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The Impact of Nuclear Power Generation on Wholesale Electricity Market Price†

Sukwan Jung*, Nara Lim**, and DooHwan Won***

ABSTRACT : Nuclear power generation is a major power source which accounts for more than 30% of domestic electricity generation. Electricity market needs to secure stability of base load. This study aimed at analyzing relationships between nuclear power generation and wholesale electricity price (SMP: System Marginal Price) in Korea. For this we conducted ARDL(Autoregressive Distributed Lag) approach and Granger causality test. We found that in terms of total effects nuclear power supply had a positive relationship with SMP while nuclear capacity had a negative relationship with SMP. There is a unidirectional Granger causality from nuclear power supply to SMP while the reverse was not. Nuclear power is closely related to SMP and provides useful information for decision making.

Keywords : Nuclear Power Generation, Electricity Price, ARDL

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* Research Professor, Pusan National University, Department of Economics, 1st author(e-mail: sukwan@pusan.ac.kr)
** Graduate Student, Pusan National University, Department of Economics, 2nd author(e-mail: nrlim1125.pnu@gmail.com)
*** Associate Professor, Pusan National University, Department of Economics, Corresponding Author (e-mail: doohwan@pusan.ac.kr)

원자력발전이 전력가격에 미치는 영향 분석

정수관* · 임나라** · 원두환***

요 약 : 국내 발전량의 30% 이상을 차지하는 원자력발전은 기저부하의 안정성 확보 측면에서 전력산업에서 중요한 위치를 차지하고 있다. 본 연구에서는 원자력 발전과 도매전력가격의 관계를 분석하고자한다. 이를 위해 자기회귀시차분포 (ARDL: Autoregressive Distributed Lag Model) 모형과 Granger 인과성을 통해 원자력발전과 전력도매가격 (SMP: System Marginal Price)의 관계를 살펴보았다. 분석결과 단기적 효과는 다르게 나타날 수 있지만 총 효과 (장기효과)로 볼 때 원자력공급량과 SMP는 양(+)의 관계로 나타났다. 일반적인 장기균형식에서 원자력발전용량은 SMP와 양 (+)의 관계인 반면에 시차변수를 포함한 ARDL 모형의 경우 발전용량은 SMP와 음 (−)의 관계로 이론에 부합하는 것으로 나타났다. 인과성 검정결과 원자력발전 공급량은 SMP에 일방향의 Granger 인과성이 있으나 그 역의 관계는 성립하지 않는 것으로 나타났다. 시계열분석을 통하여 원자력발전은 SMP와 밀접한 연관성을 갖고 있음을 발견할 수 있었다.

주제어 : 원자력발전, 전력가격, ARDL모형

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* 부산대학교 경제학부 연구교수, 제1저자(e-mail: sukwan@pusan.ac.kr)

** 부산대학교 경제학부 대학원생, 제2저자(e-mail: nrlim1125.pnu@gmail.com)

*** 부산대학교 경제학부 부교수, 교신저자(e-mail: doohwan@pusan.ac.kr)

I. Introduction

Nuclear power plants have a finite life, so decommissioning an aging facility needs when their operation is economically or technically infeasible. There is controversy about another extension of Kori-1, the oldest nuclear reactor. The nuclear reactor in Korea started commercial operation in 1978, and its initial designed lifespan was supposed to expire in 2007. However, its service life was extended for ten years, and it has operated until now. Korean government has not yet decided whether to decommission the reactor or extend its lifespan again. The shortage of electricity supply and concerns on aging reactor have increased energy price since the blackout in recent years. Nuclear power generation is a major power source which accounts for more than 30% of the domestic electricity generation and secures stability of base load.

Given this situation, this paper examines dynamic relationships between electricity prices and nuclear power generation (nuclear supply and nuclear capacity) with time series data. There is no study to analyze the relationships among electricity price and nuclear power generation in terms of supply base in South Korea even though a little of literature analyzed the effect of decommission on electricity price abroad.

A range of studies analyzes price movement and its volatility (Kim et al., 2005; Ahn et al., 2014; Park et al., 2014). Kim et al. (2005) implemented an autoregressive moving average (ARMA) model for forecasting purpose, Ahn et al. (2014) examined price volatility using the autoregressive conditional heteroskedasticity (ARCH), generalized autoregressive conditional heteroskedasticity (GARCH), and Park et al. (2014) conducted a vector autoregression (VAR) model for Granger causality analysis. Unlike empirical studies above, Kim and Wang (2003), Kim and Sonn (2008) conducted research based on the economic theories. Kim and Wang (2003) analyzed how equilibrium price forms by market participants after adopting competition. The result showed that the more private generation companies are made, the lower the price would get. Kim and Sonn (2008) examined determinants of capacity price and settlement price according to the change of institution. They found that fuel price affected capacity price, and the time of the conferences held by the Cost Evaluation Committee affects the settlement price of base load generation.

The impact of nuclear power on electricity price is analyzed when the nuclear power plants decommission based on dynamics or general equilibrium theories (Andersson and Hådén, 1997; Traber and Kemfert, 2012; Glomsrød et al., 2013; Woo et al., 2014). These studies argue that its decommission increases electricity price given its responsibility of the base load supply. Its decommission reduces the overall electricity supply and increases the price if renewable energy such as wind and waterfall does not sufficiently replace nuclear power generation. Even though much research analyzes the wholesale electricity price, system marginal price (SMP), empirical studies based on economic models are rare, especially the study on the impact of nuclear power on the SMP.

