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Elasticity of substitution of renewable energy for nuclear power: Evidence from the Korean electricity industry

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ABSTRACT

This study suggests a simple economic model to analyze electricity grid that consists of different power sources. The substitutability of renewable energy for nuclear power in Korean electricity transmission network is investigated by suggested model. The monthly data from January 2006 to December 2013 reported by Electricity Power Statistics Information System (EPSIS) of Korea Power EXchange (KPX) are used. To estimate the elasticities of substitution among four power sources (i.e. coal, natural gas, nuclear power, and renewable energy), this paper uses the trans-log cost function model on which local concavity restrictions are imposed. The estimated Hicks-Allen and Morishima elasticity of substitution shows that renewable electricity and nuclear power are complementary. The results also evidenced that renewable electricity and fossil fueled thermal power generation are substitutes.

1. Introduction

1.1. Background

Nuclear power has been a controversial issue worldwide. Specifically, there are many questions whether nuclear power plants can be continuously used in the future and, if not, whether renewable energy can substitute nuclear power. In Korea, the Moon Jae-in administration, established in 2017, is in favor of renewable energy and proposed the Korean government's new long-term plan of electricity supply, which recommends the suspension of two nuclear power plants under construction [1]. After serious debate, the Committee for Public Debate of Sin-Gori Units No. 5·6 finally allowed continuing construction of those plants. The debate reflects Korea's increasing fear of the risk of nuclear power since the Fukushima Daiichi accident in Japan, followed by the great earthquake in 2011 [2].

Fear of nuclear power is a global phenomenon. Global electricity generation from nuclear power plants in 2013 was less than its average between 2001 and 2010. The main driver of this decline was the shutdown of nuclear power plants in Japan, Germany, and the US [3]. The IAEA [4] reports that the rapid shutdown of nuclear power plants, beginning in the 2010s, has affected the current capacity of global nuclear power. Yet, the same report states that nuclear power still accounts for one-third of the total low carbon power generation and renewable energy cannot easily substitute nuclear power because of its intermittent characteristic. The IAEA projects that increasing global demand for electricity, especially in emerging economies, may lead to the expansion of nuclear power use, which presents a paradox concerning nuclear power [4]. Although nuclear power is inexpensive and a massive electricity supplier with low carbon emissions, simultaneously, it could bring about a fatal accident.

CO_2 emission from fossil fuel use is a common problem and seen as a significant cause of global climate change. In the electricity industry, however, the reduction of fossil fuel-based thermal power generation creates instability in the power supply. Nuclear power generation is a strong alternative as a substitute for thermal power generation [4]. As mentioned, however, nuclear power generation faces strong opposition as it has latent risks. Facing these two problems, CO_2 emission and nuclear power's risk, renewable energy is being discussed as an effective solution. However, as the IAEA report [4] points out, the technological and economic problems associated with renewable energy are still the basis of argument whether renewable energy is unsuitable for the base-load of the electricity system. Moreover, Madrigal and Stoft pointed out that intermittency of renewable energy such as wind power and photovoltaic affects grid stability [5]. According to them, transmission companies face challenges to balance supply and demand

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in the grid. As another example concerning renewable energy, in Japan, Kyushu Electric Power Company (KEPC) restricted power supply from renewable energy into its grid to prevent massive blackouts [6]. This is a similar situation to what Madrigal and Stoft pointed out [5]. According to an article [6], the expansion of renewable power supply requires the improvement of electricity transmission network (i.e. grid). In these respects, the substitutability of renewable energy for conventional power generation technology (i.e., nuclear power and thermal power) should be investigated prior to designing a power supply system with a high capacity of renewable energy.

1.2. Objective and literature review

KEPC's example implies that all power sources have their own technological and environmental limits which affect the unit cost of power generation. From KEPC's case, it could be suggested that the characteristic of each power source affects grid stability. Since the controllability of the power generation differs by power sources, electricity generated from different sources incurs a wide range of stabilization costs in the transmission stage. From the perspective of production economics, this implies that the elasticity of substitution among power sources (i.e., inter-source elasticity of substitution) is not infinite in the transmission stage of the electricity industry. In this study, therefore, we address the issue of inter-source elasticity of substitution between nuclear power and renewable energy as well as fossil fuel-based energy in the transmission stage.

