window of the maturity of the given CoCo instrument.

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Discovery and Imitation of Export Products and the Role of Existing Exporters in Korean Manufacturing†

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This paper empirically examines what role of existing exporters play in the discovery of new export products and whether there are evidence of spillovers from export discovery. We find that existing exporters are more likely to discover new export products than non-exporters. We also find evidence of export discovery spillovers; export discovery of a product by some plants had an effect of increasing the probability of subsequent export market penetration of the same product by other plants. Export discovery spillovers are found to be stronger among geographically closely located plants. We argue that information spillovers is a part of the story: you learn from your neighboring discoverers about the profitability of potentially exportable products.

Key Word: Export Discovery, Imitation, Export Spillovers
JEL Code: F14, F61, O12

I. Introduction

One of the distinguishing characteristics of countries which have exhibited rapid industrialization and catch-up growth since World War II, such as Korea, is the remarkable growth of manufacturing exports. More noteworthy is the fact that the rapid export growth of Korea has been, upon a casual observation, sustained by the continual introduction of new export products and the subsequent development of new export industries. Hence, understanding how new export products are discovered and how these export discoveries eventually lead to a development of new export industries is likely to be critically important for understanding sustained industrialization and growth.[1]

Utilizing a plant-product dataset in the Korean manufacturing sector, this paper empirically examines initially the types of plants that are more likely to discover new export products and secondly whether there is evidence of spillover from export discovery. In doing so, the study particularly focuses on the role played by existing

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exporters. Foremost, a better understanding of the export discovery process is important *per se,* not only because the continual upgrading of an export product portfolio is key to the economic growth of many developing countries (Hausmann, Hwang, and Rodrik, 2007) but also because learning generated by a firm from the discovery of an export product can potentially spill over to other imitators who subsequently start exporting the same product. This leads to the question of who discovers new export product for the first time in an economy and who imitates the product. Do existing exporters play a leading role in the discovery? The first part of our main empirical analysis attempts to address these issues.

In the second part of our main empirical analysis, we ask whether there is evidence of spillover from export discovery. One key issue in the literature on export spillover is how to identify it. In an effort to do this, to the best of our knowledge, most existing studies examined whether the presence or prevalence of exporting activities in a product market by exporters in close proximity to each other affects the likelihood of subsequent export market penetration by a firm. A positive effect of existing export activity was interpreted as evidence of export spillover.

In this paper, we utilize detailed year-plant-product level information on domestic and export shipments to define export discovery and identify spillover from export discovery. Identifying spillover from export discovery is likely to be important because there should be export discovery in the development process of any export industry. This is one novel feature of this paper. This paper's focus on spillover from export discovery is motivated by Hausmann and Rodrik (2003), who show theoretically that self-discovery of what one is good at producing is key to developing growth in a country. They also show that there is too little self-discovery and too much imitation, as self-discovery is easily imitated. To the best of our knowledge, however, there are few empirical studies which rigorously examine spillover from export discovery.

Before moving ahead, we briefly explain why we expect that existing exporters play a leading role in the discovery of a new export product. First, all other factors being equal, exporters have a cost advantage over non-exporters in export discovery. Suppose that when a firm exports a product for the first time to a market (country), it must incur a fixed firm-specific export market entry cost, a product-specific fixed entry cost, and a market-specific fixed entry cost.[2] When a non-exporter attempts to export a product for the first time in an economy, it must pay all three of these entry costs. However, when an existing exporter attempts to do the same, it does not have to incur again the firm-specific export entry cost, which gives existing exporters a cost advantage over non-exporters in export discovery. Second, related to this, a plant may learn from its own previous exporting experience "what one is good at exporting." Through previous exporting experience of a product, the plant may learn not only about the profitability of exporting that particular product but also about the

[1]There is a vast body of literature on economic growth which shows that the creation of new knowledge and its domestic diffusion is a key process of economic growth for both developed and developing countries. (e.g., Hausmann and Rodrik, 2003; Parente and Prescott, 1994; Grossman and Helpman, 1991a; 1991b). To the extent that the discovery of new export products and the development of new export industries are associated with knowledge creation and diffusion, understanding the former process is likely to be necessary for understanding the process of economic growth.

[2]Our dataset does not have information about the destination market (country) to which a plant-product is exported.

profitability of exporting other related products, including those that have never been exported by any other plant in the economy.[3] Third, existing exporters can be better than non-exporters at discovering new export products due to their superior observable characteristics, such as their higher productivity and larger size. In our empirical analysis below, we will control for the effects of these superior observable characteristics.

We present evidence that existing exporters are more likely to discover new export products than non-exporters. We also find that export discovery of a product by some plants had the effect of increasing the probability of subsequent export market penetration of the same product by other plants. We show some additional evidence that information spillover is a part of the underlying story: you learn from your neighboring discoverers about the profitability of potentially exportable products.

This paper is related to the existing literature in several ways. First, the paper is related to various studies examining firm-level exporting activity, such as those by Clerides, Lach, and Tybout (1998), Bernard and Jensen (2004), Eaton, Kortum, and Kramarz (2004; 2011), and Feenstra and Kee (2008), among others. The paper differs from these studies in that it distinguishes between export discovery and imitative exports during a firm's export market entry by examining the firm's entry into the export market. Second, the paper is related to the literature on export spillover, such as studies by Aitken, Hanson, and Harrison (1997), Alvarez, Faruq, and Lopez (2008), Koenig, Mayneris, and Poncet (2010), and Fernandes and Tang (2014). These studies examined whether the presence or prevalence of exporting activities in a product market by closely located exporters, as mentioned above, affects the likelihood of subsequent export market penetration by a firm.[4] However, these studies do not examine spillover from export discovery as is done in this paper. Third, there is a small but growing body of work on export discovery, including studies most directly related to this paper. Iacovone and Javorcik (2010) present evidence from Mexico that once a firm introduces an export product previously not exported by any other firm, other firms quickly follow. Freund and Pierola (2010) and Artopoulos, Friel, and Hallak (2013) document an important role of export pioneers in the emergence of a new export industry in Peru and Argentina, respectively. However, these studies rely on descriptive analysis or a case-study approach. In contrast, this paper provides systematic econometric evidence of the importance of existing exporters in export discovery, as well as evidence on spillover from export discovery.

Hahn (2018) shows that there is evidence of export discovery spillover in the Korean manufacturing sector while utilizing the same dataset used in this study. This paper also shows evidence of export discovery spillover in addition to some other results, but it differs from Hahn (2018) mainly in that the present paper examines export spillover among geographically closely located plants—i.e., regional export discovery spillover. If export discovery spillover estimated in this paper is information spillover in nature, geographical proximity would matter with regard to

[3]Albornoz *et al.* (2012) and Nguyen (2012) theoretically explain firms' export strategies and dynamics while assuming that a firm's export performance in a market can inform the firm about the performance in other markets. In a similar vein, a firm's exporting experience of a product may inform the firm about the export market performance of other related products.

[4]Swenson (2008) examines the spillover effect from multinational firms on Chinese new exports.

such spillover. In this respect, this paper's results help strengthen the interpretation that the estimated export spillover effect is indeed spillover.

This paper is organized as follows. In the next section, we explain the data and provide some basic facts about export discovery and imitation. In section III, we estimate a multinomial logit model of a plant's choice among export discovery and imitation. In section IV, we estimate a linear probability model of product-level export entry to examine the existence of spillover from export discovery. The final section concludes the paper.

II. Data and Basic Patterns

This study utilizes two datasets. The first consists of unpublished plant-level census data underlying the *Mining and Manufacturing Census* published by Statistics Korea for the period from 1991 to 1998. It is an unbalanced panel dataset and covers all plants with five or more employees in the mining and manufacturing sector. The dataset has information about various plant characteristics, such as production, shipments, production and non-production workers, tangible fixed assets, and R&D expenditures.

The second dataset is an unpublished plant-product-level dataset for the same period, which can be matched to the plant-level dataset through plant identification numbers. A product is identified by an eight-digit product code which is devised by combining the five-digit KSIC (Korea Standard Industrial Classification) code to which the product belongs and the three-digit code based on Statistics Korea's internal product-classification scheme.[5] The product code is consistent over time during the period of the analysis. For each plant-product observation, the values of total shipments (domestic plus export shipments) and export shipments are available. The plant-product dataset covers roughly 70 to 80 percent of plants in the plant-level dataset.[6] The coverage ratio is much higher for total and export shipments. Yearly total shipments and exports from the plant-product dataset account for more than 84.1 percent of shipments and virtually all (99.9 percent) of the exports in the plant-level dataset. Using the information on the plant-product-level total and export shipments, we can identify which plant made a discovery of a new export product for the first time in the economy and which plant began exporting the same product later on.

Table 1 shows the number of plants, products, and the product varieties in the dataset. Here, a product variety is a product produced by a plant. The number of plants in the sample increases from 57,679 in 1991 to a peak of 75,053 in 1996 and then declines to 62,458 in 1998 with the outbreak of the Korean financial crisis.

[5]The product categories are quite narrow. For example, the number of products listed under *television, sound recording and apparatus* (KSIC five-digit code "32300") is 60 in 1997. Among those, there are 16 product categories related to televisions: mono TV receivers, color TV receivers (more than 20 inch), color TV receivers (less than 20 inch), combination TV receivers (color), combination TV receivers (mono), LCD color TVs, multi-vision TVs, projection TV receivers, VCRs, TV tuners (mechanical type), TV tuners (electronic type), laser disc players, VCR &TV receivers, video accompaniment equipment, closed-circuit TVs, and TV components not elsewhere classified. This example gives us a rough sense of what new products are captured in this paper, i.e., major product innovation output.

[6]Only those plants included in the plant-product dataset are included in the sample.

TABLE 1—NUMBERS OF PLANTS, PRODUCTS, AND VARIETIES

Year	Number of Plants		Number of Products		Number of Product-Varieties	
	All	Exporting	All	Exported	All	Exported
1991	57,679	11,018	3,147	2,232	81,453	14,639
1992	58,143	11,433	3,108	2,233	80,355	14,903
1993	68,397	11,345	3,126	2,294	94,313	14,942
1994	69,645	11,045	3,129	2,288	93,568	14,476
1995	73,582	11,056	3,185	2,374	100,172	14,484
1996	75,053	10,634	3,203	2,357	100,812	13,871
1997	71,505	11,160	3,351	2,521	97,065	14,589
1998	62,458	11,755	3,299	2,560	86,215	15,660
Total	536,462	89,446	25,548	18,859	733,953	117,564

Between 14 and 20 percent of plants are engaged in exporting. The number of eight-digit products varies between 3,108 in 1992 and 3,351 in 1997. Between 71 and 78 percent of those products are those exported by some plant. The share of exported products is highest in 1998, when there was a large depreciation of the Korean won. The number of product varieties varies between 80,355 in 1992 and 100,812 in 1996. The share of exported product varieties is between 14 and 19 percent.

Table 2 shows the number of export-discovery products and the number of newly exported product varieties during the sample period. Column A shows the number of exported products, which is from the fourth column of Table 1. It is very interesting to note that the discovery of a new export product is very frequent, which likely reflects the fact that Korea maintained a respectable level of economic growth by relying on export manufacturing. The numbers of yearly export-discovery products, as shown in column B, are between 270 and 495 during the sample period. They account for between 13 and 20 percent of all exported products.

Column C shows the number of export product varieties, which is taken from the sixth column of Table 1. It is surprising to find that more than half of these export product varieties are those which are exported for the first time from the plant's viewpoint (column D, new to the plant). We can further classify these newly exported product varieties into two categories: those that are new to the economy (column E) and those that are new only to the plant (column F). Column E shows that between 7 and 17 percent of newly exported product varieties are newly discovered export

TABLE 2—EXPORT DISCOVERY PRODUCTS AND NEWLY EXPORTED PRODUCT VARIETIES

Year	Exported Product		Exported Product Variety			
	All	Discovery	All	Newly Exported Product Variety		
				(New to the Plant)	(New to the Economy)	(New only to the Plant)
	A	B	C	D = E + F	E	F
1991	2,232		14,639			
1992	2,233	377	14,903	8,337	973	7,364
1993	2,294	414	14,942	9,074	1,073	8,001
1994	2,288	300	14,476	7,473	559	6,914
1995	2,374	342	14,484	7,812	621	7,191
1996	2,357	270	13,871	6,925	467	6,458
1997	2,521	495	14,589	7,812	1,069	6,743
1998	2,560	445	15,660	9,245	1,559	7,686

product varieties, which do not appear to be small numbers.[7] The remaining the newly exported product varieties are first-time exports of a product by a plant which other plants have already begun exporting for the first time in Korea. In short, we observe fairly frequent new exports of products and product varieties from the viewpoint of the economy, as well as fairly frequent imitative exports.

The discussion above shows that there are plants which discover a new export product as well as those which follow and imitate. When a product is newly exported for the first time in the economy by some plants, how quickly and how frequently do other plants imitate it and export the same product? Table 3 provides an answer to this question.

The upper panel of Table 3 shows the mean and median of the number of plants exporting a product which was newly exported from the perspective of the economy in 1992. In 1992, there were 377 new export product discoveries. An average of 2.6 plants simultaneously exported those products in that year. The corresponding median value is one. After one year, the average number of plants increases to 3.4 and the median value increases to two. The imitative exporting continues in later years but appears to slow rapidly. Although the average number of plants exporting a product discovered in 1992 increases to 3.8 in 1998,[8] the median value remains at two. The lower panel in Table 3 shows a case where we focused on 111 products which were exported in 1992 for the first time in the economy and survived in the export market through 1998. We see more clearly that a small number of plants start exporting a product for the first time in the economy and that other plants join in exporting the same product quickly thereafter.

TABLE 3—NUMBER OF PLANTS EXPORTING PRODUCTS DISCOVERED IN 1991

Year	Mean	Median	s.d.	Max	Min	Number of Product
Upper Panel: All 1992 export discovery						
1992	2.6	1	5.0	55	1	377
1993	3.4	2	6.0	54	1	250
1994	3.6	2	5.3	45	1	223
1995	3.4	2	4.7	34	1	237
1996	3.7	2	5.0	43	1	223
1997	3.4	2	4.3	34	1	237
1998	3.8	2	5.0	41	1	228
Lower Panel: 1992 export discovery surviving through 1998						
1992	4.4	2	6.8	45	1	111
1993	5.1	3	7.1	40	1	111
1994	5.0	3	5.9	36	1	111
1995	5.1	3	5.6	34	1	111
1996	5.2	4	5.2	29	1	111
1997	5.3	4	5.5	34	1	111
1998	5.6	4	6.4	41	1	111

[7]The figures in column E are larger than those in column B because two or more plants can start exporting a product for the first time in the economy in the same year.

[8]The increase in the average number of plants in 1998 is likely to reflect again the huge exchange rate depreciation associated with the Korean financial crisis.

TABLE 4—EXPORT DISCOVERY OF PRODUCT VARIETIES: EXPORTERS VS. NON-EXPORTERS

Year	All Plants	Exporters	Non-exporters
	Number of Economy-wide New Export Varieties		
1992	973	595	378
1993	1,073	624	449
1994	559	287	272
1995	621	363	258
1996	467	242	225
1997	1,069	671	398
1998	1,559	846	713
Total	6,321	3,628	2,693
	Per Plant		
1992	0.017	0.054	0.008
1993	0.018	0.055	0.010
1994	0.008	0.025	0.005
1995	0.009	0.033	0.004
1996	0.006	0.022	0.004
1997	0.014	0.063	0.006
1998	0.022	0.076	0.012
Total	0.012	0.041	0.006

Do exporters play a leading role in export discovery? Although we will address this issue more rigorously in the main empirical analysis below, we will provide a simple table here which shows that the answer is likely to be yes. Table 4 shows the number of export discoveries of product variety in year t made by exporters and non-exporters in year t-1. Out of 6,321 product varieties which were discovered during the period of 1991-1998, 3,628 product varieties were discovered by existing exporters. In terms of the number of export discoveries per plant, the role of existing exporters becomes much clearer. Existing exporters discovered 0.041 product varieties per plant while for non-exporters the value of 0.006.

Our plant-level dataset has information about the location of plants at the region level. The original plant dataset has 16 regions at the major city or provincial level. These are Seoul, Busan, Daegu, Incheon, Gwangju, Daejeon, Ulsan, Gyunggi, Gangwon, Chungbuk, Chungnam, Jeonbuk, Jeonnam, Gyungbuk, Gyungnam, and Jeju. Due to changes of the administrative regions within the sample period, however, we reclassified the regions into 13 regions so that the definition of a region would remain consistent over the years.[9] The number of plants, exporting plants, and workers for each of the 13 regions is provided in the Table A1. Using the regional location information of the plants, we are able to examine whether geographical proximity among plants matters with regard to export discovery spillover.