This study examines the impact of the nuclear power generation (nuclear supply and nuclear capacity) on SMP. For this we conducted an autoregressive distributed lag (ARDL) approach and Granger causality analysis. While the traditional Engle and Granger (1987) approach is the most popular method in application of cointegration, this method has some drawbacks. This technique confronts bias with small sample, and it is not practical when the variables are ordered of different or ambiguous integration. The results are also sensitive to choice of variables.[1] The ARDL approach avoids these problems through using lagged dependent variable and current and lagged explanatory variables. While the ARDL approach examines the dynamic effect of nuclear power generation on SMP based on a single equation, Granger causality analyzes temporal ordering by testing whether lagged values of nuclear power are correlated with current values of SMP in a multivariate setting based on a VAR model. This Granger causal analysis may complement the ARDL approach, even though direct comparisons between them are difficult because of different methods. The result showed that the nuclear power

1) Short term coefficient of OLS estimate has consistency, and long term coefficient of ARDL estimate has super-consistency (Ozturk and Acaravci, 2010)

generation (nuclear electricity supply and nuclear capacity) had significant impact on SMP, and we found that there was a unidirectional causality from nuclear power supply to SMP.

This study differs from previous research in two points. First, it is the first case that analyzed the impact of nuclear power on SMP in Korea. Second, for this we integrated the ARDL approach based on a single equation with Granger causality based on a VAR model. In addition, we strictly evaluated accuracy of forecast. Long-term forecast is of importance for planning or determining the future sites or fuel sources of power plants. However, wholesale electricity market created in 2001 does not have enough data for long-term forecast. Thus, this study focused on short-term or mid-term (a few months ahead) forecasts in terms of model accuracy which contributes to risk management.

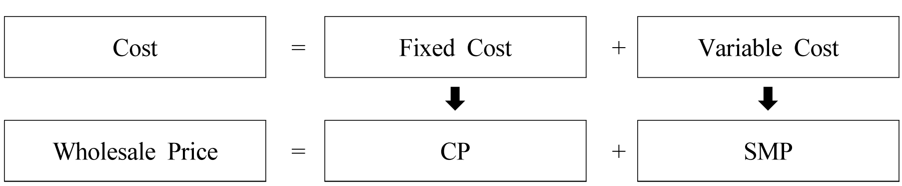
II. The Current State of Wholesale Electricity Price and Electricity Market

The Korean government introduced restructuring in electricity industry for improving efficiency and competitiveness: (i) competition in generation (until 2002), (ii) wholesale competition (2003-2008), and (iii) retail competition (after 2008). In the process wholesale electricity market was established, and competition in generation was incorporated. Competition in generation remains after public opposition stop the restructuring plan. The current wholesale electricity market has the following characteristics. First, six public generators and multiple small independent power producers (IPPs) supply the electricity and KEPCO (Korea Electric Power Corporation) demands it exclusively. In spite of increasing participation of private company, public generators maintain their share (85%) in terms of quantity and capacity of power generation. Secondly, the market is cost-based pool (CBP) where the market price is decided based on the cost. Unlike usual private goods, generating costs vary by the methods. For base load generator using nuclear power and coal for fuel fixed cost is high while variable cost is low. The other generators using compounds, LNG, heavy oil for fuel have low fixed cost bus high variable cost. The one with the highest variable cost of power sources that satisfies demand determines electricity price. Third, participation in the market is mandatory, and the settlement price of a generator owned by public power company is regulated.[2] The price was categorized in base load generation price and general price at the beginning, but it is unified afterwards. The price is still regulated, however, by applying settlement adjustment coefficient (Electricity Market Surveillance Committee, 2014).

The electricity price is basically composed of SMP on generation quantity and capacity price (CP) compensating fixed cost of the facility. CP is for collecting fixed cost of the power facility which needs large initial investment. Regardless of whether actually generated or not, CP is paid according to hourly supply capacity of bidding generator. The SMP is a concept of marginal cost on generated quantity.

<Figure 1> shows price system in the electricity market. Nuclear power, coal, heavy oil and LNG are put in to produce electricity in the order of cost, among them the last generator is considered marginal price setter and its cost is determined as the hourly SMP. LNG decides the SMP frequently while nuclear power hardly does.

〈Figure 1〉 Electricity price system

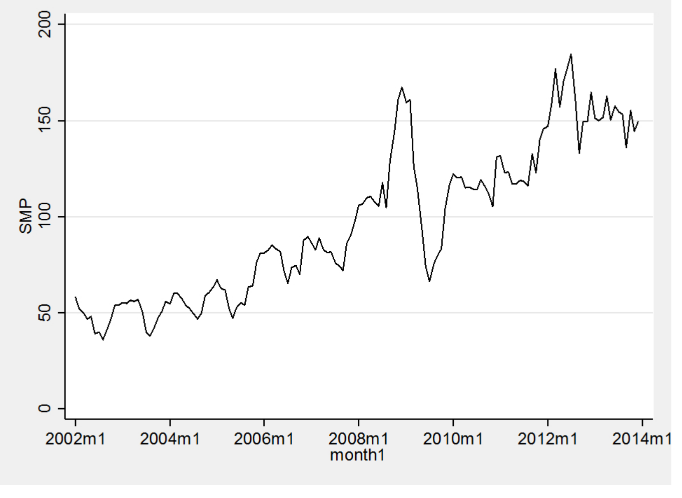


Source: Korea Power Exchange (www.kpx.or.kr)

2) All traders should take part in the electricity market but there is an exception. For example, a provider who signed a private contract with KEPCO is allowed to supply electricity to distributor outside of the market.

<Figure 2> shows that the transition of monthly average of SMP. Throughout the whole data (2002.1~2013.12) SMP goes up and down and shows an upward trend in the long-term. Right before the financial crisis SMP skyrocketed, but after the crisis it dropped drastically.

〈Figure 2〉 Monthly average of SMP transition



III. Research Methods and Data

To examine the nuclear power generation and electricity price, the basic long-run model is applied which has the following form including SMP, electricity supply, nuclear capacity, and temperature (see Carlton, and Perloff, 1994).

$$\ln SMP_t = \beta_0 + \beta_1 \ln Q_t + \beta_2 \ln NC_t + \beta_3 TEMP_t + \beta_{4m} D_{mt} + \epsilon_t \quad (1)$$

where SMP_t is system marginal price of electricity, Q_t is electricity supply, NC_t is nuclear power capacity, $TEMP_t$ is average temperature. All variables excluding $TEMP_t$ are taking logarithm. $TEMP_t$ is employed because zero values of $TEMP_t$ are lost with taking logarithm. $D_{m\,t}$ is monthly dummy which adjusts for seasonality. Model 1 is a long-run model without monthly dummy while model 2 is a model with monthly dummy. The long-run parameters of the basic models are compared with those of ARDL models.

The coefficient of electricity supply would be positive (+) because the higher the price the higher the quantity supplied. Producers supply more at a higher price which increases revenue. The coefficient of nuclear power capacity is negatively expected because when generation capacity increases (shift of supply curve), the price decreases. Monthly average temperature ($TEMP_t$) adjusts for temperature change. It would be determined by the relative size of the effect of price rise/fall according to supply increment/reduction for air cooling/heating when temperature increases. Monthly dummy variables are used for controlling seasonality. The basic long-run models in equation (1) are often estimated using conventional Engle and Granger (1987), Johansen (1988) cointegration methods. However, these cointegration approaches are invalid when variables are integrated of different orders. Therefore, this study employs the ARDL bounds test approach because the involved variables are integrated of the different orders or uncertain orders.

1. ARDL bounds test

This study employs the ARDL bounds test approach recently developed by Pesaran and Shin (2001) to ascertain the presence of cointegration among the variables. The ARDL bounds test has certain advantages over the standard cointegration approaches. First, the ARDL bounds test allows the involved variables to be integrated of different orders i.e., I (1) and/or I (0). Second, it is appropriate for small samples while the Johansen approach requires large samples. Third, the inclusion of lagged variables may mitigate endogeneity. However, a unit root test should identify order of integration on variables since the ARDL bounds test fails to provide robust results in the presence of I (2) variables.

The ARDL bounds test approach ascertains the presence of cointegration to estimate the following n-order equation:

$$d\ln SMP_t = a_0 + \sum_{i=1}^{n} a_{1i} d\ln SMP_{t-i} + \sum_{i=1}^{n} a_{2i} d\ln Q_{t-i} + \sum_{i=1}^{n} a_{3i} d\ln NC_{t-i} + \sum_{i=1}^{n} a_{4i} TEMP_{t-i} + a_5 \ln SMP_{t-1} + a_6 \ln Q_{t-1} + a_7 \ln NC_{t-1} + a_8 TEMP_{t-1} + \epsilon_t \quad (2)$$

where ϵ_t is the white noise error term, d is the first difference operator. The use of AIC (Akaike Information Criterion) selects an appropriate maximum of lag lengths for the ARDL bounds test similar to the lag selection procedure in a VAR model. The bounds test procedure for the absence of any long-run relationship among variables excludes the lagged level variables in equation (3). The method tests the joint hypothesis that all parameters of the lagged level variables are equal to zero ($H_0 : a_5 = a_6 = a_7 = a_8 = 0$). Rejection of the null hypothesis indicates the presence of cointegration. The standard F statistics obtained by implementing the Wald test are compared with critical values provided by Pesaran et al. (2001) since these statistics have non-standard distribution. If the F-statistic falls outside the upper bound of the critical values, there exists cointegration. If the F-statistic falls is less than the lower bound of the critical values, this indicates no cointegration. If the statistic lies between the upper bound and the lower bound, the result is inconclusive.

2. ARDL models

Once there exists cointegration, we can conduct OLS to estimate the long-run parameters in equation (1). However, the long-run parameters may be sensitive to sample size and endogeneity. To reduce thess problems, the following ARDL (p_1, q_2, q_3, q_4) models are used.

$$\ln SMP_t = b_0 + \sum_{i=1}^{p_1} b_{1i} \ln SMP_{t-i} + \sum_{i=0}^{q_2} b_{2i} \ln Q_{t-i} + \sum_{i=0}^{q_3} b_{3i} \ln NC_{t-i} + \sum_{i=0}^{q_4} b_{4i} TEMP_{t-i} + \sum_{m=1}^{11} c_m D_{mt} + \epsilon_t \quad (3)$$

For ARDL models, a maximum of lags are based on AIC, and its lag of each variable is determined through the model specification process. The short-run effects (b_{20}, b_{30}, b_{40}) are then obtained using OLS. The long-run effects (total effects) are calculated using equation (4) by rearranging lagged dependent variables to the left hand side and then dividing both sides with coefficient of dependent variable (Bentzen and Engsted, 2001).

$$\sum_{i=0}^{q_j} b_{ji} / (1 - \sum_{i=1}^{p_1} b_{1i}), \qquad j = 2, 3, 4 \quad (4)$$

Using a delta method can calculate standard errors of the long-run parameters since the long-run parameters are nonlinear functions of the short-run estimates.

Because we are interested in the relationship between nuclear power and SMP, three types of ARDL models are estimated depending on a source of electricity supply: (i) a total of electricity supply (Q) (model 3), (ii) nuclear power supply (NUKE) versus the others (Q_1) (model 4), and (iii) nuclear power supply, thermal power supply (COAL) and the others (Q_2) (model 5).

3. Granger Causality

ARDL approach determines whether variables in a single equation are cointegrated and estimates the dynamic effect. Unlike the single equation approach, Granger (1969) causality test considers all variables endogenous based on a VAR model and checks temporal ordering by testing whether lagged values of one variable are correlated with current values of another variable. Hence, caution is used for interpretation of causality among variables from Granger causality measures (Enders, 2010).