III. Who Discovers and Who Imitates Export Product Varieties?

As discussed in the previous section, there are fairly frequent new export discoveries of product varieties as well as much more frequent follow-up or imitative exports in the data. This leads to the question of who (or what type of plant) discovers

[9]Gwangju, Daejeon, and Ulsan were integrated with Jeonnam, Chungnam, and Gyungnam, respectively.

new export products and who imitates. Answering this question is important for understanding how Korea added new products to her export product portfolio. More importantly, if export discovery creates new knowledge of "learning what you are good at exporting" and if this new knowledge can potentially spill over to the rest of the economy, as in Hausmann and Rodrik (2003), finding answers to the above question would be important for devising appropriate policies to promote knowledge creation and diffusion.

A. *Empirical Model: Multinomial Logit*

In this section, we estimate a multinomial model and attempt to understand the plant characteristics which determine the choice from among three alternatives of starting to export a product variety which is new to the economy between year $t-1$ and t (export discovery, alternative 2), starting to export a product variety which is new to the plant but not new to the economy (imitation, alternative 3), and doing neither (not starting to export any new product variety, alternative 1). The probability of plant j choosing an alternative i is expressed as

$$(1) \qquad p_{ij} = \Pr(y_j = i) = \begin{cases} \dfrac{1}{1+\exp(X_j\beta_2)+\exp(X_j\beta_3)}, & \text{if } i=1 \\ \dfrac{\exp(X_j\beta_i)}{1+\exp(X_j\beta_2)+\exp(X_j\beta_3)}, & \text{if } i=2,3 \end{cases}$$

where y_j is the choice of alternative by plant j, X_j is the row vector of the characteristics of plant j, and β_i denotes the coefficient vector for alternative i. We estimated this model using plant-level data during the period of 1991-1998. We used one-year lagged values of X_j.

As plant characteristics, we consider exporting status (EXPORTER) for all plants above, taking a value of 1 if the plant exported at year $t-1$ and 0 otherwise. As discussed above, a plant's previous exporting status may importantly affect the exporting mode choice because previous exporting gives a plant a cost advantage over non-exporters for reasons related to sunk costs. More importantly, a plant may learn from its own previous exporting experience about "what you are good at exporting." Information or knowledge pertaining to the profitability of exporting a product acquired through its own experience may spill over to other related products, including those that have never been exported by any other plants in the economy.

In the analysis below, we also considered as explanatory variables certain observable plant characteristics. More productive plants can more easily export a new product, new to the plant or new to the economy, because the various sunk costs required to export a new product can be more easily justified by the higher expected operating profit. In order to estimate the (log of) the plant total factor productivity (LNTFP), we applied the methodology by Levinsohn and Petrin (2003) to each of the two-digit industries. The plant size can also affect the export mode choice with imperfections in the financial market. With an imperfect financial market, larger plants are expected to be able to finance more easily various sunk-entry costs or R&D expenditures which may be required to introduce a new product to an export market. Or, a larger plant may, for example, have more foreign contacts and obtain better deals in contracts with foreign distributors.[10] We used the (log of) the number of workers (LNWORKER) as a proxy for the plant size. Plants that are engaged in R&D activities may introduce a new export product more easily if exporting a new product requires a modification of product specifications or the upgrading of product attributes. We used an innovation status dummy variable for plants (INNOVATOR), which takes a value of one if a plant had a positive R&D expenditure in year t-1 and zero otherwise.

We also controlled for other plant characteristics which may determine a plant's choice of exporting a new product. These are plant's plant age (AGE); multiproduct plant dummy variable (MULTI), which takes a value of one if the plant is a multiproduct plant and zero otherwise; the (log of) the capital intensity (LNKI); and the (log of) the non-production worker ratio as a proxy for skill intensity (LNSI). We also included year and KSIC (Korea Standard Industrial Classification) three-digit level industry dummy variables in order to control for year and industry fixed effects.[11]

B. *Estimation Results*

The average marginal effects of the explanatory variables estimated from the multinomial logit model are displayed in Table 5. Here, the baseline is "do neither." The regression results are consistent with our previous expectation that exporting plants are more likely to discover new export products than non-exporters. The estimated average marginal effect of the EXPORTER variable in the discovery equation is significantly positive. Other factors being equal, the probability that an exporting plant will discover new export products is higher than for non-exporters by 0.02. The estimated average marginal effect of the EXPORTER variable in the imitation equation is also significantly positive. This result most likely reflects the point that exporting plants have a cost advantage over non-exporters because they have already paid the firm-specific export market entry cost.

It is important to note that the estimated marginal effect of EXPORTER in the "imitation" equation, which is 0.065, is also highly significant, which is consistent with the explanations provided earlier as to why existing exporters are at an advantage when introducing new export products. It is interesting to observe that the estimated marginal effect of EXPORTER in the imitation equation is much larger than in the discovery equation. We conducted the Wald test to determine if the estimated marginal effect of EXPORTER is statistically significantly larger in the imitation equation than in the discovery equation, and we were able to reject at the 1 percent level the null hypothesis of the equality of the marginal effects between

[10] Alvarez, Faruq, and Lopez (2008).

[11] One may consider estimating equation (1) using a plant fixed effect model. However, we decided not to pursue this approach because we wanted to utilize both cross-plant and over-time variations in the data to estimate the model. In fact, the exporter dummy does not have any variations over time within plant for a large number of plants. That is, for a large number of plants, their export status does not change over time within the sample.

TABLE 5—EXPORT DISCOVERY AND IMITATION: MULTINOMIAL LOGIT

Variables	Discovery	Imitation
EXPORTER	0.020***	0.065***
	(0.001)	(0.001)
LNTFP	0.001*	0.005***
	(0.000)	(0.001)
LNWORKER	0.005***	0.032***
	(0.000)	(0.001)
INNOVATOR	0.003***	0.010***
	(0.001)	(0.001)
AGE	-0.001*	-0.006***
	(0.000)	(0.001)
MULTI	0.006***	0.010***
	(0.000)	(0.001)
LNKI	0.001***	0.005***
	(0.000)	(0.001)
LNSI	0.002***	0.011***
	(0.000)	(0.001)
Year Dummy	Yes	
Industry Dummy	Yes	
Observations	286,371	
Log likelihood	-97991	
Pseudo R^2	0.143	

the two equations. Hence, existing exporters are not only more likely to discover new export products but also even more likely to start imitative exports.[12]

Other plant characteristics, which we used as control variables, also have significant effects on the export mode choice. Larger plants, innovative plants, or multiproduct plants are more likely to discover new export products or start imitative exporting than smaller, non-innovative, or single-product plants, respectively. Plants with higher capital intensity or with higher skill intensity levels are also more likely to discover or imitate. There is some weak evidence that plants that are young or with higher productivity rates are more likely to discover new export products.

All in all, the above result suggests that plants which have previous exporting experience play a leading role in the discovery of new export product varieties. These results are not driven by the observable characteristics of existing exporters which are superior to those of non-exporters, such as higher productivity, a larger size, and a greater tendency to be engaged in R&D. As explained above, existing exporters' leading role in export discovery may be due to, among others factors, their sunk-cost-related cost advantage or export-related learning spillover across products within the plant. Viewed from the perspective of Hausmann and Rodrik (2003), the above results may indicate that existing exporters play a leading role in the creation of new learning, which is "learning what you are good at exporting."

[12]Understanding why existing exporters have a greater advantage over non-exporters when beginning imitative exporting appears to require further scrutiny, which we leave as a future study.

IV. Spillover from Export Discovery

A. *Empirical Strategy*

In this section, we are mainly interested in examining whether plants learn from past export discoveries of products by other plants. To do so, we start by largely following the convention in the existing literature on export spillover, investigating studies by Fernandes and Tang (2014), and we estimate the probability of introducing a new export product variety. While the key explanatory variables in the existing literature are measures of the presence or prevalence of existing exporters or the exporting activity, the key explanatory variable in this study is the measure of export discovery, which will be explained below.

In order to define the dependent variable of the regression, we initially let X_{rjpt} be equal to one if product p by plant j located at region r is exported in year t and zero otherwise.[13] The dependent variable Y_{rjpt} is equal to one if $X_{rjpt}=1$ and $X_{rjpt-1}=0$, and zero if $X_{rjpt}=0$ and $X_{rjpt-1}=0$. That is, the product variety of a plant located in a certain region is a new export product variety if, from the plant's point of view, it is exported in year t and was not exported in the previous year. The probability of introducing a new export product variety by a plant located in region r can then be estimated using the following a linear probability model:

$$Y_{rjpt} = c + Z_{rpt-1}\alpha + V_{jpt-1}\beta + W_{jt-1}\gamma + \delta_{pt} + \delta_{jt} + \delta_{rt} + \varepsilon_{rjpt}. \tag{2}$$

Z_{rpt-1} is a variable or a vector of variables which measures other plants' exporting activities in region r for product p at time $t-1$. As discussed above, one key issue in the literature on export spillover is how to identify export spillover. In most existing studies, export spillover was identified by examining whether the presence or prevalence of existing exporters in a product market and/or in a geographical unit affects the likelihood of the export entry of a firm. We start by following this approach and consider the export dummy variable $XDUM_{rpt-1}$, which takes a value of one if product p was exported at region r in year $t-1$ and zero otherwise. We consider as alternative explanatory variables the export shipments of product p at region r at time $t-1$, $XVOL_{rpt-1}$, or the number of plants which are exporting product p at region r at year $t-1$, $XNUM_{rpt-1}$, because a larger export volume or a larger number of exporters may provide a stronger positive signal about the profitability of exporting product p. The coefficient α captures export spillover or learning from others.

Next, in order to examine whether plants learn from past export discoveries of products by certain other plants, we break down $XDUM_{rpt-1}$ further into two

[13]A plant is always located in only one region.

variables and let Z_{rpt-1} be equal to $[XDISCDUM_{rpt-1}, XCONTDUM_{rpt-1}]$. Here, $XDISCDUM_{rpt-1}$ is a measure of export discovery, which is equal to one if product p is exported for the first time in the region in year $t-1$ and zero otherwise, and $XCONTDUM_{rpt-1}$ is equal to one if product p is exported by any other plant in the region in both year $t-1$ and year $t-2$. If there is export spillover from export discovery, the estimated coefficients on $XDISCDUM_{rpt-1}$ is expected to be positive.

W_{jt-1} is a vector of plant characteristics which include the plant's exporting status $(EXPORTER)$, the (log of) the plant total factor productivity $(LNTFP)$, the (log of) the number of workers $(LNWORKER)$ as a proxy for the plant size, the plant's innovation status dummy variable $(INNOVATOR)$, plant age (AGE), a multiproduct plant dummy variable $(MULTI)$, the (log of) the capital intensity $(LNKI)$, and the (log of) the non-production worker ratio as a proxy for skill intensity $(LNSI)$. These are the same variables used in section III.

V_{jpt-1} is a vector of the plant-product (or plant-variety) characteristics, measuring the importance of the variety j to the plant p at time $t-1$. We considered two such measures, following Iacovone and Javorcik (2010), which are the share of the variety p in the plant's total domestic shipments at year $t-1$ (variety relevance in the domestic market: $VRRELEVD$) and the plant's share of the national domestic shipments of product p (variety domestic market share: $VMSD$). Based on the predictions from recent multiproduct firm trade models, such as Bernard, Redding, and Schott (2011), Mayer, Melitz, and Ottaviano (2014), we expect positive coefficients on these variables.

Meanwhile, it is possible that a positive demand shock in the export market will cause the first export shipment of a given product (export discovery) as well as subsequent export shipments by other plants. Because we are interested in estimating spillover effects from export discovery working across plants on the supply side, e.g., information spillover, we include product$\times$year fixed effects, δ_{pt}, in all regression specifications in order to control for demand side factors which may affect the probability of introducing a new export product variety by a plant. Here, the product dummy variables used are those for the KSIC five-digit industries. We also include plant$\times$year fixed effects, δ_{jt}, and region$\times$year fixed effects, δ_{rt}, in order to control for any unobserved time-varying plant-specific or region-specific factors which determine the introduction of a new export product variety.

In the regressions below, we used lagged values of the explanatory variables above to allow for possible time lags in the export spillover outcomes. The data used are a plant-product-year data for the period of 1991-1998.[14] Because we are estimating the probability of a new export product entry, we confined the analysis with plant-

[14] Because we used one-year lagged values of the explanatory variables in the baseline regressions, the observations for 1991 were not used in the estimation.

product-year observations which have positive domestic shipments but which were not exported in year $t-1$ $(X_{jpt-1}=0)$.

B. *Results*

1. Evidence of Export Spillover

Table 6 shows the estimation results when we used $XDUM$, $XVOL$, and $XNUM$ as the independent variables. Overall, the results are quite consistent with the existence of export spillover arising from the presence or prevalence of existing exports, as reported in previous studies. The coefficients of $XDUM$, $XVOL$, and

TABLE 6—EXPORT SPILLOVER AND PRODUCT-LEVEL EXPORT MARKET ENTRY

Model	[1]	[2]	[3]	[4]	[5]	[6]
XDUM	0.013*** (0.001)	0.010*** (0.002)				
XVOL			0.001*** (0.000)	0.001*** (0.000)		
XNUM					0.002*** (0.000)	0.001*** (0.000)
EXPORTER	0.096*** (0.005)		0.096*** (0.005)		0.096*** (0.005)	
LNTFP	0.010*** (0.002)		0.009*** (0.002)		0.009*** (0.002)	
LNWORKER	0.037*** (0.001)		0.037*** (0.001)		0.037*** (0.001)	
INNOVATOR	0.012*** (0.003)		0.012*** (0.003)		0.012*** (0.003)	
AGE	-0.005*** (0.001)		-0.005*** (0.001)		-0.005*** (0.001)	
MULTI	0.006*** (0.002)		0.006*** (0.002)		0.006*** (0.002)	
LNKI	0.006*** (0.001)		0.006*** (0.001)		0.006*** (0.001)	
LNSI	0.008*** (0.001)		0.008*** (0.001)		0.008*** (0.001)	
VRRELEVD	0.051*** (0.003)	0.029*** (0.002)	0.050*** (0.003)	0.028*** (0.002)	0.050*** (0.003)	0.028*** (0.002)
VMSD	0.101*** (0.009)	0.047*** (0.013)	0.105*** (0.009)	0.048*** (0.013)	0.105*** (0.009)	0.047*** (0.013)
product*year dummy	Y	Y	Y	Y	Y	Y
plant*year dummy	N	Y	N	Y	N	Y
region*year dummy	N	N	N	N	N	N
Observations	221,517	221,517	221,517	221,517	221,517	221,517
R-squared	0.046	0.120	0.047	0.120	0.047	0.120

Note: Numbers in the parenthesis are robust standard errors. Asterisks ***, **, and * indicate that the coefficient is significant at the 1, 5, and 10 percent level. Constants are not reported.

$XNUM$ are all significantly positive with and without control of the plant×year fixed effects or region×year fixed effects.[15]

All of the plant characteristics included, except for AGE, are estimated to be positive and highly significant. Product varieties which have been previously produced for the domestic market only by existing exporters, large plants, innovator plants, multiproduct plants, young plants, and capital- or skill-intensive plants are more likely to be exported for the first time from a plant's viewpoint. Both $VRRELEVD$ and $VMSD$ are estimated to be positive and significant in all regressions, suggesting that product varieties that are important to the plant in the domestic market or have large domestic market shares are more likely to be introduced into the export market.

Table 7, which presents our main empirical results, shows regression results with $XDUM$ replaced with $XDISCDUM$ and $XCONTDUM$. Overall, the results

TABLE 7—SPILLOVER FROM EXPORT DISCOVERY

Model	[1]	[2]	[3]	[4]
XDISCDUM	0.004* (0.002)	0.004** (0.002)	0.011*** (0.003)	0.011*** (0.003)
XCONTDUM	0.016*** (0.002)	0.016*** (0.002)	0.010*** (0.003)	0.010*** (0.003)
EXPORTER	0.096*** (0.005)	0.095*** (0.005)		
LNTFP	0.010*** (0.002)	0.009*** (0.002)		
LNWORKER	0.037*** (0.001)	0.037*** (0.001)		
INNOVATOR	0.012*** (0.003)	0.012*** (0.003)		
AGE	-0.005*** (0.001)	-0.006*** (0.001)		
MULTI	0.006*** (0.002)	0.006*** (0.002)		
LNKI	0.006*** (0.001)	0.006*** (0.001)		
LNSI	0.008*** (0.001)	0.007*** (0.001)		
VRRELEVD	0.051*** (0.003)	0.050*** (0.003)	0.029*** (0.002)	0.029*** (0.002)
VMSD	0.102*** (0.009)	0.103*** (0.009)	0.047*** (0.013)	0.047*** (0.013)
product*year dummy	Y	Y	Y	Y
plant*year dummy	N	N	Y	Y
region*year dummy	N	Y	N	Y
Observations	221,517	221,517	221,517	221,517
R-squared	0.047	0.047	0.120	0.120

Note: Numbers in the parenthesis are robust standard errors. Asterisks ***, **, and * indicate that the coefficient is significant at the 1, 5, and 10 percent level. Constants are not reported.