Causal relationships among key variables (SMP, NUKE, Q_1, NC) are investigated by assuming TEMP as exogenous variable as follows.

$$\ln SMP_t = a_0 + \sum_{i=1}^{p} a_{1i} \ln SMP_{t-i} + \sum_{i=1}^{p} a_{2i} \ln NUKE_{t-i} + \sum_{i=1}^{p} a_{3i} \ln Q_1 + \sum_{i=1}^{p} a_{4i} \ln NC + \sum_{i=1}^{p} TEMP_{t-i} + e_{1t} \tag{5-a}$$

$$\ln NUKE_t = b_0 + \sum_{i=1}^{p} b_{1i} \ln NUKE_{t-i} + \sum_{i=1}^{p} b_{2i} \ln SMP_{t-i} + \sum_{i=1}^{p} b_{3i} \ln Q_{1t-i} + \sum_{i=1}^{p} b_{4i} \ln NC + \sum_{i=1}^{p} b_{5i} TEMP_{t-i} + e_{1t} \tag{5-b}$$

$$\ln Q_{1t} = c_0 + \sum_{i=1}^{p} c_{1i} \ln Q_{1t-i} + \sum_{i=1}^{p} c_{2i} \ln NUKE_{t-i} + \sum_{i=1}^{p} c_{3i} \ln SMP_{t-i} + \sum_{i=1}^{p} c_{4i} \ln NC + \sum_{i=1}^{p} c_{5i} TEMP_{t-i} + e_{1t} \tag{5-c}$$

$$\ln NC_{1t} = d_0 + \sum_{i=1}^{p} d_{1i} \ln NC_{1t-i} + \sum_{i=1}^{p} d_{2i} \ln NUKE_{t-i} + \sum_{i=1}^{p} d_{3i} \ln Q_{1t-i} + \sum_{i=1}^{p} d_{4i} \ln NC + \sum_{i=1}^{p} d_{5i} TEMP_{t-i} + e_{1t} \tag{5-d}$$

where $\ln SMP_t$, $\ln NUKE_t$, $\ln Q_{1t}$, $\ln NC_{1t}$ are natural logarithm taking wholesale electricity price (SMP), nuclear power supply (NUKE), the other power supply (Q_1) and nuclear power capacity (NC). The optimal lag was chosen using AIC. Sources of causation can be identified by testing for the parameters on the dependent variables in Equations. For example, the null hypothesis $(H_0 : a_{21} = a_{22} = \cdots = a_{2p} = 0)$ in (5-a) i.e., NUKE does not Granger cause SMP. There exists Granger causality running from NUKE to SMP if the null hypothesis test is rejected. If not, NUKE does not Granger cause SMP. The null hypothesis $(H_0 : b_{21} = b_{22} = \cdots = b_{2p} = 0)$ in (5-b) i.e., SMP does not Granger cause NUKE. There is causality from NUKE to SMP if the null hypothesis is rejected. Similar reasoning can be applied to the other causal relationships.

4. Data

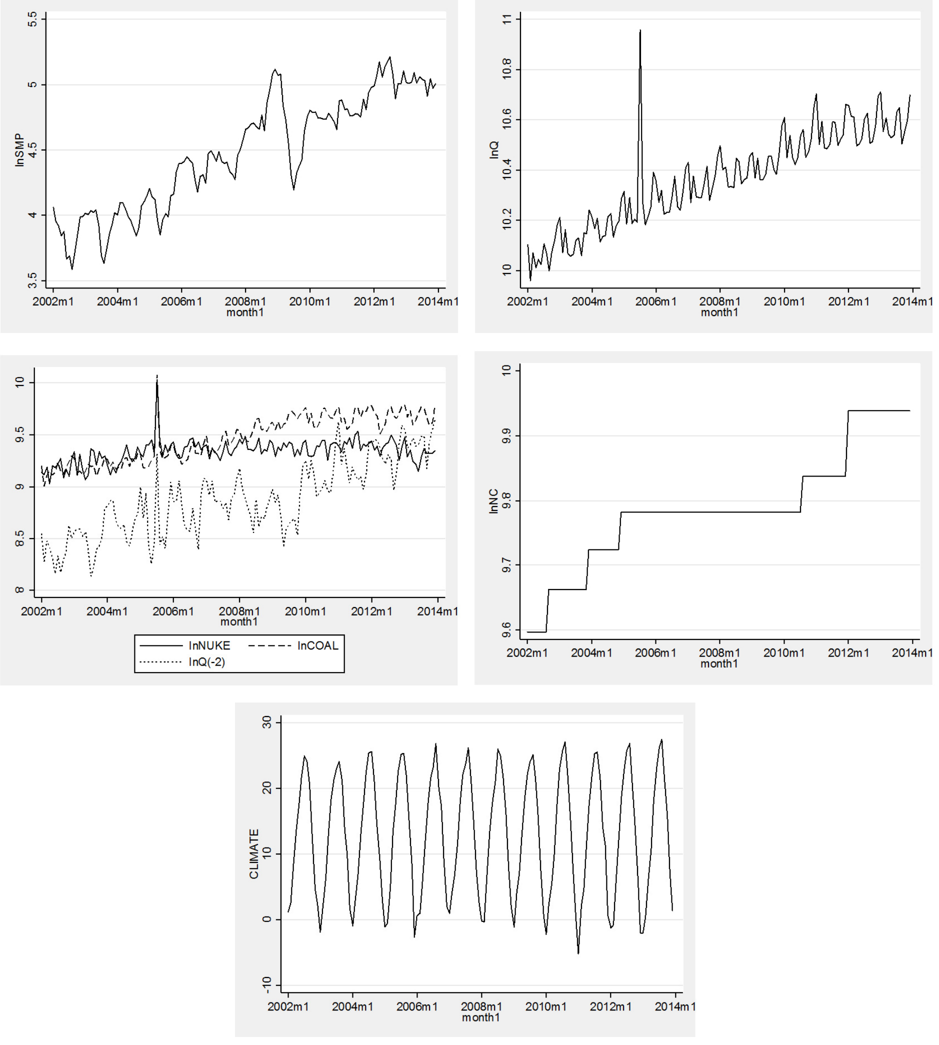
The monthly data (2002.1 to 2013.12) are used: system marginal price (SMP), electricity supply (Q), nuclear power capacity (NC), average temperature ($TEMP$). The generation mix may change the shape of supply curve and then affect the likely on SMP. Because we focus on examining the role of a nuclear power, we classified electricity supply (Q) as (i) nuclear power supply ($NUKE$) and the others ($Q_1 = Q - NUKE$), (ii) nuclear power supply ($NUKE$), thermal power supply ($COAL$), and the others ($Q_2 = Q - NUKE - COAL$). For modeling purposes, all variables except for $TEMP$ were converted to their natural logarithm form, which reduces heteroskedasticity and serial correlation. The summary statistics of data are shown in <Table 1>.

〈Table 1〉 Descriptive statistics of variables

Variables	Description	Mean	Std Dev.	Min	Max
SMP	Wholesale electricity price (₩/kWh)	96.64	40.14	36.08	184.64
$TEMP$	Average temperature	12.95	9.34	−5.20	27.50
Q	Supply quantity (GWh)	32282.43	6222.45	21132.16	57401.20
$NUKE$	Nuclear power supply quantity (GWh)	11428.41	1449.30	8320.17	22648.10
$COAL$	Thermal power supply quantity (GWh)	13217.33	2942.63	8110.94	23676.57
NC	Nuclear power capacity(MW)	144.00	17875.40	1615.758	14715.68
Q_1	Q_1=Q-NUKE (GWh)	20854.02	5404.67	12061.50	34753.20
Q_2	Q_2=Q-NUKE-COAL: Supply (GWh)	7636.70	2853.05	3418.22	15323.96

<Figure 3> shows time-series plots of logs of the variables. There is an upward trend in electricity price ($\ln SMP$) and electricity supply ($\ln Q$) with seasonality. Electricity supply by nuclear power has not changed a lot even though electricity supply by other power sources has increased. $TEMP$ has seasonal cycles without trend. Nuclear power capacity ($\ln NC$) has increased stepwise.

〈Figure 3〉 Trends



IV. Estimation Results

We implemented augmented Dickey-Fuller (ADF) and Phillip-Perron (PP) tests to verify the order of integration because the ARDL bounds test is invalid in the presence of I (2). <Table 2> presents the test results. As seen, the order of integration may be different depending on the test methods and the models with drift/drift and trend. However, we do not find the presence of I (2) variables.

〈Table 2〉 Unit root test

	ADF			
	drift		drift and trend	
	Level	1st difference	Level	1st difference
lnSMP	− 1.763 (3)	− 6.191 (2)***	− 5.295 (3)***	− 6.169 (2)***
lnQ	− 1.474 (4)	− 9.813 (4)***	− 4.993 (4)***	− 9.802 (4)***
lnNUKE	− 3.951 (2)**	− 7.783 (4)***	− 4.320 (2)***	− 7.820 (4)***
lnCOAL	− 1.482 (4)	− 9.998 (4)***	− 3.503 (4)**	− 9.992 (4)***
$\ln Q^{-1}$	− 1.190 (4)	− 9.410 (4)***	− 6.164 (4)***	− 9.378 (4)***
$\ln Q^{-2}$	− 2.161 (2)	− 10.774 (1)***	− 5.493 (2)***	− 10.761 (1)***
lnNC	− 1.383 (1)	− 12.245 (0)***	− 2.387 (1)	− 12.221 (0)***
TEMP	− 16.573 (2)***	− 5.085 (1)***	− 16.510 (2)***	− 5.070 (1)***
	PP			
lnSMP	− 1.404 (3)	− 10.336 (2)***	− 4.255 (3)***	− 10.299 (2)***
lnQ	− 2.854 (4)**	− 24.923 (4)***	− 10.067 (4)***	− 24.837 (4)***
lnNUKE	− 6.976 (2)***	− 24.645 (4)***	− 7.888 (2)***	− 24.702 (4)***
lnCOAL	− 2.385 (4)	− 21.180 (4)***	− 7.909 (4)***	− 21.144 (4)***
$\ln Q^{-1}$	− 2.075 (4)	− 20.660 (4)***	− 9.342 (4)***	− 20.563 (4)***
$\ln Q^{-2}$	− 2.798 (2)*	− 14.651 (1)***	− 6.653 (2)***	− 14.228 (1)***
lnNC	− 1.344 (1)	− 12.245 (0)***	− 2.391 (1)***	− 12.221 (0)***
TEMP	− 4.910 (2)***	− 4.994 (1)***	− 4.890 (2)***	− 4.991 (1)***

Notes: 1) Coefficients are significant in the level of *: $p<0.10$, **: $p<0.05$, ***: $p<0.01$
2) ( ) is optimal time lag determined by AIC

We implement ARLD bounds test to ensure the presence of cointegration. <Table 3> reports the ARDL bound test results for three models. One is to test for cointegration among variables i.e. electricity price (SMP), electricity supply (Q), nuclear capacity (NC) and temperature (TEMP) for models 1, 2 and 3 in Tables 5 and 6. The other two models are divided depending on power sources: (i) nuclear power supply (NUKE) and the others (Q_1) (model 4) and (ii) nuclear power supply (NUKE), thermal power supply (COAL) and the others (Q_2) (model 5). For the ARDL bounds test, an appropriate maximum of the lag length was determined by AIC, which is suitable for a small sample (for selection of maximum lags of each model (see Table 4). The test results regarding the null hypothesis of none cointegration indicate that the F-statistics (3.91, 4.25, 4.94) of all models are greater than the critical values provided by Pesaran et al. (2001) at the 5% significance level. Therefore, we conclude that all models in Tables 5 and 6 have stable relationships among the variables.