[15]The additional inclusion of region×year dummy variables scarcely affects the results and is thus not reported.

indicate the existence of export spillover from export discovery. In the first two columns, which show the results without plant×year fixed effects, the coefficients on $XDISCDUM$ are estimated to be positive and significant at the ten and five percent level. However, when we controlled for plant×year fixed effects in the third and fourth columns, the estimated coefficient of $XDISCDUM$ increased and became highly significant at the one percent level. Thus, when a product was exported for the first time (discovered) at the region level by some plants in the prior year, it raises the probability that other plants in the region will start to export the same product in the present year, consistent with the interpretation that one can learn from the export discoveries of one's neighbors. This is most likely the most novel empirical result in this paper.

The coefficient of $XCONTDUM$ is also estimated to be positive and highly significant in all of the regression specifications shown in Table 7, and the size of the estimated coefficient of $XCONTDUM$ is comparable to or larger than the coefficient of $XDISCDUM$. This result suggests that when a product is newly discovered, plants may immediately start imitative exporting or take a wait-and-see approach to determine if the product survives in the export market before they start imitative exporting.

Motivated by the observation that there may be some time lag between export discovery and imitative exporting, we additionally included several lagged variables of $XDISCDUM$ and $XCONTDUM$ in Table 8. Again, we always include product×year dummy variables and run the analyses with and without plant×year or region×year dummy variables. Here, the coefficients of $XDISCDUM(t-1)$ and $XDISCDUM(t-2)$ are estimated to be significantly positive, indicating that it takes approximately one to two years for the initial response of an imitative export to export discovery to take place.

Thus far, we have argued that the positive and significant coefficient of export discovery dummy variable captures export spillover from export discovery. We have also been inclined to argue that the nature of export spillover is likely to be basically information spillover, i.e., learning from neighbors about the profitability of potentially exportable products. If information spillover is actually behind the relationship between initial export discovery by some plants and subsequent exports by some other plants, the spillover effect should be most pronounced in industries where information is especially important. To test this idea, we divided manufacturing industries into "machinery" and "non-machinery" industries and ran separate regressions for each group. The basic premise is that the machinery industries are characterized by higher search costs in relation to the matching between international buyers and sellers, as in the differentiated goods industries in Rauch (1999).[16]

[16]A possible alternative approach may be to use the classification in Rauch (1999) and divide industries into differentiated goods and homogeneous or reference-priced goods industries. Rauch (1999) argues that the search barriers for differentiated goods are higher than those for homogeneous goods during the processes used by international buyers and sellers. However, it was not possible to match eight-digit product code in our dataset, which is based on Statistics Korea's international classification scheme, with SITC Rev. 2, on which Rauch's classification is based. Furthermore, by looking at the names of the industries, we concluded that most differentiated goods industries according to the classification in Rauch largely correspond to the "machinery" industry in this paper. For

TABLE 8—LAGGED SPILLOVER EFFECTS OF EXPORT DISCOVERY

Model	[1]	[2]	[3]	[4]
XDISCDUM(t-1)	0.007*** (0.002)	0.008*** (0.002)	0.015*** (0.003)	0.015*** (0.003)
XDISCDUM(t-2)	0.015*** (0.003)	0.016*** (0.003)	0.013*** (0.004)	0.013*** (0.004)
XDISCDUM(t-3)	0.002 (0.003)	0.001 (0.003)	0.000 (0.004)	0.000 (0.004)
XCONTDUM(t-1)	-0.005** (0.002)	-0.004 (0.002)	-0.004 (0.004)	-0.004 (0.004)
XCONTDUM(t-2)	0.026*** (0.003)	0.028*** (0.003)	0.022*** (0.005)	0.022*** (0.005)
XCONTDUM(t-3)	0.009*** (0.003)	0.010*** (0.003)	0.004 (0.004)	0.004 (0.004)
EXPORTER	0.095*** (0.005)	0.095*** (0.005)		
LNTFP	0.009*** (0.002)	0.009*** (0.002)		
LNWORKER	0.037*** (0.001)	0.037*** (0.001)		
INNOVATOR	0.012*** (0.003)	0.012*** (0.003)		
AGE	-0.005*** (0.001)	-0.006*** (0.001)		
MULTI	0.006*** (0.002)	0.006*** (0.002)		
LNKI	0.006*** (0.001)	0.006*** (0.001)		
LNSI	0.008*** (0.001)	0.008*** (0.001)		
VRRELEVD	0.050*** (0.003)	0.050*** (0.003)	0.028*** (0.002)	0.028*** (0.002)
VMSD	0.104*** (0.009)	0.106*** (0.009)	0.049*** (0.013)	0.049*** (0.013)
product*year dummy	Y	Y	Y	Y
plant*year dummy	N	N	Y	Y
region*year dummy	N	Y	N	Y
Observations	221,517	221,517	221,517	221,517
R-squared	0.047	0.048	0.121	0.121

Note: Numbers in the parenthesis are robust standard errors. Asterisks ***, **, and * indicate that the coefficient is significant at the 1, 5, and 10 percent level. Constants are not reported.

Table 9 shows the regression results. The first column is identical to column [3] of Table 7, while the second and third columns are the regression results for the machinery and non-machinery industries, respectively. The remaining three columns show regression results similar to those of region×year fixed effects. Consistent with our expectation, the estimated effect of export discovery on the introduction of a new export product variety is greater in the machinery industry in this case than in

these reasons, we use the machinery and non-machinery grouping. In this paper, products belonging to the machinery industry are those with KSIC two-digit product codes between 29 and 35, and products belonging to the non-machinery industry encompass all of the other manufacturing products (two-digit product codes between 15 and 28, as well as 36 and 37).

TABLE 9—SUBGROUP ESTIMATION: MACHINERY VS. NON-MACHINERY

Model	All Industries [1]	Machinery [2]	Non-machinery [3]	All Industries [4]	Machinery [5]	Non-machinery [6]
XDISCDUM	0.011*** (0.003)	0.014** (0.006)	0.007* (0.004)	0.011*** (0.003)	0.014** (0.006)	0.007* (0.004)
XCONTDUM	0.010*** (0.003)	0.004 (0.005)	0.010*** (0.003)	0.010*** (0.003)	0.004 (0.005)	0.010*** (0.003)
VRRELEVD	0.029*** (0.002)	0.046*** (0.006)	0.021*** (0.003)	0.029*** (0.002)	0.046*** (0.006)	0.021*** (0.003)
VMSD	0.047*** (0.013)	0.039* (0.022)	0.052*** (0.018)	0.047*** (0.013)	0.039* (0.022)	0.052*** (0.018)
product*year dummy	Y	Y	Y	Y	Y	Y
plant*year dummy	Y	Y	Y	Y	Y	Y
region*year dummy	N	N	N	Y	Y	Y
Observations	221,517	68,383	153,134	221,517	68,383	153,134
R-squared	0.120	0.097	0.143	0.120	0.097	0.143

Note: Numbers in the parenthesis are robust standard errors. Asterisks ***, **, and * indicate that the coefficient is significant at the 1, 5, and 10 percent level. Constants are not reported.

the non-machinery industry. This result strengthens our argument that the estimated positive spillover effects from export discovery indeed reflect information spillover.[17]

2. Additional Analysis

Thus far, we have restricted our analysis to the export spillover occurring at the regional level, implying that the key independent variables in the regression equation (2), $XDISCDUM$ and $XCONTDUM$, were defined and measured at the regional level. As a robustness check, we alternatively defined and measured $XDISCDUM$ and $XCONTDUM$ at the country level, $XDISCDUM\_E$ and $XCONTDUM\_E$, respectively, and ran similar regressions. The dependent variable in the country-level regressions are identical to those in the region-level regressions (i.e., $Y_{jpt} = Y_{rjpt}$), as the introduction of a new export product variety is measured at the plant-product level and a plant is located at only one region. All other control variables in the country-level regressions are identical to those in the region-level regressions. Another reason for running country-level regressions is to facilitate an examination of the spillover effects from country-level export discovery, and by doing this we do not have to limit the geographical scope of export spillover to the regional level.

Table 10 shows the country-level regression results, indicating that these results

[17]However, the estimated coefficient of XCONTDUM is not significant for the machinery industry but is significantly positive for the non-machinery industry. Although we cannot clearly interpret this result, we conjecture that not only the value of new information about foreign buyers or markets but also certain unobserved product characteristics are important for determining the behavior of imitative exporting.

TABLE 10—ECONOMY-WIDE SPILLOVER FROM EXPORT DISCOVERY

Model	All Industries [1]	Machinery [2]	Non-machinery [3]	All Industries [4]	Machinery [5]	Non-machinery [6]
XDUM_E	0.013*** (0.002)	0.016** (0.007)	0.013*** (0.002)			
XDISCDUM_E				0.008** (0.003)	0.018* (0.009)	0.006* (0.003)
XCONTDUM_E				0.014*** (0.002)	0.015** (0.007)	0.015*** (0.002)
VRRELEVD	0.028*** (0.002)	0.045*** (0.006)	0.020*** (0.003)	0.028*** (0.002)	0.045*** (0.006)	0.020*** (0.003)
VMSD	0.051*** (0.013)	0.048** (0.023)	0.056*** (0.018)	0.052*** (0.013)	0.048** (0.023)	0.058*** (0.018)
product*year dummy	Y	Y	Y	Y	Y	Y
plant*year dummy	Y	Y	Y	Y	Y	Y
Observations	221,517	68,383	153,134	221,517	68,383	153,134
R-squared	0.120	0.097	0.143	0.120	0.097	0.143

Note: Numbers in the parenthesis are robust standard errors. Asterisks ***, **, and * indicate that the coefficient is significant at the 1, 5, and 10 percent level. Constants are not reported.

are largely similar to the region-level results. The coefficients of $XDUM\_E$ are estimated to be significantly positive in all industries and in each subgroup of the industries, i.e., machinery and non-machinery. The coefficients of $XDISCDUM\_E$ are positive as well, although their significance is somewhat low, which suggests the existence of country-wide spillover from export discovery. The size of the coefficient of $XDISCDUM\_E$ in regression [4] of Table 10, which is 0.008, is slightly smaller than in the comparable region-level regression [3] in Table 7 (0.011), indicating that geographical proximity matters with regard to spillover from export discovery. The coefficient of $XDISCDUM\_E$ in the machinery industry is again larger than that in the non-machinery industry, which is consistent with the argument that the nature of spillover is likely to be related to information.

Table 11 shows the results with our key independent variables measured at the regional and economy-wide levels. For all industries, both $XDISCDUM$ and $XDISCDUM\_E$ are estimated to be positively significant at the five and ten percent level, respectively, whereas the coefficient of $XDISCDUM$ is approximately 1.5 times larger than that of $XDISCDUM\_E$, indicating that although spillover from export discovery exists at the country level, it is stronger at the regional level. When the model was estimated separately for the machinery and non-machinery industry samples, $XDISCDUM$ was significantly positive only for the machinery sample, consistent with our earlier results. $XDISCDUM\_E$ was not significant in either sample. These results indicate that although export discovery spillover is not limited by regional boundaries, it is stronger among plants which are more closely located to each other geographically.

TABLE 11—REGIONAL AND ECONOMY-WIDE SPILLOVER FROM EXPORT DISCOVERY

Model	All Industries [1]	Machinery [2]	Non-machinery [3]
XDISCDUM	0.009** (0.003)	0.011* (0.007)	0.005 (0.004)
XCONTDUM	0.007*** (0.003)	0.002 (0.005)	0.007** (0.003)
XDISCDUM_E	0.006* (0.003)	0.014 (0.009)	0.005 (0.003)
XCONTDUM_E	0.012*** (0.002)	0.014** (0.007)	0.013*** (0.003)
VRRELEVD	0.028*** (0.002)	0.045*** (0.006)	0.020*** (0.003)
VMSD	0.054*** (0.013)	0.048** (0.023)	0.059*** (0.018)
product*year dummy	Y	Y	Y
plant*year dummy	Y	Y	Y
Observations	221,517	68,383	153,134
R-squared	0.120	0.097	0.143

Note: Numbers in the parenthesis are robust standard errors. Asterisks ***, **, and * indicate that the coefficient is significant at the 1, 5, and 10 percent level. Constants are not reported.

TABLE 12—RESULTS WITH SEVEN-DIGIT PRODUCT*YEAR DUMMY VARIABLES

Model	All Industries [1]	Machinery [2]	Non-machinery [3]	All Industries [4]	Machinery [5]	Non-machinery [6]
XDUM	0.010*** (0.002)	0.009* (0.004)	0.008*** (0.003)			
XDISCDUM				0.010*** (0.003)	0.015** (0.007)	0.006 (0.004)
XCONTDUM				0.010*** (0.003)	0.006 (0.005)	0.008** (0.003)
VRRELEVD	0.028*** (0.002)	0.044*** (0.006)	0.020*** (0.003)	0.028*** (0.002)	0.044*** (0.006)	0.020*** (0.003)
VMSD	0.029*** (0.013)	0.024 (0.022)	0.031* (0.018)	0.029*** (0.013)	0.024 (0.022)	0.032* (0.018)
product*year dummy	Y	Y	Y	Y	Y	Y
plant*year dummy	Y	Y	Y	Y	Y	Y
region*year dummy	Y	Y	Y	Y	Y	Y
Observations	221,517	68,383	153,134	221,517	68,383	153,134
R-squared	0.196	0.169	0.227	0.196	0.169	0.227

Note: Numbers in the parenthesis are robust standard errors. Asterisks ***, **, and * indicate that the coefficient is significant at the 1, 5, and 10 percent level. Constants are not reported.

Finally, Table 12 shows again the region-level regression results with demand side factors controlled with seven-digit, instead of five-digit, product×year fixed effects.

Most of our main regression results remain intact, at least qualitatively.[18]

V. Summary and Concluding Remarks

Utilizing a plant-product dataset in the Korean manufacturing sector, this paper empirically examined, first, which types of plants are more likely to discover new export products, paying special attention to the role of existing exporters and, second, whether there is evidence of spillover from export discovery. We find that existing exporters are more likely to discover new export products than non-exporters and that larger plants, innovative plants, or multiproduct plants are more likely to discover new export products or begin to engage in imitative exporting as compared to smaller, non-innovative, or single-product plants, respectively. We also find evidence of spillover from the discovery of new export products. Export discovery of a product by some plants had the effect of increasing the probability of any subsequent export market penetration of the same product by other plants. This effect is more pronounced in the machinery (heterogeneous goods) industry than in the non-machinery (homogeneous goods) industry. The evidence suggests that information spillover is a part of the story: you learn from your neighboring discoverers about the profitability of potentially exportable products.

One important limitation of this study is that it uses plant-product level data, not firm-product level data. Export decisions or export discovery and imitation decisions, in particular, are likely to be made at the firm level, not at the plant level. It would be interesting to observe whether an analysis of firm-product level data, if such a dataset is available,[19] would provide results similar to those found in this paper. This is left for a future study.

[18]The regression results with six-digit product×year fixed effects are quite similar to those in Table 11.

[19]It appears that the Statistics Korea has a firm-plant matching table which is not released into the public domain. Unfortunately, the author could not gain access to this information.

APPENDIX

TABLE A1—NUMBER OF PLANTS AND WORKERS BY REGION: 1995

Region	Number of Plants	Exporting Plants		Number of Workers (person)
		Number	Share (%)	
Seoul	13,452	1,963	14.6	336,672
Busan	7,301	1,217	16.7	119,472
Daegu	4,579	769	16.8	112,682
Incheon	5,710	882	15.4	206,625
Gyunggi	21,043	3,054	14.5	673,592
Gangwon	1,232	106	8.6	34,249
Chungbuk	1,773	331	18.7	96,189
Chungnam	3,465	488	14.1	130,561
Jeonbuk	1,803	270	15.0	68,299
Jeonnam	3,400	281	8.3	122,407
Gyungbuk	3,818	657	17.2	205,050
Gyungnam	5,729	1,024	17.9	388,484
Jeju	277	14	5.1	4,502
Total	73,582	11,056		2,498,784

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Assessing Alternative Renewable Energy Policies in Korea's Electricity Market†

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This paper, focusing on the renewable portfolio standard (RPS), evaluates alternative renewable energy policies. We propose a tractable equilibrium model which provides a structural representation of Korea's electricity market, including its energy settlement system and renewable energy certificate (REC) transactions. Arbitrage conditions are used to define the core value of REC prices to identify relevant competitive equilibrium conditions. The model considers R&D investments and learning effects that may affect the development of renewable energy technologies. The model is parameterized to represent the baseline scenario under the currently scheduled RPS reinforcement for a 20% share of renewable generation, and then simulated for alternative scenarios. The result shows that the reinforcement of the RPS leads to higher welfare compared to weakening it as well as repealing it, though there remains room to enhance welfare. It turns out that subsidies are welfare-inferior to the RPS due to financial burdens and that reducing nuclear power generation from the baseline yields lower welfare by worsening environmental externalities.