〈Table 3〉 ARDL bound test

		F-statistics
$F_{SMP}(\ln SMP \mid \ln Q, \ln NC, TEMP)$: Model 3		4.94**
$F_{SMP}(\ln SMP \mid \ln NUKE, \ln Q_1, \ln NC, TEMP)$: Model 4		3.91**
$F_{SMP}(\ln SMP \mid \ln NUKE, \ln COAL, \ln Q_2, \ln NC, TEMP)$: Model 5		4.25**
Obs, df	Critical values (significance level of 5%)	
	I (0)	I (1)
n=139, k=3	2.79	3.67
n=139, k=4	2.56	3.49
n=139, k=5	2.39	3.38

〈Table 4〉 Selection of lag length for ARDL bounds test

	Lag	LR	AIC	SBIC
Model 3 Test	0		3.1812	3.2652
	1	999.05	−3.7267	−3.3060
	2	206.62	−4.9735	−4.2171
	3	87.11	−5.3671	−4.2745*
	4	64.30*	−5.5979*	−4.1691
Model 4 Test	0		1.6744	1.7795
	1	1088.60	−5.7440	−5.1137
	2	220.41	−6.9612	−5.8056*
	3	104.13	−7.3478	−5.6669
	4	70.39*	−7.4935*	−5.2873
Model 5 test	0		0.6217	0.74787
	1	1259.80	−7.8622	−6.9797
	2	236.30	−9.0357	−7.3968*
	3	112.68	−9.3263	−6.9309
	4	108.62*	−9.5878*	−6.4361

<Table 5> reports estimation results: standard cointegration models (models 1~2) and ARDL models (models 3~5). All models except for model 1 were seasonally adjusted using monthly dummy. Model 4 classified electricity supply (Q_t) as nuclear power supply ($NUKE$) and the others (Q_1) while model 5 divided electricity supply as nuclear power supply ($NUKE$), thermal power supply ($COAL$), and the others (Q_2). The residuals of all models are stationary confirming stable long-run relationships among variables. Newey-West robust standard errors are used for models 1 and 2 to adjust for heteroskedasticity and/or autocorrelation. We do not find any serious problems from ARDL models (models 3, 4 and 5). The results were expected except for the nuclear power capacity ($\ln NC$). The positive signs of the coefficients of $\ln NC$ in models 1 to 3 are against the theory. However, models 4 and 5 show reasonable results. Total effects (long term effects) in period $t-1, t-2, t-3$ and $t-4$ have negative signs, being

consistent with the expectation while short-term effects of each are different since the effects of nuclear power capacity ($\ln NC$) on electricity price take time. It is interesting to note that even for same base load generation, nuclear power supply has significant positive effects on SMP in the long term, while thermal power supply does not.

〈Table 5〉 Estimation results

	Model 1	Model 2	Model 3	Model 4	Model 5
$\ln SMP_{t-1}(b_{11})$			0.872***	0.881***	0.923***
			(0.052)	(0.054)	(0.051)
$\ln Q_t(b_{20})$	0.926***	1.362***	0.257**		
	(0.351)	(0.500)	(0.114)		
$\ln NUKE_t(b_{20NUKE})$				−0.379***	−0.215**
				(0.094)	(0.091)
$\ln NUKE_{t-1}(b_{21NUKE})$				0.307***	0.241***
				(0.090)	(0.064)
$\ln NUKE_{t-2}(b_{22NUKE})$				0.094*	0.098*
				(0.058)	(0.052)
$\ln COAL_t(b_{20COAL})$					−0.009
					(0.086)
$\ln Q_{1t}\,(b_{20}^1)$				0.476***	
				(0.066)	
$\ln Q_{1t-1}\,(b_{21}^1)$				−0.284***	
				(0.076)	
$\ln Q_{2t}(b_{20}^2)$					0.338***
					(0.046)
$\ln Q_{2t-1}\,(b_{21}^2)$					−0.196***
					(0.055)
$\ln NC_t(b_{30})$	2.462***	1.731*	0.273	0.017	−0.048
	(0.651)	(0.899)	(0.345)	(0.223)	(0.242)
$\ln NC_{t-1}(b_{31})$			0.266	−0.024	−0.055
			(0.487)	(0.491)	(0.409)

〈Table 5〉 Estimation results (continuation)

$\ln NC_{t-2}(b_{32})$			0.068	0.614*	0.548*
			(0.408)	(0.366)	(0.329)
$\ln NC_{t-3}(b_{33})$			− 1.423***	− 1.213***	− 1.369***
			(0.415)	(0.429)	(0.510)
$\ln NC_{t-4}(b_{34})$			0.884**	0.585*	0.682*
			(0.396)	(0.329)	(0.412)
$TEMP(b_{40})$	− 0.005	0.035***	0.010**	0.009**	0.009**
	(0.003)	(0.013)	(0.005)	(0.004)	(0.003)
Cons(b_0)	− 29.139***	− 26.639***	− 2.724	− 1.333	0.392
	(3.139)	(3.788)	(1.833)	(1.704)	(1.442)
PP test for residual	− 3.941**	− 4.711**	− 11.620**	− 10.832**	− 10.705**
Bresuch-Godfrey autocorrelation test	1.669	9.78**	3.223	0.390	0.168
Breusch-Pagan heteroskedasticity test	26.92**	82.645**	3.280	0.320	0.010
AIC	− 194.174	− 54.177	− 322.737	− 365.509	− 358.021

Notes: 1) *: p<0.10, **: p<0.05, ***: p<0.01
2) Monthly dummy adjusts seasonality of all models except for model 1.
3) ( ) indicates standard errors.

<Table 6> summarizes long-run effects of basic models (models 1 and 2) and ARDL models (models 3, 4 and 5). The coefficients sensitively responded depending on models and variable selection. The signs of coefficients in model 4 and 5 are persuasive with respect to both theory and practice rather than models 1 to 3. Conclusively, model 4 is preferable to model 5 in terms of AIC (-365.509 vs. -358.021).