Key Word: Electricity Market, Renewable Portfolio Standard, Technology, Renewable Energy Certificate, Welfare
JEL Code: Q21, Q28, Q31

I. Introduction

In July of 2017, the new government of South Korea announced its policy goal, termed Renewable Energy 3020 (RE3020), which involved increasing the share of renewable power generation, which was 7% in 2016, to more than 20% by 2030.[1] Later, in December of 2017, the Ministry of Trade, Industry and Energy (MOTIE)

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unveiled its Implementation Plan for RE3020. It proposes to expand public and private large-scale projects by enhancing local acceptability, where 95% of new power generation facilities will be based on solar and wind power. Subsequently, MOTIE issued the 8th Basic Plan for Long-Term Electricity Supply and Demand (MOTIE, 2017) which specifies the aggregate capacity and generation schedules for power sources from 2017 to 2031. Specifically, in the plan, the share of renewable energy generation, counting business-purpose generation only, becomes 20% by 2030, and it reaches 21.6% when adding self-consumption-purpose generation.

In terms of scale, RE3020 heavily relies on the expansion of business-purpose renewable power generation. As a main vehicle to achieve this goal, the government plans to strengthen the renewable portfolio standard (RPS). The promotion of renewable generation under RE3020 has fundamental significance in terms of i) ultimately improving environmental problems caused by greenhouse gases (GHG) and air pollutants, and ii) improving the nation's energy independence through energy diversification. On the other hand, one can figure that if the obligation under the RPS is strengthened drastically to meet the RE3020 target, the burden of compliance may eventually be reflected in the retail electricity price and then passed on to consumers. At the same time, this concern can be relieved to a certain degree when considering that the latest forecast by the International Renewable Energy Agency (IRENA, 2018), grid parity—the price of renewable energy is equal to that of existing power sources—will not be long due to the cost reduction from technology development. After all, it is not an easy task to determine the overall welfare effects of the currently planned RPS reinforcement. This is also true when estimating the effects of renewable energy policies as alternatives to the current policy.

In this paper, we propose a competitive equilibrium model designed to evaluate alternative renewable energy policies, including RE3020. The model provides a structural representation of Korea's electricity market, including its energy settlement system and renewable energy certificate (REC) transactions. Arbitrage conditions are used to define the core value of REC prices to identify relevant competitive equilibrium conditions. The model considers R&D investments and learning effects that may affect the development of renewable energy technologies. The model is parameterized to represent the baseline scenario under the currently scheduled RPS reinforcement and then simulated for alternative scenarios. As well as market effects, how the distributional effects of certain welfare factors—government net income, consumer surplus, producer surplus, and environmental effects—differ among alternatives is also examined.

It is found that achieving a 20% share of renewable energy generation via the RPS increases social welfare compared to the absence of the RPS. To be specific, from its absence, the introduction of the RPS results in an increase of the retail electricity price, thus hurting consumers. On the other hand, as nonrenewable energy generation shrinks, there is a significant decrease in externality costs. Overall, welfare is higher

[1]Following the Implementation Plan for RE3020, the definition of renewable energy in this paper includes some nonrenewable waste (e.g., industrial waste and nonrenewable urban waste) and new energy sources (e.g., fuel cells), which play a small role in the plan. Meanwhile, the International Energy Agency's (IEA) definition of renewable energy only includes hydropower, geothermal, solar, wind, tidal and bioenergy sources, excluding nonrenewable waste and new energy sources (IEA, 2002). Based on the IEA definition, South Korea's share of renewable energy in 2016 was 2.8% (IEA, 2018a).

under the RPS. Furthermore, there is room for enhancing welfare through an additional strengthening of the RPS. It turns out that such welfare ranking remains the same throughout various sensitivity analyses. In addition, a simple production subsidy for renewable generation can achieve the target share of renewable generation under the RPS, but it is found to be inferior to the RPS in terms of overall welfare due to the high financial burden borne by the government. Next, if reducing nuclear power generation from the baseline, welfare is lowered due to the increased environmental externality costs caused by the expanded generation from fossil fuels, which overwhelms any reduction in nuclear accident costs.

The rest of the paper proceeds as follows. Section II provides a literature review as well as a historical background of relevant policies. In Section III the model is described, followed by Section IV, where the model is parameterized using various sources of data. Simulation results are shown in Section V, and Section VI concludes the paper.

II. Background and Literature

After two oil crises in the 1970s, the government enacted the Act on the Promotion of the Development of Alternative Energy in 1987 and established the Basic Plan for the Development of Alternative Energy Technologies (1988-2001) in order to diversify Korea's energy sources. Since the United Nations Framework Convention on Climate Change (UNFCCC) in 1992, various efforts to reduce GHG emissions have been made, and the commercialization of developed technologies has progressed gradually. In 1997, the Act on the Promotion of the Development Alternative Energy was revised as the Act on the Promotion of the Development and Use of Alternative Energy, by which the use and diffusion of alternative energy was actively promoted.

In 2002, the government set a target share of alternative energy generation within total electricity generation. In addition, under the Feed-in Tariff (FIT), renewable-based producers begun to receive price support when the market price dropped below the standard price through government contracts lasting 15 to 20 years. Thereby, renewable-based producers were able to sell electricity at a fixed price, greatly reducing market uncertainty and ultimately leading to the formation of an early renewable energy generation market. Despite the improved policy support, as the financial burden caused by the FIT grows, discussions focusing on the introduction of the RPS started. The introduction of the RPS was considered beneficial in comparison to the FIT in terms of: i) inducing technology development based on market principles, ii) responding to the UNFCCC, and iii) fostering industries by expanding the renewable energy market. In the end, the government enacted what was termed the Renewable Portfolio Agreement (RPA) as a pilot project for 2009-2011, implementing the RPS in 2012 with the abolition of the FIT.

The RPS obligates producers who are based on nonrenewable sources to supply an additional amount, in general calculated by multiplying nonrenewable generation by the supply-obligation rate, using renewable sources. In order to comply with this obligation, the obligated party can (partially) choose self-generation or external procurement. To illustrate this, for each 1MWh of renewable generation, a REC, which can be submitted to prove compliance, is granted, and by selling RECs producers can make up their additional costs. At the same time, one can purchase

RECs and use them to prove their compliance. Either approach is legitimate under REC market transaction rules.

In July of 2017, the new government released the Five-Year Plan for National Administration, incorporating RE3020. RE3020 aims to raise the share of renewable generation, which was 7% in 2016, to 20% by 2030, mainly by applying higher supply-obligation rates for business-purpose generation. Table 1 shows the historical changes of the RPS supply-obligation-rate schedule. RE3020 plans to avoid biomass and waste-based development and to supply more than 95% of new generation facilities with solar and wind power in the future. Figure 1 shows MOTIE's (2017) projected generation for 2017-2031 together with the actual generation for 2005-2016. In 2030, the share of business-purpose generation accounts for 20% (126 TWh), while it was 6.2% in 2017. Regarding domestic generation potential, Lee, Jo, and Yoon (2014), by considering technology development and physical area conditions, estimate these values to be 311 TWh for 2015 and 314 TWh for 2030. Such generation potential rates represent 54% of the total generation for 2017 and 47% of the projected total generation for 2030.

Mandated policies, such as the RPS or the Renewable Fuel Standard (RFS), stipulate production in a way that is considered to have a high non-market value

TABLE 1—RPS SUPPLY OBLIGATION RATE

	'12	'13	'14	'15	'16	'17	'18	'19	'20	'21	'22	'23	'24	…	'30
Enactment	2.0	2.5	3.0	3.5	4.0	5.0	6.0	7.0	8.0	9.0	10.0				
Revision 1	2.0	2.5	3.0	3.0	3.5	4.0	4.5	5.0	6.0	7.0	8.0	9.0	10.0		
Revision 2	2.0	2.5	3.0	3.0	3.5	4.0	5.0	6.0	7.0	8.0	9.0	10.0			
RE3020															28.0

Note: New provision in Sep 2010, first revision in Mar 2015, second revision in Dec 2016, Renewable Energy 3020 in Jul 2017.

Source: Enforcement Decree of the Act on the Promotion of Development, Use and Diffusion of New and Renewable Energy, Annex 3; National Planning Advisory Committee (2017).

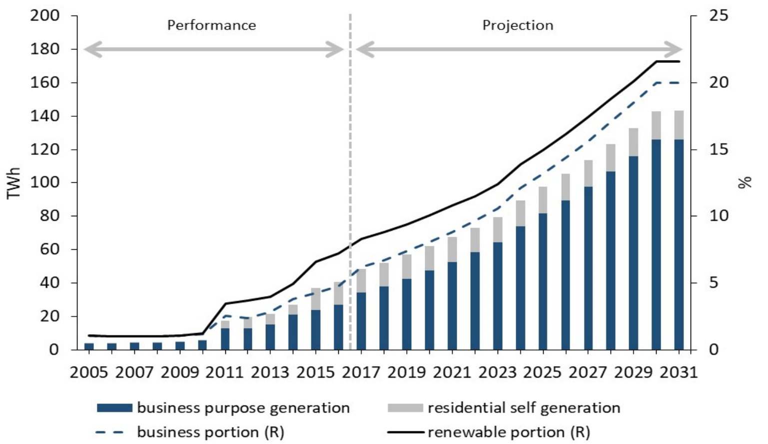

FIGURE 1. RENEWABLE ENERGY GENERATION: PAST AND FUTURE

Source: Korea Energy Agency, New and Renewable Energy Center, New and Renewable Energy Supply Statistics (https://www.knrec.or.kr/pds/st atistics.aspx, accessed Nov 19, 2018); MOTIE (2017).

despite low profitability. As a result, introducing the RPS affects the generation mix as well as wholesale and retail prices by affecting supply-side incentives. In this sense, there has been a line of literature to analyze the economic impact of an RPS together with related energy and environmental policies. Kydes (2007) sought to analyze the impact of increasing renewable generation by 20% through an RPS in the United States. The National Energy Modeling System (NEMS) of the US Energy Information Administration (EIA) was used for the simulation. As a result, if implementing an RPS there, the elasticity cost is increased by 3% and the total electricity consumption is decreased by 0.6%. On the other hand, GHG emissions were 16.5% less than those in the absence of an RPS.

Fischer and Newell (2008) analyze the relative welfare effects of environmental policies—an RPS, renewable generation subsidies, carbon taxes, emissions trading, and R&D investment support. Specifically, their competitive equilibrium model consists of two stages, where R&D investment in the first stage induces a cost reduction in the second stage, and it is simulated to compare the performance outcomes of alternative policies. Considering GHG emissions as the cause of environmental externalities, they compare social welfare when each policy option achieves the same GHG emission reduction target. They found that the use of a carbon tax is least likely to decrease welfare, followed by emissions trading systems, an RPS, and R&D support. Fischer, Preonas, and Newell (2017) extend the model of Fischer and Newell (2008) to simulate policy alternatives after proposing a model that takes into account demand-side efficiency improvements. Compared to Fischer and Newell (2008), nuclear and hydropower are considered as additional endogenous sources, while renewable energy is subdivided into solar and others. Their analysis found that carbon taxes are most efficient among various policy options, achieving a 40% reduction of GHG emissions.

On the other hand, Bhattacharya, Giannakas, and Schoengold (2017) analyze the welfare effects of an RPS in a situation where consumers could purchase both general and renewable-energy electricity separately. Using a partial equilibrium model considering heterogeneous consumer preferences, simulations are carried out under the assumption of exogenous RPS-induced cost reductions. It was found that the introduction of an RPS increases consumer surplus for those who prefer eco-friendly electricity. Other results regarding prices, the total supply, and overall social welfare are found to depend on assumptions about consumer preferences and the degree of the price increase for renewable-energy-based electricity under an RPS.

Focusing on South Korea's circumstances, Kim and Moon (2005) examined the economic effects of an RPS using an input-output table. Electricity demand forecasts from 2003 to 2020 and power generation plans depending on the power source were inserted into the input table, and the final electricity prices are reflected by simplifying the manner in which the REC cost is partly based on the supply-obligation rate. As a result, when the renewable share reaches 3% in 2011, there are an increase in price by 0.268% and a decrease in GDP by 1.940%. Kim and Cho (2010) analyze RPS-inducing economic impacts on domestic industries by simulating a general equilibrium model that considers renewable technology development and learning effects under imperfect competition. Simulations are conducted by dividing the share of renewable generation by 2022 into three cases: 7%, 8%, and 10%. The main result is that in the short run, an RPS could lead to a decrease in GDP due to the increase in investment costs. This is due mainly to the burden of production costs, but they argue that it results in long-run economic growth with the advantage of being able to achieve the target precisely as compared to the FIT.

Meantime, there have been several attempts to monetize environmental externality costs as a component of social welfare. One way is to measure the environmental gains from externality cost savings through the use of marginal damage estimates of GHG emissions from the existing literature (Chen, Huang, Khanna, and Önal, 2014; Moschini, Lapan, and Kim, 2017). Furthermore, the annual environmental damage estimates for air pollutants as well as GHG can be used to include relevant environmental benefits within the welfare effects (Parry and Small, 2005).

In this paper, we propose a model for South Korea's electricity market based on work by Fischer and Newell (2008) and Fischer, Preonas, and Newell (2017). Through simulations, we examine the effects of reinforcing the RPS under RE3020 along with other alternative situations. Compared with previous studies which analyzed RPS policies, this study can add to the literature by presenting a model based on a detailed representation of South Korea's electricity market as well as the RPS structure, and by analyzing welfare effects including environmental externalities from GHG and air pollutants. Thereby, this paper provides a useful measure for distributional the welfare effects of alternative renewable-energy policy scenarios.

III. Model

We contemplate a competitive power market model for analyzing the effects of renewable policies from a mid- and long-term perspective.[2] In the following sections, the electricity supply is limited to business-purpose generation and demand means net consumption after deducting self-generation. It is assumed that individual producers are price takers under perfect competition. In particular, prices in a future stage are treated as fully predictable and accepted as given. The generation cost structure is assumed to be symmetric between firms and separable between energy sources. Finally, for each source the model deals with a representative firm's profit maximization problem through aggregation.

As in Fischer and Newell (2008) and Fischer, Preonas, and Newell (2017), the model consists of two stages: the first stage for renewable-energy technology development and second stage under newly developed technologies, where each stage consists of a specific number of years, $\tilde{n}_1$ and $\tilde{n}_2$, respectively. Generation, consumption, and externality costs occur in both stages. The representative firm of each energy source determines the annual power generation for each stage. We apply a discount rate r, based on market interest rates. When dealing with a constant monetary stream for each stage, one can devise discounted effective years for each

[2]In South Korea, every two years MOTIE establishes the Basic Plan for Long-Term Electricity Supply and Demand, setting a schedule for generation capacity. This plan is actually based upon survey results regarding construction and abolishment intentions in the private sector in order to reflect the long-term market reaction to the plan. Therefore, an analysis regarding long-term market equilibria can be a useful criterion in terms of approximating market results under possible national plans.

stage, as follows: $n_1 \equiv 1/(1+r)+\cdots+1/(1+r)^{\tilde{n}_1}$ for the first stage, and $n_2 \equiv 1/(1+r)+\cdots+1/(1+r)^{\tilde{n}_2}$ for the second. Note that multiplying $\delta \equiv 1/(1+r)^{\tilde{n}_1}$ by n_2 can provide fully discounted values based on the beginning of the first stage.

For a concise model, it is assumed that the generation levels of minor and stable sources are determined exogenously. Specifically, for stage t, let X_t denote the amount of annual pumping-up generation and heavy oil generation and Y_t denote the renewable generation except for solar and wind power. The remaining energy sources can be divided into nonrenewable and renewable sources. Below, nonrenewable sources are represented by the subscript i, as follows: nuclear power $(i=n)$, coal $(i=c)$, and (liquefied natural) gas $(i=l)$. Renewable sources are represented by subscript j, as follows: solar $(j=s)$, and wind $(j=w)$.

The RPS supply-obligation rate, applied to nonrenewable-based producers, is denoted by α_t, and the price of a REC, endowed to renewable-based producers for 1 MWh of generation, is denoted by B_t. Depending on the energy source, REC weights are applied in consideration of policy factors (e.g., environment, technological development, and industrial activations; generation costs; potential capacities; GHG reduction effects; and power supply stability levels) in order to differentiate incentives depending on the source. The average REC weight, χ_j, is considered for both solar and wind power. The average weight for other renewable energy is set to 1.