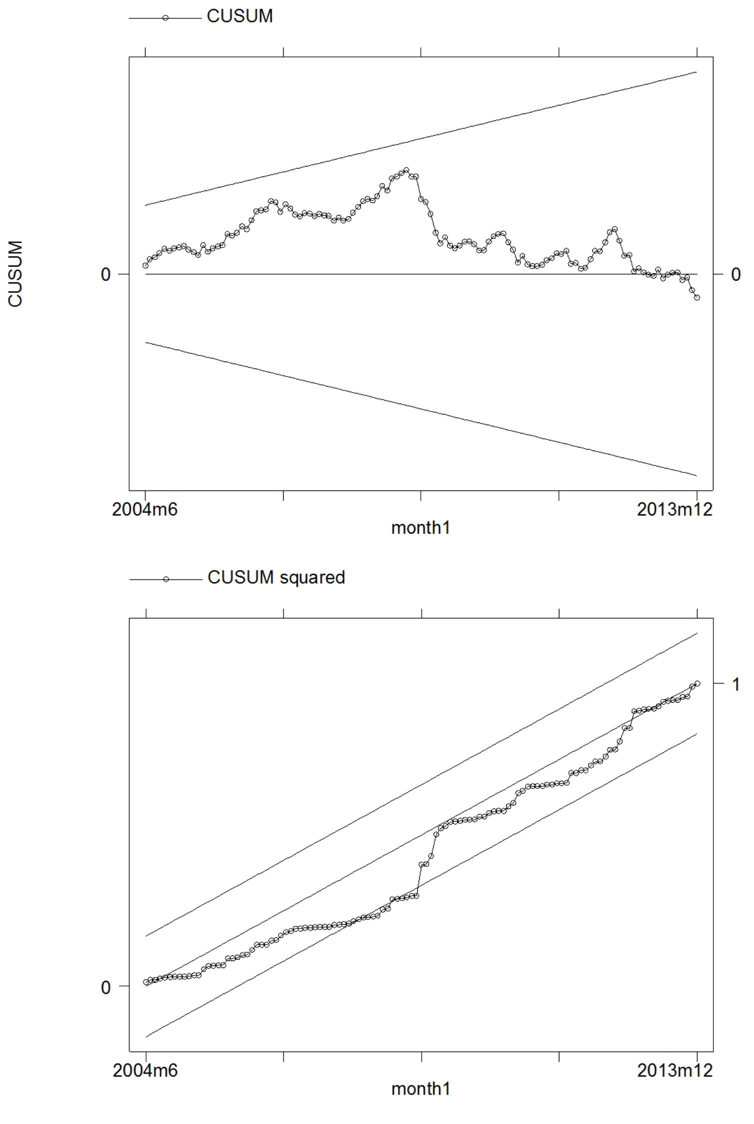
〈Table 6〉 Long term effects

	Model 1	Model 2	Model 3	Model 4	Model 5
$\ln Q$	0.926**	1.362**	2.011**		
	(0.351)	(0.500)	(0.805)		
$\ln NUKE$				0.189***	1.629***
				(0.024)	(0.238)
$\ln COAL$					−0.120
					(1.154)
$\ln Q_1$				1.616**	
				(0.517)	
$\ln Q_2$					1.859***
					(0.046)
$\ln NC$	2.462**	1.731**	0.537	−0.186**	−3.165**
	(0.651)	(0.899)	(1.637)	(0.063)	(1.114)
$TEMP$	−0.005	0.035*	0.081*	0.072**	0.116**
	(0.003)	(0.013)	(0.049)	(0.014)	(0.021)
b_0	−29.139***	−26.639***	−21.303**	−11.207	5.077
	(3.139)	(3.788)	(8.731)	(10.954)	(20.954)

Notes: 1) *: $p<0.10$, **: $p<0.05$, ***: $p<0.01$
2) All models except for Model 1 were seasonally adjusted with monthly dummy.
3) ( ) indicates standard errors, and those of models 3, 4 and 5 were estimated using delta method.

It is necessary to ensure the stability of the parameters of model 4 because there was exogenous shock such as financial crisis in 2008. For this cumulative sum of recursive residual (CUSUM) and cumulative sum of squares (CUSUMSQ) test were conducted. CUSUM test is a way to diagnose structural change of estimates by imposing restriction on observations while CUSUMSQ test sees if the variance and covariance of residual are stable (Brown et al., 1975). <Figure 4> displays the CUSUM and CUSUMSQ tests, respectively. We can inspect the lines fall inside the 95% confidence band. This means that the estimated parameters are stable over the period shown.