Generation costs of producers can be divided into fixed costs (e.g., construction costs, fixed operation maintenance costs) and variable costs (e.g., fuel costs, variable operation maintenance costs). In South Korea's wholesale market, the cost-based pool is operated hourly by the Korea Power Exchange (KPX), where the system marginal price (SMP), p_t^*, is determined based on the variable costs of participating generators. To be specific, in order to minimize the aggregate generation costs, participating generators are ranked in the order of lower variable costs, and the last generator that meets the forecast demand is defined as a marginal price generator. Because generators cannot easily recover their fixed costs, the capacity payment (CP), ϕ_{it}, is additionally paid to all generators participating in the market. The Korea Electric Power Corporation (KEPCO), a monopolistic distributer, purchases electricity by paying various settlement amounts—capacity settlement amounts, energy settlement amounts, RPS obligation compliance costs, and other charges—and supplies electricity to consumers at the retail electricity price p_t. By abstracting hourly decisions during a year, the model addresses the problem of choosing annual generation levels at annual average prices.

A. *Nonrenewable Generation*

The generation of nonrenewable energy source i is denoted by x_{it}, and its aggregate capacity is denoted by K_{it}. Let ζ_i denote the annualized construction cost for adding one unit (MW) of capacity for source i, taking its average lifespan into account. For each source at stage t, the wholesale settlement price according to the energy source is p_{it}, which is a function of the SMP, as explained below. In addition, τ_i represents various policy charges levied on the amount of power generated by each nonrenewable energy source.

Under the assumed cost structure, for each energy source, the sum of individual firms' cost functions is that of the representative firm, as is the profit. The cost function of the representative nonrenewable-based firm for source i at stage t is $C_i(x_{it}, K_{it})$, which corresponds to the annual power generation costs (excluding construction costs) for generating x_{it}.[3] Suppressing subscripts for simplicity, it is assumed that cost functions satisfy $C_x \equiv \partial C / \partial x > 0$ and $C_{xx} \equiv \partial^2 C / \partial x^2 > 0$. That is, total costs and marginal costs increase in the generation amount. Further we assume $C_K < 0$ and $C_{KK} > 0$. Therefore, total costs decrease in the capacity, while the marginal reduction of generation costs decrease in the capacity. By assuming $C_{xK} < 0$, we deal with situations where an additional capacity increase leads to a reduction in the marginal cost.

A representative nonrenewable energy firm has the follows profits:

$$\begin{aligned} \Pi_i^N = {} & n_1[(p_{i1} - \alpha_1 B_1 - \tau_i)x_{i1} - C_i(x_{i1}, K_{i1}) - (\zeta_i - \phi_i)K_{i1}] \\ & + \delta n_2[(p_{i2} - \alpha_2 B_2 - \tau_i)x_{i2} - C_i(x_{i2}, K_{i2}) - (\zeta_i - \phi_i)K_{i2}]. \end{aligned} \tag{1}$$

Equation (1) reflects the additional costs $\alpha_t B_t$ incurred to comply with the RPS obligation for one unit of nonrenewable generation. If a firm is simultaneously generating using nonrenewables and renewables, due to the separable cost structure, it can be understood that REC purchases and REC sales are occurring separately, where equation (1) only shows purchases.

In a competitive market, individual firms determine the amount of generation where the marginal cost curve (i.e., supply curve) matches the given price (e.g., Stoft, 2002; Borenstein and Holland, 2005; Biggar and Hesamzadeh, 2014). Given a linearly increasing individual supply curve, the slope becomes infinite (i.e., vertical marginal cost curve) after a firm's generation reaches its maximum capacity. Thus, there are two situations: i) if the market price belongs to the vertical part of the supply curve, a firm generates to the maximum level of capacity, and ii) if the market price falls within the incremental part, it generates at the point where the price meets its supply curve. Note that the market price is determined at the point where the market-level supply curve and demand curve meet, where the annual market supply curve can be derived by horizontally summing individual marginal cost curves with respect to firms and hours.

[3]Note that x_{it} is the amount of electricity sold to the wholesale electricity market after subtracting plants' intra-consumption amounts, and this value is used as the basis for calculating the obligatory supply under the RPS.

The SMP in the wholesale electricity market is determined by the variable costs of a marginal generator. From an annual perspective, we consider that a representative gas-fired firm's generation is determined at the point at which the aggregate marginal costs equal the wholesale settlement price under the given capacity.[4] Assuming an interior solution, we exclude situations where the annual gas-fired generation becomes zero or reaches the maximum aggregate capacity. Then, for $t = 1,2$ and $i = l$ equation (2) is established as a short-term equilibrium condition that determines the annual gas-fired generation.

$$(2) \qquad p_{lt} - \alpha_t B_t - \tau_l - C_{x,l}(x_{lt}, K_{lt}) = 0 .$$

On the other hand, we consider corner solution situations for nuclear and coal. The annual generation can be determined by multiplying the given capacity by the annual average capacity factor (β_{it}) and by 8,760 hours (= 24 hours × 365 days). Therefore, for $t = 1,2$ and $i = n,c$, equation (3) holds as a short-term equilibrium condition.

$$(3) \qquad 8{,}760\beta_{it}K_{it} - x_{it} = 0 .$$

In the long run, the generation capacity can increase or decrease freely. In the end, the long-run equilibrium condition is that the utility's profit becomes zero (Borenstein and Holland, 2005). Therefore, over the long term, for $t = 1,2$ and $i = n,c,l$, equation (4) holds together with the short-term equilibrium conditions.

$$(4) \qquad (p_{it} - \alpha_t B_t - \tau_i)x_{it} - C_i(x_{it}, K_{it}) - (\zeta_i - \phi_i)K_{it} = 0 .$$

In the pricing structure of the domestic electricity market in South Korea, the settlement price for nonrenewable energy, p_{it} , is determined by an adjustment process based on the SMP (to maintain the financial balance between KEPCO and its generation subsidiaries). Specifically, a typical settlement price is calculated by $C_{x,i}(x_{it}, K_{it}) + [p_t^* - C_{x,i}(x_{it}, K_{it})] \times \lambda_i$, where p_t^* is the SMP, $C_{x,i}(x_{it}, K_{it})$ denotes the variable costs, and λ_i represents the adjustment coefficients. Furthermore, we consider that the per-MWh compliance costs and various policy charges are also offset for producers, reflecting the actual settlement process. Taking this feature into consideration, we have equation (5) for $t = 1,2$ and $i = n,c,l$.

$$(5) \qquad p_{it} - C_{x,i}(x_{it}, K_{it}) - \left[p_t^* - C_{x,i}(x_{it}, K_{it}) \right] \times \lambda_i - \alpha_t B_t - \tau_i = 0 .$$

[4]According to SMP determination data by fuel source from the Electric Power Statistics Information System (EPSIS) (http://epsis.kpx.or.kr/epsisnew/selectEkmaSmpNsmGrid.do?menuId=050203, accessed Aug. 31, 2018), the fuel-type shares of marginal generators for 2010-2017 are 87% for gas (LNG), 9% for oil, and 4% for coal. We abstract daily demand fluctuations and consider gas-fired plants as marginal on an annual basis.

B. *Renewable Generation*

Following Fischer and Newell (2008) and Fischer, Preonas, and Newell (2017), we assume that the accumulative knowledge is $S_{jt} = S_j\left(H_{jt}, L_{jt}\right)$. Note that S_{jt} is a function of knowledge from R&D, H_{jt}, and that from learning-by-doing, L_{jt}. We assume that $S_H > 0$ and $S_L > 0$, as well as $S_{HL} = S_{LH}$. The annual new R&D knowledge generated in each stage, h_{jt}, increases the cumulative R&D knowledge; i.e., $H_{j2} = H_{j1} + n_1 h_{j1}$, and the annual production in each stage increases the accumulative experience knowledge; i.e., $L_{j2} = L_{j1} + n_1 y_{j1}$. The R&D expenditure, $R_j\left(h_{j1}\right)$, is increasing and convex, i.e., $R_h > 0$ and $R_{hh} > 0$, and $R(0) = 0$. The government supports proportion σ_j of renewable energy R&D expenditures.

When the above is reflected, profits for the representative renewable-based firm can be expressed as equation (6).

$$
\begin{aligned}
\Pi_j^R &= n_1\left\{\left(p_{j1} + \chi_j B_1\right) y_{j1} - G_j\left(Z_{j1}, S_{j1}\right) - \left(1 - \sigma_j\right) R_j\left(h_{j1}\right)\right\} \\
&\quad + \delta n_2\left\{\left(p_{j2} + \chi_j B_2\right) y_{j2} - G_j\left(Z_{j2}, S_{j2}\right)\right\}
\end{aligned}
\tag{6}
$$

As mentioned above, the generation amount (MWh) is directly determined according to the capacity factor, and renewable generation satisfies equation (7).

$$8{,}760\beta_{jt} Z_{jt} - y_{jt} = 0. \tag{7}$$

With regard to knowledge accumulation, the degree of appropriability of newly acquired knowledge, ρ, can be considered, where we assume that solar power and wind power have the same value.[5] Below, the incomplete transfer rate is considered ($0 < \rho < 1$), and for knowledge that a specific firm appropriates, other firms can use it by paying a license royalty. In particular, it is assumed that newly acquired knowledge is ultimately utilized through the use of either imitation or permission.[6] As a result, the license revenue does not appear in equation (6), as this represents a simple transfer between firms.

The model takes into account second-stage cost savings which arise due to appropriable parts of new R&D-based knowledge in the first stage. Therefore, ρ

[5]For example, ρ=0 implies that the newly acquired knowledge of an individual firm is completely spilled over to other firms, while ρ=1 implies that new knowledge is fully attributed to the corresponding firms.

[6]Qiu and Anadon (2012) attempt empirically to identify the impact of expanding wind power on the decline in China's electricity prices during the period of 2003-2007 (without distinguishing between R&D innovations and learning effects), finding that knowledge spillover among firms has contributed significantly to the decline. The authors rationalize the results considering that both the government and business operators are gaining information about management and operation during the expansion of the industry.

appears in the representative firm's first-order conditions, which are derived from those of the individual firms (see Appendix A. for the derivation). Finally, for $j = s, w$, the first-order condition associated with setting the value of the annual R&D knowledge, h_{jt}, can be expressed as equation (8).

$$(8) \qquad \left(1-\sigma_j\right)R_{h,j}\left(h_{j1}\right)+\delta\rho n_2 G_{S,j}\left(Z_{j2},S_{j2}\right)S_{H,j}\left(H_{j2},L_{j2}\right)=0\,.$$

The first term in equation (8) is the amount of R&D net investment that must be paid in the first stage to acquire additional units of knowledge, and the negative of the second term represents discounted gains in the second stage from appropriating the new knowledge. Finally, the amount of new R&D knowledge is determined at the point where the cost and benefit are equal.

The long-term equilibrium condition of the representative renewable-based firm is to obtain a zero profit. This means that the excess profits from R&D investment are transferred to the consumers in the long run. For $j = s, w$, the long-term equilibrium condition is as follows:

$$(9) \qquad \left(p_{j1}+\chi_j B_1\right)y_{j1}-G_j\left(Z_{j1},S_{j1}\right)-\left(1-\sigma_j\right)R_j\left(h_{j1}\right)=0\,;$$

$$(10) \qquad \left(p_{j2}+\chi_j B_2\right)y_{j2}-G_j\left(Z_{j2},S_{j2}\right)=0\,.$$

In the case of renewable-energy sources, the SMP itself is the settlement price; thereby, $p_{jt} = p_t^*$.

C. *Consumers*

The electricity demand function is derived from the quasi-linear utility function of the representative consumer such that the consumer welfare can be consistently evaluated for each scenario in the simulation later. Specifically, the utility function can be expressed as $U = I + \Theta(P) - M$. Here, I is the monetary income expressed by reference goods, and the price of the reference goods is normalized by 1. The demand function then becomes $D(P) = -\partial\Theta / \partial P$. For the sake of simplicity, peak demand during the year and resulting fluctuations in demand are not taken into consideration. In addition, it is assumed that the consumer considers environmental costs, M. Specifically, such costs apply to only coal and gas, which heavily emit GHG, and to the three major air pollutants NO_X, SO_X and $PM_{2.5}$. Furthermore, it is assumed that consumers consider the possible nuclear accident costs (NAC), which are proportional to the capacity of nuclear plants. The five external costs above are expressed as $\varepsilon_{i,m}$, where $m = GHG, NO_X, SO_X, PM_{2.5}$ for $i = c, l$ and $m = NAC$ for $i = n$. Finally, the total external cost can be expressed as $M_t = \Sigma_{i\in\{c,l\}}\Sigma_{m\in\{GHG,\, NO_X,\, SO_X,\, PM_{2.5}\}}\varepsilon_{i,m}x_{it} + \varepsilon_{n,AC}K_{nt}$ for $t = 1, 2$. Except for external costs, the consumer welfare for the two stages is expressed by equation (11).

(11) $$CS = n_1 \int_{P_1}^{\infty} D(P)\,dP + \delta n_2 \int_{P_2}^{\infty} D(P)\,dP \, .$$

The retail electricity price, P_t, is calculated by summing the aggregate settlement price, $\tilde{P}_t$, and the transmission and distribution costs per unit, Δ, and then adding the *ad valorem* sales tax ψ. As a result, for $t = 1,2$ equation (12) holds.

(12) $$P_t - \left(\tilde{P}_t + \Delta\right)(1+\psi) = 0 \, .$$

To be concrete, the aggregate settlement price, $\tilde{P}_t$, is equal to the 'total expenditure paid' divided by the 'total amount of electricity purchased' by the distributer in the wholesale market:

(13) $$\tilde{P}_t = \frac{\sum_i \phi_i K_{it} + \phi_X K_{Xt} + \sum_i p_{it} x_{it} + \sum_j p_t^* y_{jt} + p_t^* X_t + p_t^* Y_t}{\sum_i x_{it} + \sum_j y_{jt} + X_t + Y_t} \, ,$$

where $\phi_X K_{Xt}$ implies capacity charges for other nonrenewable energy sources.

In South Korea, although the discussion on price rationalization continues, the government regulates the retail electricity price, ensuring that it is not directly connected to the wholesale price. Under this circumstance, changes in the RPS obligation compliance costs cannot easily be fully reflected in the retail price. To examine the mid- and long-term market effects, however, in this paper we assume that the wholesale price is connected to the retail price in the future as well as in earlier periods.

D. *Equilibrium*

First, for $t = 1,2$ equilibrium in the power market must satisfy the equation

(14) $$D_t(P_t) - \left(\sum_i x_{it} + \sum_j y_{jt} + X_t + Y_t\right)(1-\ell) = 0 \, ,$$

where ℓ is the loss ratio due to transmission and distribution.

Assuming full compliance under the RPS, the total amount of RECs, $\sum_j \chi_j y_{jt} + Y_t$, equals the obligation amount, $\alpha_t \times \left(\sum_i x_{it} + X_t\right)$. As a result, the supply-obligation rate, α_t, can be expressed as

(15) $$\alpha_t = \frac{\sum_j \chi_j y_{jt} + Y_t}{\sum_i x_{it} + X_t} \, .$$

Note that the numerator in equation (15) is based on effective units of renewable generation considering REC weights; accordingly, the physical amount of renewable generation decreases as the weights exceed 1, and vice versa. Later, we will look at the renewable share based on physical units, which is essentially related to achieving the policy goal.

Equilibrium in the integrated REC market requires that the demand and supply for RECs meet across renewable energy sources. In order to grasp the amount that a (marginal) buyer is willing to pay, equation (2) can be rewritten as

$$p_{lt} - C_{x,l}(x_{lt}, K_{lt}) - \tau_l = \alpha_t B_t . \tag{16}$$

From the short-term standpoint of gas-fired firms, the left-hand side of equation (16) corresponds to the per-MWh gain that a gas-fired firm can earn in the wholesale market, and the right-hand side corresponds to per-MWh compliance costs. Regarding the long-term behavior, rearranging equation (4) yields the following expression for $t = 1,2$ and $i = n,c,l$,

$$p_{it} - \frac{C_i(x_{it}, K_{it}) + (\zeta_i - \phi_i)K_{it}}{x_{it}} - \tau_i = \alpha_t B_t , \tag{17}$$

where the left-hand side of equation (17) corresponds to the per-MWh gain in the long run. Note that for a gas-fired firm, it holds that $C_{x,i}(x_{it}, K_{it}) = [C_i(x_{it}, K_{it}) + (\zeta_i - \phi_i)K_{it}] / x_{it}$ from equations (16) and (17), indicating that for the marginal energy source, marginal costs equal average costs in the long run. Let the left-hand side of equation (17), identical for all i, be Φ_t. In a competitive integrated REC market, arbitrage cannot occur across energy sources. Thus, all nonrenewable-based firms pay Φ_t to comply with their per-MWh obligations.

For renewable sources, equations (9) and (10) can be rearranged as follows:

$$\frac{1}{\chi_j}\left\{\frac{G_j(Z_{j1}, S_{j1}) + (1-\sigma_j)R_j(h_{j1})}{y_{j1}} - p_{j1}\right\} = B_1 , \tag{18}$$

$$\frac{1}{\chi_j}\left\{\frac{G_j(Z_{j2}, S_{j2})}{y_{j2}} - p_{j2}\right\} = B_2 . \tag{19}$$

The left-hand sides of equations (18) and (19) correspond to the minimum acceptable amount for a REC seller, while the right-hand sides correspond to the REC sales revenue per 1MWh of renewable generation. In the competitive REC market, each left-hand side has a unique value regardless of the source, denoted by Ψ_t.

Using equations (17)-(19), for $t = 1,2$ REC market equilibrium can be defined as

(20) $$\sum_i \Phi_t x_{it} + \Phi_t X_t - \sum_j \Psi_t y_{jt} - \Psi_t Y_t = 0 .$$

Finally, equation (20) implies that the total compliance costs for nonrenewable generation and the total REC revenue for renewable generation are balanced. As long as the equilibrium REC price is greater than zero, the RPS imposes a burden on nonrenewable generation through the market mechanism and assists in the development of renewables. However, the burden of nonrenewables will eventually be passed on to consumers due to the compliance cost return mechanism, as explained in the context related to equation (13).

Under the RPS, equilibrium can be characterized by 34 equations from equations (2)-(5), (7)-(10), (12), (14), and (20), which can be solved for 34 endogenous variables (x_{it} , K_{it} , y_{jt} , Z_{jt} , h_t , p_{it} , p_t^* , P_t , B_t for $i = n,c,l$, $j = s,w$, and $t = 1,2$). In order to analyze a situation without the RPS, equation (20) should be dropped. Furthermore, in order to consider renewable energy subsidies, b_{jt} , in the absence of the RPS, one can replace B_t with b_{jt} in equations (9) and (10).

After finding the equilibrium values, the social welfare value can then be calculated. The consumer surplus, except for the externality costs, is equal to equation (11), and the external costs are equal to $EX = n_1 M_1 + \delta n_2 M_2$. The government net revenue is given by equation (21),

(21) $$\begin{aligned} RV = n_1 &\left[\left\{ \psi \tilde{P}_1 + (1+\psi)\Delta \right\} Q_1 + \sum_i \tau_i x_{i1} - \sum_j \sigma_j R_j \left(h_{j1} \right) \right] \\ &+ \delta n_2 \left[\left\{ \psi \tilde{P}_2 + (1+\psi)\Delta \right\} Q_2 + \sum_i \tau_i x_{i2} \right] \end{aligned},$$

where $Q_t \equiv \sum_i x_{it} + \sum_j y_{jt} + X_t + Y_t$ and $\tilde{P}_t$ is based on equation (13). Social welfare can be defined as $W = PS + CS + RV + EX$, where $PS = 0$ in the long run. This welfare measure has its limitations such that it ignores benefits from enhancing national energy self-sufficiency or potential grid costs due to the unstable characteristics of renewable energy sources. In the context of a lack of related research in Korea, however, it still provides a useful metric of resulting welfare effects caused by alternative renewable energy policies.

IV. Parameterization

To simulate the model, it is necessary to specify functions and set all parameters in the model. In this section, based on raw data and information from the literature, we set the parameter values by i) directly quoting raw data, ii) using the equilibrium conditions in the model, or iii) introducing assumptions. In terms of the time horizon, we set $\tilde{n}_1 = 5$ in that it generally takes five years to obtain energy-related R&D results, and $\tilde{n}_2 = 20$, having year 2030 positioned in the middle of the second stage. Roughly, five years from 2015 to 2019, after the REC market is stabilized, can be regarded as the first stage, and 20 years from 2020 to 2039 are considered as the second stage.[7] Accordingly, the actual number of years in the first stage is $n_1 = 4.7$, while that in the second stage is $n_2 = 10.6$. The discount rate for the entire second stage is $\delta = 0.82$. The energy market interest rate is assumed to be $r = 0.07$.[8] As explained below, we use the raw data from 2016 for the first stage; thereby, all monetary values are expressed in 2016 Korean won (₩). See the tables in Appendix B. for a summary of values chosen in this section.

A. *Primary Data*

Information about capacity, generation, and price levels in the first stage are based on 2016 data from KEPCO (2017). For the second stage, we use projected values for the year 2030 provided by MOTIE (2017), reflecting RE3020. Other nonrenewable energy generation, X_t, is assumed to be fixed over the first and second stages; these values are calculated using the 2016 raw data of KEPCO (2017). For other renewable energy generation, Y_1 is based on KEPCO's (2017) raw data, while Y_2 is constructed using projected values from MOTIE (2017), reflecting an increasing trend of the other renewable category. For the amount of electricity that is actually supplied in the wholesale market, based on KPX (2018), intra-plant load factors, ω_i, are considered for nonrenewable sources though not for renewable sources.

Figures regarding R&D spending on core renewable technologies is collected from internal data of Korea Energy Technology Evaluation and Planning (KETEP). Cumulative R&D knowledge of solar power in the first stage is normalized as $H_{s1} = 1$, and cumulative knowledge of wind power is calculated as $H_{w1} = 0.69$ by considering the proportion of relative R&D expenditures during 2007-2016. Cumulative experience knowledge, L_{j1}, is estimated using cumulative generation volumes during 2005-2016. The amount of new R&D knowledge obtained through the first stage, h_{j1}, can be calculated using equation (9), which requires information about second-stage generation. Therefore, we start with the projected 2030 capacity values to calculate $\hat{h}_{j1}$ and then input $\hat{h}_{j1}$ in equation (9) to obtain the estimated capacity values. Iterating this procedure until precisely replicating the first stage value can give us the reference value of h_{j1}.

Hourly CP rates for nonrenewable sources are derived using internal data of the KPX, and corresponding annual rates are calculated by considering plant utilization factors (KPX, 2014). Annualized fixed costs for nonrenewable and renewable energy sources come from KPX (2018)'s data, which are similar to 'overnight costs divided

[7]Regarding the length of the stage required for innovation, Newell, Jaffe, and Stavins (1999) consider that the energy efficiency enhancement of household appliances is up to five years. On the other hand, EIA (2011) and EIA (2014) establish typical cost recovery periods for power generation technology of 18 years and 28 years, respectively. Practically, Fischer and Newell (2008) and Fischer, Preonas, and Newell (2017) assume five years for their first stages and 20-21 years for their second stages.

[8]In IEA and NEA (2015), a discount rate of 7% is applied as a median value for calculating the levelized cost of energy for each country. In addition, IEA (2018b) has recently stated that the energy industry's market interest rate remains stable at around 6%.

by the plant lifetime' based on figures from the International Energy Agency (IEA) and Nuclear Energy Agency (NEA) (2015). Retail costs are calculated using KEPCO's Electricity Cost Information for 2013-2017. Specifically, the total sales figure of the retail market minus the cost of purchasing electricity is regarded as the residual retail cost, which is ₩19,355/MWh. The degree of appropriability is set to 0.5 for both solar power and wind power in keeping with Fischer, Preonas, and Newell (2017), meaning that the social return of R&D is double the private return.

B. *Functional Assumptions*

For nonrenewable sources $i = n, c, l$, we employ quadratic cost functions that satisfy foregoing assumptions, $C_i(x_{it}, K_{it}) = c_{0,i} + c_{1,i}(x_{it} - x_{i1}^{BL}) + 0.5c_{2,i}(K_{i1}^{BL} / K_{it})(x_{it} - x_{i1}^{BL})^2$, where the superscript BL indicates baseline values. Because $C_i(x_{i1}^{BL}, K_{i1}^{BL}) = c_{0,i}$, we can calibrate $c_{0,i}$, which corresponds to all fixed costs except for the annualized construction costs, based on equation (4). Given the above cost functions, marginal cost functions are $C_{x,i}(x_{it}, K_{it}) = c_{1,i} + c_{2,i}(K_{i1}^{BL} / K_{it})(x_{it} - x_{i1}^{BL})$, and at the baseline $C_{x,i}(x_{i1}^{BL}, K_{i1}^{BL}) = c_{1,i}$. First, one can obtain $c_{1,l}$, which corresponds to gas power marginal costs at the baseline, using equation (2). Based on the internal data of KPX, we horizontally sum individual marginal cost functions to obtain aggregate marginal cost functions according to the energy type and derive $c_{1,i}$ for $i = n, c$ and $c_{2,i}$ for $i = n, c, l$.

Cost functions for renewable sources $j = s, w$ are specified as $G_j(Z_{jt}, S_{jt}) = (g_{0,j} + \xi_j Z_{jt})S_{jt}^{-1}$, where $g_{0,j}$ captures fixed costs apart from annualized construction costs. One can calibrate $g_{0,j}$ using equation (9). For $j = s, w$, knowledge functions are $S_j(H_{jt}, L_{jt}) = (H_{jt} / H_{j1})^{s_{1,j}}(L_{jt} / L_{j1})^{s_{2,j}}$, where the cumulative knowledge stock has constant elasticity with respect to R&D knowledge and experience knowledge, and the first-stage knowledge stock is normalized to 1, i.e., $S_j(H_{j1}, L_{j1}) = 1$. R&D knowledge parameters are set to $s_{1,s} = s_{1,w} = 0.3$ and learning knowledge parameters are set to $s_{2,s} = s_{2,w} = 0.3$; thus, projected outcomes under RE3020 are roughly implemented in the baseline. R&D expenditure functions are $R_j(h_{j1}) = \gamma_{1,j} h_{j1}^{\gamma_{2,j}}$ for $j = s, w$, which yield constant elasticities, $\gamma_{2,j}$. Following Fischer and Newell (2008) and Fischer, Preonas, and Newell (2017), we set $\gamma_{2,j} = 1.2$ for $j = s, w$,[9] with $\gamma_{1,j}$ calculated using equation (8).

A constant elasticity aggregate demand function is utilized, in this case $D(P_t, N_t) = N_t \times (P_t)^{\eta}$, where the price elasticity of electricity demand, η, is

[9]The elasticity of patent R&D is estimated to be 0.8 by Jaffe (1986); based on the reciprocal of the estimate, Fischer and Newell (2008) calculate the elasticity of new knowledge of R&D as 1.2.

assumed to be -0.3 from a mid- to long-term perspective. Several recent domestic studies estimate the elasticities of electricity demand as follows. Kim and Park (2013), using monthly consumption data for 1981-2011, suggest that the price elasticity rates of industrial (residential) consumption are -0.127 (0.143) before 1997 and -0.088 (0.123) after 1997. Lim, Lim, and Yoo (2013), based on survey data of 521 households in 2012, estimate the price elasticity of residential consumption as -0.68. As examples of elasticity application for a model simulation, Borenstein and Holland (2005) assume that the demand elasticity is -0.1 in the short run and -0.3 or -0.5 in the long run. In Fischer and Newell (2008), it is assumed to be -0.2 from a long-term perspective, while Fischer, Preonas, and Newell (2017) apply -0.1 from a short-term perspective. Note that N_t represents exogenous changes in the power demand level. We apply $N_1 = 1.64 \times 10^{10}$ considering the baseline price and quantity and $N_2 = 1.85 \times 10^{10}$ $(= N_1 \times 1.125)$ based on MOTIE's (2017) projected increase in demand.

The solar and wind capacity factors in the first stage are calculated as $\beta_{s1} = 0.138$ and $\beta_{w1} = 0.182$, respectively, using aggregate generation and capacity data from KEPCO (2017). For the second stage, $\beta_{s2} = 0.14$ which is the average of the predicted capacity factor values for 2017-2031. We also set $\beta_{w2} = 0.21$ by assuming that the wind capacity factor increases at a rate identical to that of the solar power.

C. *Externality Costs*

GHG social costs in the first stage are assumed using Yi's (2018) results, which are the basis of the recently published Financial Reform Special Committee (2018): ₩35,680/MWh for coal and ₩15,720/MWh for gas. When referring to figures in old publications—emission factors in MOTIE (2014) and marginal damages in MOTIE (2015)—we have externality costs of ₩20,575/MWh for coal and ₩9,063/MWh for gas. Accordingly, it appears that external costs are experiencing upward adjustments to reflect increasing environmental damages.

With respect to GHG externality costs in the second stage, an additional discussion regarding the trends of the estimates in the literature is necessary. The US Government (2016) specifies that under three discount rate assumptions (5%, 3%, and 2.5%), the US CO_2 social costs in 2030 compared to 2015 are greatly increased (46%, 39%, and 30%). Nordhaus (2017), relying on the updated Dynamic Integrated Model of Climate and the Economy (DICE), presents estimates of the global CO_2 social cost of \$31.2/tCO_2 in 2015 and \$51.6/tCO_2 in 2030, indicating an increase of 65%. In addition, applying the discount rate of Stern (2007), which is approximately 1.4%, the corresponding values are estimated to be \$197.4/tCO_2 in 2015 and \$376.2/tCO_2 in 2030, resulting in an increase of 91%. Along with the trends in these estimates, we assume that the discounted GHG social costs in the second stage are 34% higher than those in the first stage, applying a discount rate of 7%; these outcomes are ₩47,759/MWh for coal and ₩21,042/MWh for gas. Thereby, we specify costs as $\varepsilon_{it,GHG}$ for $i = n, c$ and $t = 1, 2$.

Air pollutant social costs follow the values given by Yi (2018): NO_X, SO_X and

$PM_{2.5}$, respectively, cause social costs of ₩16,590/MWh, ₩15,740/MWh, and ₩800/MWh for coal, and ₩4,630/MWh, ₩310/MWh, and ₩320/MWh for gas. These figures are applied in both stages without trends because air pollutants cause damages locally and do not stay in the atmosphere for a long time. In addition, the nuclear accident risk cost is based on the value provided by KPX (2018), where several alternatives are specified depending on how the probability of an accident is handled. We employ the estimate of ₩67,644,000/MW, as finally determined in the analysis by KPX (2018).

V. Numerical Simulation

A numerical simulation is carried out for six policy scenarios: i) the baseline RPS, ii) repealing the RPS, iii) the past RPS, iv) the optimal RPS, v) a renewable generation subsidy, and vi) nuclear power reduction. The baseline RPS scenario presents market outcomes under the 2016 RPS in the first stage and under the implementation of RE3020 (i.e., 20% share of business-purpose renewable generation) in the second stage. Renewable generation occupies 5.0% in the first stage and 20% in the second stage, where the corresponding RPS supply-obligation rates are 5.5% and 28%, respectively. In this scenario, while the supply-obligation rate determines the amount of renewable generation, the market drives the amount of generation for the remaining energy sources, where the wholesale and retail prices remain connected for both stages.

The repeal of the RPS scenario deals with a situation in which only the RPS is removed, where we assume that a certain level of renewable energy (mostly hydro) continues.[10] Compared to the baseline, the past RPS scenario is based on the second-stage supply-obligation rate as stipulated before RE3020. Specifically, it was to apply 4% in 2017 and, by increasing by 1% each year, reach 10% in 2023. Reflecting this trend, we apply 17% in 2030. In the optimal RPS scenario, the second-stage supply-obligation rate is set such that it maximizes the social welfare, while we hold the first-stage rate at the same level.

The subsidy scenario, in the absence of the RPS, introduces a direct production subsidy for renewable generation. To compare with the baseline, the subsidy level is set precisely using the REC prices for each stage in the baseline, i.e., ₩98,807/MWh and ₩5,781/MWh, respectively. The nuclear reduction scenario forces a 5% reduction in the aggregate nuclear power capacity in the second stage compared to the baseline, maintaining the same capacity factor.[11]

Equilibrium outcomes for each scenario can be obtained by solving the calibrated model based on corresponding sets of equilibrium conditions and assumed policy parameters. The welfare effects, aggregated over both stages, refer to relative welfare

[10] An average renewable generation level of 102,150 MWh for 1999-2000, which was before the introduction of the FIT, is regarded as the minimum amount of renewable energy generation.

[11] As shown later, in the baseline, the second-stage aggregate nuclear capacity is 23,024 MW. On the other hand, MOTIE (2017) forecasts that the nuclear capacity will increase from 22,529 MW in 2017 to 28,200 MW in 2023 and then decline to 20,400 MW in 2029. In order partially to reflect the capacity projections around 2030 in MOTIE (2017), which appears to be based on the government's plan, the scenario of 'nuclear power reduction' artificially reduces the aggregate nuclear capacity from the baseline.

changes compared to the scenario without the RPS. As a result of the simulation, the market results for each scenario are as shown in Table 2 and the welfare effects are as shown in Table 3. When the parameters were set correctly, the first-stage baseline outcomes are consistent with the figures from primary data. It turns out that the first-stage market results are consistent with the raw data.