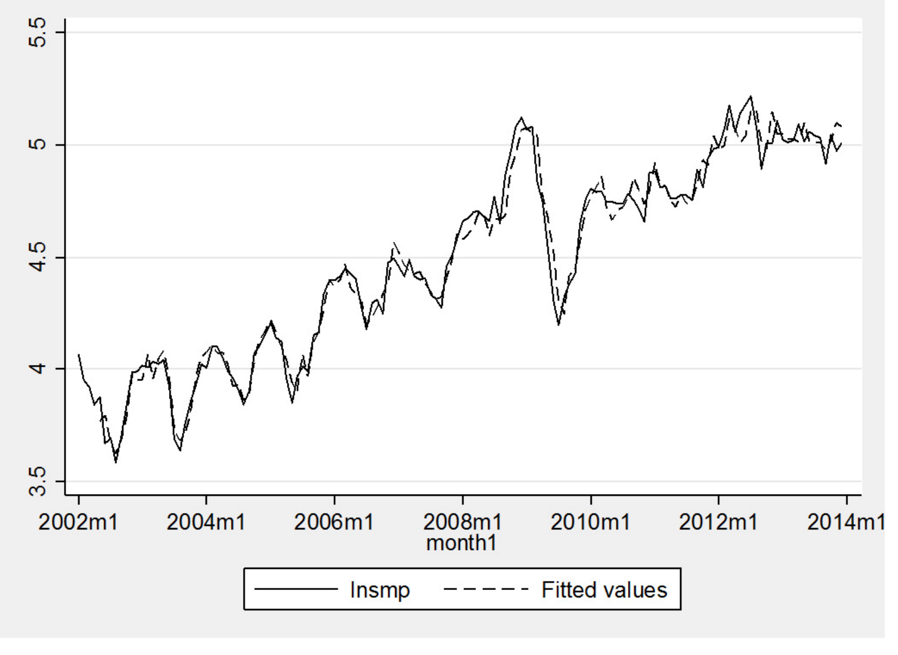
〈Figure 4〉 CUSUM, CUSUM square Test



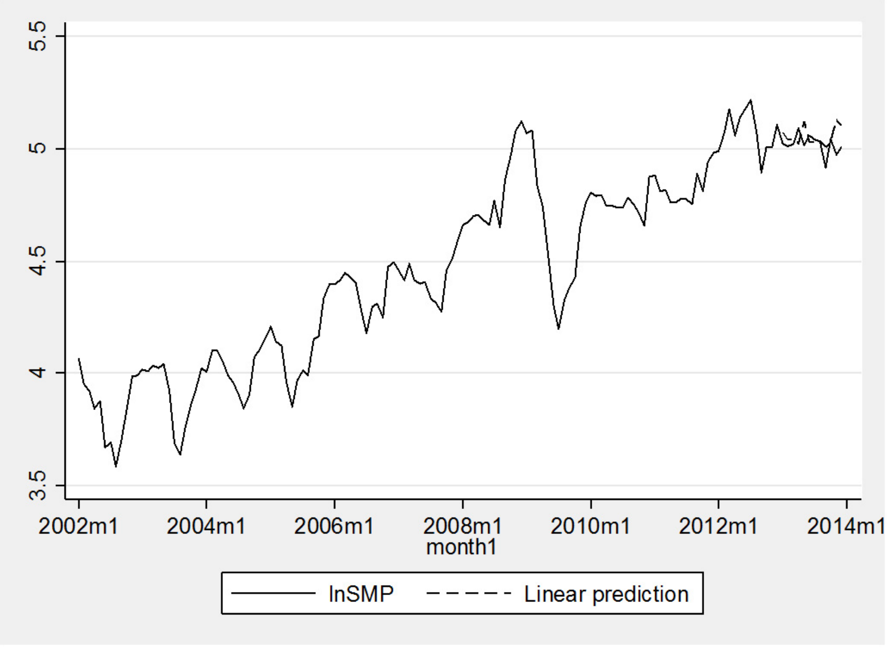
Next, we checked reliability of model 4 in terms of within-sample and out-of-sample forecasts. <Figure 5> shows within-sample forecast for the whole sample period (2002.1~2013.12). The movements of predicted value (dot line) and actual value (solid line) are highly similar. <Figure 6> shows out of sample forecasts. We estimated models without observations for the last one year, and then compared estimated values and actual values. Out-of-sample forecast and seems to reflect actual value as well.

In order to evaluate accuracy in prediction of the model, absolute errors (AE), absolute percentage errors (APE) and root mean square errors (RMSE) were measured (for definition, see Appendix). The results are shown in <Table 7>. Mean of AE is 5.7%, mean of APE is 1.2%, and RMSE is 7.3%, which means that model 4 is reasonable.

〈Figure 5〉 Within-sample forecast



〈Figure 6〉 Out-of-sample forecast



〈Table 7〉 Forecast errors (%)

	RMSE	Mean AE	Mean APE
% Error	7.3	5.7	0.01.2

Lastly, we conducted Granger causality tests among SMP and variables of interest ($\ln NUKE$, $\ln Q_1$, $\ln NC$). The results indicate that there is a unidirectional Granger causality running from nuclear power supply ($\ln NUKE$) to electricity price ($\ln SMP$). There is a unidirectional causal relationship among the other supply ($\ln Q_1$) to electricity price. In addition, $\ln Q_1$ has a unidirectional causality to nuclear supply ($\ln NUKE$).

〈Table 7〉 Granger causality

Dependent Variable	χ^2	Null Hypotheses
$\ln SMP$	10.073**	$\ln NUKE$ does not Granger cause $\ln SMP$
	10.05**	$\ln Q_1$ does not Granger cause $\ln SMP$
	5.357	$\ln NC$ does not Granger cause $\ln SMP$
$\ln NUKE$	3.951	$\ln SMP$ does not Granger cause $\ln NUKE$
	13.069**	$\ln Q_1$ does not Granger cause $\ln NUKE$
	5.079	$\ln NC$ does not Granger cause $\ln NUKE$
$\ln Q_1$	6.129	$\ln SMP$ does not Granger cause $\ln Q_1$
	6.343	$\ln NUKE$ does not Granger cause $\ln Q_1$
	7.316	$\ln NC$ does not Granger cause $\ln Q_1$
$\ln NC$	3.312	$\ln SMP$ does not Granger cause $\ln NC$
	0.349	$\ln NUKE$ does not Granger cause $\ln NC$
	1.109	$\ln Q_1$ does not Granger cause $\ln NC$

V. Conclusions

This study examined the relationship between nuclear power generation and SMP. Unclear order of integration of time series makes classical cointegration analysis ineffective. Thus, the ARDL bounds approach was used since this approach is more flexible with respect to the order of integration. ARDL bound test results support the evidence of cointegration among the key variables. While the Engle-Granger long term equilibrium coefficients with no lagged variables were biased, the long-term effect of ARDL model which controls lagged variables showed the reasonable results. Model 4 was the most valid in terms of reasonability, reliability, and stability. It is appeared that nuclear power supply and SMP have a significant positive relationship while nuclear power capacity and SMP have a significant negative relationship. In aspect of Granger causality, nuclear power has a unidirectional causality from nuclear supply to SMP.

The implications of the results are as follows. First, our ARDL model indicates that there is potential for the role of nuclear power generation in coordinating electricity price and market operation. Even though there is no systematic relation between the nuclear power generation and electricity price in Korea Power Exchange, the real electricity market, the ARDL analysis shows the close relation between them. Second, the impact on SMP by different power source may vary. Therefore, policy decision should be made considering it. Also research on difference among power sources needs to be reached. Third, given that nuclear power supply has one-way Granger causality on SMP, nuclear power supply provides useful information on analyzing electricity price.

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[Appendix]

In order to evaluate models absolute errors (AE), absolute percentage errors (APE), root mean square errors (RMSE) were measured as follows (Weron, 2014).

$$AE_t = |P_t - \widehat{P}_t| \tag{a}$$

$$APE_t = AE_t / P_t \tag{b}$$

$$\text{RMSE} = \text{SE} = \sqrt{\frac{1}{T}\sum(AE_t)^2} \tag{c}$$

where P_t is actual values, $\widehat{P_t}$ is forecast.