TABLE 2—SIMULATION RESULTS: MARKET OUTCOME

	No RPS	Past RPS	Baseline RPS	Optimal RPS	Subsidy	Nuclear
Obligation rate (1st/2nd) (%)	0 %/ 0%	5.5% / 17%	5.5% / 28%	5.5% / 31%	0% / 0%	5.5% / 28%
First Stage Outcome						
Retail price (₩/MWh)	105,120	109,981	110,355	110,576	105,093	110,355
Wholesale price (₩/MWh)	77,104	77,061	77,060	77,060	77,070	77,060
REC price (₩/REC)	0	91,768	98,807	102,960	0	98,799
Nuclear capacity (MW)	23,101	23,116	23,116	23,116	23,113	23,116
Coal capacity (MW)	31,989	32,034	32,035	32,035	32,025	32,035
Gas capacity (MW)	32,465	32,622	32,624	32,625	32,591	32,624
Solar capacity (MW)	0	3,878	3,716	3,647	3,716	3,716
Wind capacity (MW)	0	936	1,051	1,097	1,051	1,051
Nuclear generation (GWh)	153,311	153,408	153,409	153,410	153,387	153,409
Coal generation (GWh)	204,336	204,626	204,630	204,633	204,564	204,630
Gas generation (GWh)	152,406	119,131	118,609	118,304	126,361	118,610
Solar generation (GWh)	0	4,701	4,505	4,421	4,504	4,505
Wind generation (GWh)	0	1,490	1,673	1,747	1,672	1,673
Renewable share (%)	0.0	5.0	5.0	5.0	4.9	5.0
Consumption (GWh)	510,783	503,904	503,390	503,088	510,823	503,391
Second Stage Outcome						
Retail price (₩/MWh)	104,606	106,028	105,807	105,669	104,491	105,870
Wholesale price (₩/MWh)	77,194	77,086	77,036	77,025	77,039	77,046
REC price (₩/REC)	0	9,970	5,781	4,838	0	5,775
Nuclear capacity (MW)	23,071	23,107	23,124	23,128	23,123	21,968
Coal capacity (MW)	31,896	32,009	32,059	32,070	32,056	32,049
Gas capacity (MW)	32,021	32,536	32,693	32,721	32,685	32,665
Solar capacity (MW)	0	17,507	26,537	29,566	26,534	26,530
Wind capacity (MW)	0	10,714	25,346	28,100	25,343	25,340
Nuclear generation (GWh)	153,110	153,352	153,462	153,487	153,456	145,789
Coal generation (GWh)	203,739	204,462	204,784	204,857	204,765	204,719
Gas generation (GWh)	219,898	138,470	100,414	91,768	102,673	108,066
Solar generation (GWh)	0	21,471	32,544	36,260	32,541	32,537
Wind generation (GWh)	0	19,709	46,627	51,693	46,622	46,615
Renewable share (%)	0.0	13.2	19.6	21.1	19.6	19.6
Consumption (GWh)	575,478	573,151	573,509	573,734	575,667	573,406
Solar cost reduction (%)	0.0	24.6	24.7	24.9	24.7	24.7
Wind cost reduction (%)	0.0	15.0	17.3	18.2	17.3	17.3

Note: All scenarios except for the no RPS scenario are under government R&D support.

TABLE 3—SIMULATION RESULTS: WELFARE OUTCOME (₩ BILLION)

	No RPS	Past RPS	Baseline RPS	Optimal RPS	Subsidy	Nuclear
Sum	**0**	**25,790**	**44,737**	**49,005**	**42,165**	**37,623**
Government revenue	**0**	**173**	**-380**	**-681**	**-20,183**	**-421**
Public R&D expenditure	0	-44	-492	-766	-491	-491
Retail tax	0	476	471	467	-21	479
Wholesale tax	0	-259	-359	-382	-342	-409
Subsidy	0	0	0	0	-19,328	0
Consumer surplus	**0**	**-18,688**	**-18,478**	**-18,309**	**637**	**-18,791**
Producer surplus	**0**	**0**	**0**	**0**	**0**	**-3,568**
Externality costs	**0**	**44,305**	**63,594**	**67,995**	**61,710**	**60,403**
GHG	0	40,038	57,678	61,700	56,072	54,139
NO_X	0	3,874	5,370	16,282	30,779	34,149
SO_X	0	148	207	220	197	195
$PM_{2.5}$	0	270	375	399	357	354
Nuclear accident risk	0	-26	-36	-38	-34	644

Note: Welfare effects are changes relative to the no RPS scenario.

A. *Baseline RPS and Repeal of the RPS*

In the baseline scenario, the first-stage market results replicate the raw data, while the second-stage results are of interest because there are no values to be replicated other than the renewable generation capacity. It was found that if an RPS supply-obligation rate of 28% is applied in the second stage, the renewable share increases to 19.6%, where the annual solar and wind power generation levels are similar to each other. Specifically, the annual generation levels are 32,544 MWh for solar and 46,627 MWh for wind. This is quite similar to the plans for these two power sources (33,530MWh for solar and 42,566MWh for wind) by MOTIE (2017).

In the baseline, the annual R&D expenditure in the first stage is approximately ₩87.1 billion/year for solar (₩435.5 billion in total during the first stage) and about ₩70.1 billion/year for wind (₩350.5 billion in total). Compared to the first stage, in the second stage the generation costs are reduced by 24.7% for solar and 17.3% for wind, owing to technology development and learning effects. Under the cost reduction, the REC price drops to ₩5,781/REC but remains positive, meaning that the RPS is binding even in the second stage. In other words, generation costs for renewable energy are still higher than the costs for fossil fuels.

The second-stage retail price fell by 4.1% from that in the first stage due mainly to a decline in the generation costs for renewable energy. Owing to the reduced REC price, the annual RPS compliance cost (= REC price × weighted renewable energy generation) dropped greatly from ₩2.7 trillion/year in the first stage to ₩76 billion/year in the second stage. In addition, due to the expansion of renewable energy, the generation volume of nonrenewable energy in the second stage is reduced compared to that in the first stage. The generation mix consists of 30% nuclear, 39% coal, 23% gas, 3% other nonrenewables, and 5% renewable in the first stage, and with corresponding rates of 26%, 35%, 17%, 3% and 20% in the second stage. The resulting capacity factors for nuclear, coal and gas are 76%, 73%, and 42% in the first stage and 76%, 73%, and 35% in the second stage, respectively, where there is a decrease only in gas-fired generation. The reduced generation volume contributes to lower nonrenewable-energy marginal costs, resulting in a slight decline of 0.03% in the wholesale electricity price. As a result of this price effect, annual electricity consumption in the second stage is increased by 13.9% from the first stage, which exceeds the exogenous demand increase of 12.5%.

When the RPS is abolished, there is no renewable generation in either the first or second stages, and no R&D investment in renewable energy occurs. The wholesale settlement price rises slightly by 0.11% from the first stage to the second because marginal costs increase as nonrenewable generation increases due to the increase in exogenous demand. The retail price declines by 0.5% in the second stage compared to the first stage because there is a decrease in capacity payments in the second stage, which overwhelms the increase in the wholesale settlement price. Compared to the repeal of RPS scenario, in the baseline scenario retail prices are increased by 5.0% in the first stage and 1.1% in the second stage. In other words, under the RPS, it can be understood that the payment for the RPS compliance cost is placed on top of the wholesale adjusted price, causing an increase in retail prices. As a result, total consumption in the baseline scenario is decreased by 1.4% in the first stage and 0.3% in the second stage, relative to the no RPS scenario.

With regard to welfare effects, the baseline scenario, compared to the no RPS scenario, shows a welfare increase of ₩44.7 trillion, which means a relative gap in the discounted 25-year welfare sum. Looking at distributional effects, government revenue in the baseline is reduced compared to the no RPS scenario mainly due to i) an additional R&D expenditure and ii) lower wholesale tax revenue. Compared to the no RPS scenario, in the baseline increased retail prices lower consumer surplus by ₩18.5 trillion, while the reduced amount of nonrenewable generation results in lower externality costs of ₩63.6 trillion.

B. *Past RPS and Optimal RPS*

In terms of the second-stage supply-obligation rate, which is 28% in the baseline, the past RPS and optimal RPS scenarios respectively apply a lower rate of 17% and a higher rate of 31%. Note that as the second-stage rate increases, i.e., when we go through 'no RPS' → 'past RPS' → 'baseline RPS' → 'optimal RPS', the second-stage wholesale price decreases. This occurs due to the merit-order effect, by which a decrease in nonrenewable energy generation due to the strengthening of the RPS results in lower marginal costs at the margin. On the other hand, first-stage retail prices increase as the RPS is strengthened because a stronger second-stage supply-obligation rate necessitates a larger expansion of wind power, which is more expensive than solar power, thereby leading to rises in the REC price and retail price in the first stage.

It is important to examine changes in R&D investments. First, as the second-stage supply-obligation rate increases, the annual R&D investment increases significantly for both solar and wind power. This arises because if second-stage renewable generation is forcibly increased, the R&D incentive becomes stronger because the marginal effects of the second-stage cost reduction from the first stage of R&D increases. It appears that as the second-stage supply-obligation rate increases, the greater cost-reduction effects realizes. In addition, strengthening the RPS results in a larger role of wind power; thereby, wind power experiences a greater cost reduction from the baseline than solar power in the optimal RPS scenario. This arises because the first-stage accumulative knowledge stock for wind is lower than that of solar, meaning that the marginal cost-reduction effects from additional knowledge is higher for wind than for solar.

In term of welfare, when normalizing the welfare increase from the no RPS scenario to the past RPS scenario as 1, the baseline undergoes an increase in welfare by 1.7 times and the optimal RPS scenario experiences an increase by 1.9 times. In detail, the stronger the RPS supply-obligation rate is in the second stage, the higher the incentive for R&D investment becomes, resulting in higher government expenditures. A stronger second-stage supply-obligation rate also lowers consumer surplus with an increase in retail prices. Despite these negative effects, overall welfare increases in the second-stage RPS target rate owing to the considerable decrease in externality costs.

C. *Renewable Generation Subsidy and Nuclear Power Reduction*

In the subsidy scenario, it turns out that when subsidy levels are precisely equal to REC prices, the resulting renewable energy generation and cost saving effects are identical to those in the baseline scenario. As the RPS obligation is not incurred, however, retail electricity price falls by 4.8% in the first stage and by 1.2% in the second stage compared to the baseline scenario. Wholesale prices are higher in the subsidy scenario because nonrenewable energy generation is greater, yielding higher marginal costs than in the baseline.

As a result, replacing the RPS with a renewable generation subsidy yields a gain of ₩19.1 trillion in consumer surplus compared to the baseline, as electricity is supplied at lower retail prices. On the other hand, compared to the baseline, there is an increase in the government expenditure of ₩19.3 trillion, and the amount of nonrenewable energy generation increases, resulting in reduced external costs of ₩1.8 trillion. In summary, the effect of raising overall welfare from the no RPS scenario is ₩2.6 trillion lower than that in the baseline scenario.

As shown in Table 2, an introduction of the RPS from its absence mainly reduces gas-fired generation, which is marginal in terms of generation, and has minor effects on the remaining nonrenewable energy sources. In the baseline scenario, the second-stage nuclear power capacity is determined to be approximately 23,124MW, and nuclear generation accounts for 26.0% of the total in the second stage. The nuclear reduction scenario is to, from the baseline, limit aggregate nuclear capacity to 21,968 MW, which is a 5% reduction, thereby reducing nuclear generation from 153 TWh to 146 TWh under the baseline nuclear capacity factor, accounting for 24.6% of the total generation.

The forced reduction in the second-stage aggregate nuclear capacity results in an increase in the retail price owing to the increases in other expensive forms of nonrenewable generation. As a result, compared to the baseline, consumer surplus is lowered by about ₩300 billion, and producer surplus in nuclear power experiences a loss of ₩3.6 trillion as the long-term equilibrium condition is not met with increased marginal costs. The costs associated with the nuclear accident risk are reduced by about ₩640 billion compared to the baseline scenario, but the environment external costs are more than ₩3.2 trillion due mainly to the increased amount of gas-fired generation. As a result, overall welfare is lower by ₩7.9 trillion than in the baseline.

The nuclear power reduction scenario can be thought of as a further reflection of MOTIE (2017) when considering the schedule of nuclear power capacity. One can also interpret the result of this scenario in the following way. When setting the nuclear power reduction scenario as the baseline, the original baseline scenario can be treated as a scenario in which market principles are applied to the nuclear power sector *ceteris paribus*. The implication is then as follows: if letting the market mechanism fully govern the nuclear power sector, there would be welfare gains partially from an increase in nuclear power generation and a decrease in gas-fired generation. This outcome mainly arises because nuclear power generation is less expensive than generation by other energy sources, resulting in overall welfare gains even if considering the negative impacts from nuclear accident risks.

D. *Sensitivity Analysis*

A sensitivity analysis is performed while changing major parameter values. Table 4 summarizes the variations of the parameters and the resulting welfare effects. To be specific, the analysis deals with changes in the discount rate, the length of the second stage, the level of demand elasticity, the R&D effect, the learning effect, and the appropriability rate, while also removing exogenous demand growth, second-stage efficiency improvements, and any increase in the second-stage GHG social costs, with 15 cases analyzed in total. It should be noted that the relative welfare rank among the six scenarios remains the same throughout the analysis. Specifically, from the highest welfare scenario, the order is as follows: optimal RPS, baseline RPS, renewable generation subsidy, nuclear reduction, past RPS, and repeal of RPS, where the magnitude of the welfare effect continues to vary.

There are several notable features. If we increase the discount rate from 7% to 9%, the present value of future benefits and costs become smaller; thus, the overall welfare effect gap between the scenarios is reduced compared to that in the baseline. On the other hand, if the discount rate is reduced to 5%, the relative gap becomes larger than in the baseline results. Note that reducing or increasing the number of years in the second stage has the same effect as raising or lowering the discount rate applied to the second stage, thereby yielding similar results compared to an adjustment of the discount rate.

Lowering the demand elasticity reduces the magnitude of the overall welfare effects for all scenarios, while increasing it results in larger welfare changes, where for the latter demand responses are more significant. The changes in welfare by varying the R&D effect, learning effect, and appropriability are lower compared to the former variations. The elimination of the natural demand growth in the second stage compared to the first lowers welfare for all scenarios, and removing the improvement in the renewable capacity factor also results in lower welfare. When assuming that the discounted second-stage GHG social costs are maintained at the

TABLE 4—SENSITIVITY ANALYSIS

	No RPS	Past RPS	Baseline RPS	Optimal RPS	Subsidy	Nuclear
Baseline	0	25,790	44,737	49,005	42,165	37,623
High discount rate ($r = 0.9$)	0	19,270	34,427	37,815	32,155	28,692
Low discount rate ($r = 0.5$)	0	33,823	57,421	62,217	54,501	48,623
Short 2nd stage ($\tilde{n}_2 = 15,\ n_2 = 9.1$)	0	20,985	37,197	40,452	34,859	31,090
Long 2nd stage ($\tilde{n}_2 = 25,\ n_2 = 10.6$)	0	29,313	50,267	54,508	47,524	42,415
Low demand elasticity ($\eta = 0$)	0	24,534	43,463	47,016	41,788	36,324
High demand elasticity ($\eta = -0.5$)	0	27,073	46,050	50,135	42,552	38,961
Low R&D effect ($s_{1,s} = s_{1,w} = 0.25$)	0	25,787	44,741	48,873	42,170	37,627
High R&D effect ($s_{1,s} = s_{1,w} = 0.35$)	0	25,791	44,734	48,548	42,161	37,620
Low learning effect ($s_{2,s} = s_{2,w} = 0.25$)	0	24,247	42,532	46,144	39,426	35,418
High learning effect ($s_{2,s} = s_{2,w} = 0.35$)	0	27,221	46,832	50,863	44,777	39,719
Low appropriability ($\rho = 0.4$)	0	25,800	44,967	48,899	42,454	37,853
High appropriability ($\rho = 0.6$)	0	25,783	44,586	48,328	41,975	37,472
No demand increase ($N_1 = N_2$)	0	21,468	38,718	42,103	36,240	31,597
No factor increase ($\beta_{s2} = 0.13,\ \beta_{w2} = 0.18$)	0	19,608	35,022	38,529	29,944	27,906
Low GHG social costs ($\varepsilon_{c2,GHG} = 92{,}032$, $\varepsilon_{l2,GHG} = 40{,}548$)	0	16,282	30,782	34,039	28,474	24,562

Note: 1) Welfare effects are changes relative to the no RPS scenario. 2) In the case of 'low GHG social costs', it is assumed that the second-stage discounted GHG costs of coal and gas are identical to those in the first stage.

level of the first stage, the magnitude of the welfare effects is lower than in the baseline for all scenarios.

VI. Concluding Remarks

This paper analyzes the market and welfare effects of South Korea's policy goal, RE3020—raising the proportion of renewable energy generation to more than 20% by 2030—together with other policy options. To carry out counterfactual simulations for alternative scenarios, we propose a model that reflects the major characteristics of the domestic electricity market. In particular, the model incorporates the energy settlement system in the wholesale electricity market and REC transactions under the RPS, as well as R&D investment and learning effects that may affect the development of renewable energy technologies. The model consists of a first stage in which knowledge related to renewable energy technology development accumulates and a second stage in which technology development is realized due to accumulated knowledge. As a reference scenario for the simulations, the first and second stage in the model are parameterized to replicate the current situation (based on raw data in 2016) and the future that reflects the implementation of RE3020 (based on projected values over 2017-2031), respectively. Subsequently, we simulate alternative scenarios to investigate the relative performance outcomes among them.

The results show that the current and planned RPS under RE3020, which is set as a baseline, increases social welfare compared to the weakened RPS before RE3020, and compared to the absence of the RPS. Although introducing or reinforcing the RPS causes an increase in retail electricity prices, hurting consumers, it crowd out nonrenewable energy generation owing to the merit order effect, thereby resulting in a significant reduction of externality costs. As long as it is feasible in terms of the physical area, it is found that welfare can be increased further by strengthening the RPS beyond what RE3020 stipulates. As an alternative to the RPS, a simple production subsidy for renewable energy is examined, and it turns out that welfare is lower than the RPS when the same level of renewable energy generation is achieved. This occurs mainly because the government must incur a major financial burden. Finally, restraining nuclear power generation from the baseline is found to lower welfare compared to the baseline because an increase in externality costs from expanded coal and gas power generation overwhelms the decrease in nuclear accident costs.

The Paris Agreement was signed at the 21st Conference of the Parties of the UNFCCC in 2015 on the basis of a global consensus on countering climate change and improving energy self-sufficiency. Since then, energy conservation has been promoted worldwide by expanding renewable energy, improving production efficiency, and saving energy. As a result of the Paris Agreement, South Korea is expected to achieve a GHG emission reduction of 37% relative to 'business as usual' by 2030, where one of the measures proposed is the use of the RPS in the power sector. In this context, the analysis in this study attempts to present a measure of the impact of South Korea's major renewable energy policy, the RPS.

However, there are several caveats to consider when interpreting the results in this paper. When the generation share of variable renewable energy sources exceeds a certain level, the power grid system may undergo daily weather fluctuations when attempting to maintain a stable supply. To illustrate this, in locations where a significant amount of solar power capacity has been installed, the amount of power that must be generated from sources other than solar energy increases sharply around sunset. Then, the grid system would require additional costs by preparing back-up generation and/or large-scale energy storage systems, factors which are not taken into account in this paper. Depending on the levels of the related costs and who pays such a burden, the results can be affected. In addition, the analysis is based on the assumption that all electricity market policies except for those we are tackling will remain identical to those in the current situation. Finally, this paper does not consider possible electricity demand management scenarios or incentives for residential self-generation.

APPENDIX

A. *Derivation of Equation (8)*

Applying Fischer and Newell's (2007) framework, we derive ρ in equation (8) from individual firms' first-order conditions, given that some innovations of a particular firm may be appropriable. For $j = s, w$, suppose that there are N_j identical firms, and let the subscript k denote an individual firm. Assume that the cumulative knowledge is completely disseminated, yielding $H_{j2} = H_{j1} + \sum_{k=1}^{N_j} h_k$ and $L_{j2} = L_{j1} + \sum_{k=1}^{N_j} y_k$. A share of ρ_j for R&D knowledge cannot be imitated and can be used by paying a license fee. We then have the following individual firm k's profit,

$$\text{(A1)} \qquad \begin{aligned} \Pi_{jk}^{R} = & n_1 \left\{ \left(p_{j1} + B_1 \right) y_{jk1} - G_{jk}\left(Z_{jk1}, S_{j1} \right) - \left(1 - \sigma_j \right) R_{jk}\left(h_j \right) \right\} \\ & + \delta n_2 \left\{ \left(p_{j2} + B_2 \right) y_{jk2} - G_{jk}\left(Z_{jk2}, S_{j2} \right) + T_{jk}\left(h_{jk1} \right) \right\} \end{aligned},$$

where $T_{jk}\left(h_{jk1} \right) = \sum_{\ell \neq k} t_{jk\ell}\left(h_{jk1} \right) - \sum_{\ell \neq k} t_{j\ell k}\left(h_{j\ell 1} \right)$. Note that $T_{jk}\left(h_{jk1} \right)$ denotes loyalty income from other firms, netting payments to other firms. To be specific, $t_{jk\ell}\left(h_{jk1} \right) = G_{j\ell}\left(S_j\left(H_{j2} - \hat{\rho}_j h_{jk1}, L_{j2} \right), Z_{j\ell 2} \right) - G_{j\ell}\left(S_j\left(H_{j2}, L_{j2} \right), Z_{j\ell 2} \right)$, meaning that the (maximum) loyalty that a firm k can collect from a firm ℓ is the amount of cost savings that firm ℓ can achieve by accessing firm k's knowledge that cannot be imitated.

When all licenses are fully accessed under a symmetric equilibrium, the marginal loyalty gain from a unit of innovation is as follows:

$$\text{(A2)} \quad \frac{\partial T_{jk}\left(h_{jk1} \right)}{\partial h_{jk1}} = \sum_{\ell \neq k} \left\{ \left(1 - \hat{\rho}_j \right) G_{S,j\ell 2} S_{H,j2} - G_{S,j\ell 2} S_{H,j2} \right\} \approx -\hat{\rho}_j \left(N_j - 1 \right) G_{S,jk2} S_{H,j2} > 0 \, .$$

If a firm k increases its R&D-based knowledge by one more unit, there will be more room for second-stage cost reductions (whether through imitation or licensing) for other firms. Here, due to ρ_j, the marginal cost reduction by using full licenses is greater than that by simply imitating. Hence, when firm k generates one more unit of innovation, other firms consider paying royalty more beneficial compared to imitating. Meanwhile, the choice of firm k to use other firms' licenses is not affected by its innovation choice. Therefore, an increase in R&D knowledge increases loyalty income, as expressed by equation (A2). Considering this feature, we have the following first-order condition for an individual firm's innovation choice.

$$\text{(A3)} \qquad \left(1-\sigma_j\right) R_{h,k}\left(h_{jk1}\right) - \delta n_2 \left\{1+\left(N_j-1\right)\hat{\rho}_j\right\} G_{S,jk2} S_{H,j2} = 0 .$$

Royalty payments refer to a simple transfer between firms: $\sum_k T_{jk}\left(h_{jk1}\right)=0$. Under symmetric equilibrium by energy sources, we have $y_{jt}=\sum_k y_{jkt}$, $Z_{jt}=\sum_k Z_{jkt}$, $h_{jt}=\sum_k h_{jkt}$, and $G_j\left(Z_{jt},S_{jt}\right)=\sum_k G_{jk}\left(Z_{jt},S_{jt}\right)$. Because accumulative knowledge is shared by all firms, we have $\partial G(Z_{jt},S_{jt})/\partial S_{jt} = N_j \partial G_{jk}(Z_{jkt},S_{jt})/\partial S_{jt}$. Moreover, total R&D spending is the sum of individual firms' R&D spending; i.e., $R_j(h_{j1})=\sum_k R_{jk}(h_{jk1})$. Thus, $R_{h,j}(h_{j1}) = R_{h,jk}(h_{jk1})$.

Based on the conditions above, we have $\Pi_j^R = \sum_k \Pi_{jk}^R$ first and then obtain the following by aggregating equation (A3).

$$\text{(A3)} \qquad \left(1-\sigma_j\right) R_h\left(h_{j1}\right) - \delta \rho_j n_2 G_{S,j2} S_{H,j2} = 0,$$

Here, $\rho_j = \left\{1+\hat{\rho}_j\left(N_j-1\right)\right\}/N_j$, and as N_j becomes larger, ρ_j approaches $\hat{\rho}_j$. For simplicity, we can assume $\rho_s=\rho_w=\rho$, which makes equation (A3) equal to equation (8).

B. *Tables*

TABLE A1—RAW AND PROCESSED DATA

Variable	Symbol	Value	Source/explanation
1st stage nuclear capacity (MW)	K_{n1}^{BL}	23,116	
1st stage coal capacity (MW)	K_{c1}^{BL}	32,035	
1st stage gas capacity (MW)	K_{l}^{BL}	32,624	KEPCO (2017)
1st stage other nonrenewable capacity (MW)	K_X	8,716	
1st stage solar capacity (MW)	Z_{s1}^{BL}	3,716	

TABLE A1—RAW AND PROCESSED DATA (CONT'D)

Variable	Symbol	Value	Source/explanation
1st stage wind capacity (MW)	Z_{w1}^{BL}	1,015	KEPCO (2017)
1st stage nuclear generation (GWh) 1)	x_{n1}^{BL}	153,409	
1st stage coal generation (GWh) 1)	x_{c1}^{BL}	204,630	
1st stage gas generation (GWh) 1)	x_{l1}^{BL}	118,609	
1st stage solar generation (GWh)	y_{s1}^{BL}	4,505	
1st stage wind generation (GWh)	y_{w1}^{BL}	1,673	
1st/2nd stage other nonrenewable generation (GWh)	X_1 , X_2	16,528	
1st stage other renewable generation (GWh)	Y_1	19,605	
2nd stage other renewable generation (GWh)	Y_2	36,886	MOTIE (2017)
System marginal price (₩/MWh)	p_1^{*BL}	77,060	KPX (2017)
Retail electricity price (₩/MWh)	P_1^{BL}	110,520	Calculated using equation (12)
REC price (₩/REC)	B_1^{BL}	98,807	KPX internal data
R&D expenditure for solar (₩K)	R_{s1}^{BL}	87,073,406	KETEP internal data
R&D expenditure for wind (₩K)	R_{w1}^{BL}	70,143,154	
1st stage R&D knowledge stock for solar generation	H_{s1}^{BL}	1.00	Assumption
1st stage R&D knowledge stock for wind generation	H_{w1}^{BL}	0.69	KETEP internal data
2nd stage learning knowledge stock for solar generation	L_{s1}^{BL}	14,347,443	KEPCO (2017)
2nd stage learning knowledge stock for wind generation	L_{w1}^{BL}	9,806,946	
1st stage new knowledge for solar generation	h_{s1}^{BL}	0.0064	Calculated using equation (8)
1st stage new knowledge for wind generation	h_{w1}^{BL}	0.0163	
2nd stage solar capacity (MW)	Z_{s2}^{BL}	26,052	
2nd stage wind capacity (MW)	Z_{w2}^{BL}	25,621	

Note: The superscript *BL* indicates values replicated from the baseline scenario. Other renewable generation includes generation from some nonrenewable waste and new energy sources which are projected to be fairly stable according to MOTIE (2017).

TABLE A2—PARAMETERS FOR THE ELECTRICITY MARKET

Parameter	Symbol	Value	Source/explanation
Nuclear capacity payment (₩K/MW/year)	ϕ_n	69,851	KPX internal data
Coal capacity payment (₩K/MW/year)	ϕ_c	61,742	
Gas capacity payment (₩K/MW/year)	ϕ_l	72,941	
Other nonrenewable capacity payment (₩K/MW/year)	ϕ_X	44,299	KPX (2017)
Adjustment coefficient for nuclear generation	λ_n	0.78	KPX internal data
Adjustment coefficient for coal generation	λ_c	0.72	
Adjustment coefficient for gas generation	λ_l	1.00	
Annualized nuclear construction costs (₩K/MW/year)	ζ_n	84,836	KPX (2018)
Annualized coal construction costs (₩K/MW/year)	ζ_c	53,829	
Annualized gas construction costs (₩K/MW/year)	ζ_l	35,316	
Annualized solar construction costs (₩K/MW/year)	ξ_s	110,000	
Annualized wind construction costs (₩K/MW/year)	ξ_w	191,300	
Various policy costs for nuclear generation(₩/MWh)	τ_n	1,056.0	
Various policy costs for coal generation (₩/MWh)	τ_c	314.5	
Various policy costs for gas generation (₩/MWh)	τ_l	305.5	
Internal load rate for nuclear generation (%)	w_n	5.3	
Internal load rate for coal generation (%)	w_c	4.6	
Internal load rate for gas generation (%)	w_l	1.8	
Internal load rate for other nonrenewable (%)	w_X	3.7	EPSIS (http://epsis.kpx.or.kr/)
1st stage capacity factor for solar generation	β_{s1}	0.138	$\beta_{s1} = y_{s1}^{BL} / (8760 \times Z_{s1}^{BL})$
1st stage capacity factor for wind generation	β_{w1}	0.182	$\beta_{w1} = y_{w1}^{BL} / (8760 \times Z_{w1}^{BL})$
2nd stage capacity factor for solar generation	β_{s2}	0.140	MOTIE (2017)
2nd stage capacity factor for wind generation	β_{w2}	0.210	
Retail sales costs (₩/MWh)	Δ	19,355	KEPCO cost data
Retail sales tax	ψ	0.037	Electric Utility Act and Decree
Public R&D expenditure ratio for solar generation	σ_s	0.71	KETEP internal data
Public R&D expenditure ratio for wind generation	σ_w	0.61	
Demand elasticity	η	-0.30	Assumption
R&D appropriability rate	ρ	0.50	

Note: Charges under the Act on the Compensation and Support for Areas Adjacent to Transmission and Substation Facilities and the Act on Assistance to Electric Power Plants Neighboring Areas.

TABLE A3—PARAMETERS IN FUNCTIONS

Parameter	Symbol	Value	Source/explanation
No-load costs for nuclear generation (₩)	$c_{0,n}$	9.07×10^{12}	Calculated using equation (4)
No-load costs for coal generation (₩)	$c_{0,c}$	1.44×10^{13}	
No-load costs for gas generation (₩)	$c_{0,l}$	1.03×10^{13}	
Intercept of nuclear electricity supply (₩/MWh)	$c_{1,n}$	5,507	KPX internal data
Intercept of coal electricity supply (₩/MWh)	$c_{1,c}$	48,081	
Intercept of gas electricity supply (₩/MWh)	$c_{1,l}$	77,060	Calculated using equation (2)
Slope for nuclear electricity supply (₩/MWh^2)	$c_{2,n}$	1.23×10^{-6}	KPX internal data
Slope for coal electricity supply (₩/MWh^2)	$c_{2,c}$	9.83×10^{-6}	
Slope for gas electricity supply (₩/MWh^2)	$c_{2,l}$	1.30×10^{-6}	
No-load costs for solar electricity (₩)	$g_{0,s}$	4.28×10^{11}	Calculated using equation (9)
No-load costs for wind electricity (₩)	$g_{0,w}$	1.06×10^{11}	Calculated using equation (10)
Solar R&D expenditure parameter	$\gamma_{1,s}$	2.03×10^{13}	$\gamma_{1,s} = R_s^{BL} / \{(h_s^{BL})^{\gamma_{2,s}}\}$
Wind R&D expenditure parameter	$\gamma_{1,w}$	2.35×10^{12}	$\gamma_{1,w} = R_w^{BL} / \{(h_w^{BL})^{\gamma_{2,w}}\}$
Solar R&D elasticity	$\gamma_{2,s}$	1.20	Fischer, Preonas, and Newell (2017)
Wind R&D elasticity	$\gamma_{2,w}$	1.20	
Solar R&D parameter	$s_{1,s}$	0.30	Assumption
Wind R&D parameter	$s_{1,w}$	0.30	
Solar learning parameter	$s_{2,s}$	0.30	
Wind learning parameter	$s_{2,w}$	0.30	
1st stage demand parameter	N_1	1.64×10^{13}	$N_1 = D^{BL} / \{(P^{BL})^{\eta}\}$
2nd stage demand parameter	N_2	1.85×10^{13}	$N_2 = N_1 \times 1.125$

TABLE A4—EXTERNALITY COSTS

Parameter	Symbol	Value	Source/explanation
1st stage GHG cost of coal generation (₩/MWh)	$\varepsilon_{c1,GHG}$	35,680	Yi (2018)
1st stage GHG cost of gas generation (₩/MWh)	$\varepsilon_{l1,GHG}$	15,720	
2nd stage GHG cost of coal generation (₩/MWh)	$\varepsilon_{c2,GHG}$	123,148	$\varepsilon_{c,GHG} \times 1.5\tilde{n}_2 / (\delta n_2)$
2nd stage GHG cost of gas generation (₩/MWh)	$\varepsilon_{l2,GHG}$	54,257	$\varepsilon_{l,GHG} \times 1.5\tilde{n}_2 / (\delta n_2)$
NO_X cost of coal generation (₩/MWh)	ε_{c,NO_X}	16,590	Yi (2018)
NO_X cost of gas generation (₩/MWh)	ε_{l,NO_X}	4,630	
SO_X cost of coal generation (₩/MWh)	ε_{c,SO_X}	15,740	
SO_X cost of gas (₩/MWh)	ε_{l,SO_X}	310	
$PM_{2.5}$ cost of coal generation (₩/MWh)	$\varepsilon_{c,PM_{2.5}}$	800	
$PM_{2.5}$ cost of gas generation (₩/MWh)	$\varepsilon_{l,PM_{2.5}}$	320	
Nuclear accident risk cost (₩K /MW)	$\varepsilon_{n,AC}$	67,644	KPX (2018)

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