Literature on the elasticity of substitution in the electricity industry generally focuses on the substitutability of fossil fuels in the generation stage (e.g., Refs. [7–16]). The main concept in these studies is usually inter-fuel elasticity of substitution. However, the results in these studies are difficult to apply to the discussion here because we are not interested in the inter-fuel substitution in the generation stage but rather in the substitutability among the electrical power sources in the transmission stage. For example, Serletis et al. [14,15] and Gao et al. [17] consider the elasticity of substitution in the electricity industry and the substitution between fossil fuels (i.e., coal, oil, and natural gas) in the generation stage. They do not discuss inter-source substitution in the transmission stage. In addition, the focus of this study is on nuclear power and renewable energy rather than fossil fuels. Our objective is to estimate the elasticity of substitution in the transmission stage among electrical power sources that include nuclear power and renewable energy.

In terms of method, there are many studies that employ the nested CES function to investigate the substitutability of inputs. The nested CES function requires an assumption on the separability of inputs, which imposes some restrictions on the elasticity of substitution. One typical study using the nested CES function is that of Papageorgiou et al. [18]. They assume that energy inputs are aggregated into two groups: clean technology based on nuclear and renewable energy and dirty technology using fossil fuels. Because of the restrictions imposed by the separability condition, Papageorgiou et al. assume implicitly that the elasticity of substitution between nuclear energy and fossil fuels is equal to that between renewable energy and fossil fuels [18]. In this regard, the trans-log function is more flexible as it does not impose a priori restrictions on the elasticity of substitution.

Moreover, most previous studies use annual data. However, annual data are unsuitable to handle the fundamental problem of renewable energy, namely, volatility. To account for volatile features in renewable energy, we need to use time series data with higher frequency. This study uses monthly data reported by the EPSIS of the KPX. Accordingly, we estimate the Hicks-Allen elasticity of substitution and the Morishima elasticity of substitution among the electrical power sources, including renewable energy, by using the trans-log cost function model.

The structure of this paper is as follows. The trans-log cost function model is introduced in Section 2. In Section 3, we show the monthly data reported by the EPSIS of the KPX used in the empirical research. The results and the discussion are presented in Section 4. Finally, Section 5 presents the conclusion of the study.

2. The trans-log cost function model

First, we assume there is a monopolistic firm in the transmission-distribution sector. The firm purchases electricity from power generation plants (i.e., coal, natural gas, nuclear, and renewable energy), and delivers electricity to the final users. Second, the firm is assumed to be responsible for keeping the transmission-distribution network (i.e. grid) stable. The transmission-distribution network is exposed constantly to disturbances of voltage and frequency caused by fluctuations in electricity demand and supply. Beyond demand, the stability of the electricity supply differs considerably among the power sources. Thus, the electricity coming from different power sources is not a homogeneous good as there are additional costs necessary to maintain grid stability. For example, the intermittency of renewable energy causes a rapid and random increase/decrease in voltage in the grid because its power generation is affected severely by weather conditions. This random and rapid change incurs an additional adjustment cost to maintain grid stability. Based on the above assumptions, the production function of the transmission-distribution sector can be written as follows.

$$Q = g(x_B,\ x_G,\ x_A,\ x_R, K, L) \tag{1}$$

where Q is the output, K is capital of the grid, L is labor employed in the transmission-distribution sector, x_B, x_G, x_A, and x_R are purchased electricity from the generation plants. Subscripts B, G, A, and R represent coal, natural gas, nuclear power, and renewable electricity, respectively. Note that Q indicates the total amount of electricity sold to the final customers. The firm in the transmission-distribution sector is assumed not to generate electricity; the transaction amounts are regarded as the output of the firm without transmission loss. Moreover, the additional costs for the grid stabilization are incurred by transmitting x_B, x_G, x_A, and x_R. Specifically, there are ancillary service costs and they are measurable in terms of some losses from x_B, x_G, x_A, and x_R. Hence, the elasticity of substitution among x_B, x_G, x_A, and x_R, as shown in equation (1), reflects the differences in grid stabilization costs.

We assume that x_B, x_G, x_A, and x_R are homothetically weakly separable from K and L [19]. That means that the production function (equation (1)) can be rewritten as

$$Q = g(h(x_B,\ x_G,\ x_A,\ x_R),\ K, L) \tag{2}$$

Our concern is inter-source elasticity of substitution in the electricity industry. Hence, we focus on the estimation of function h in equation (2). With the same assumptions for production technology, the dual cost function to the function h in equation (2) as

$$C_p = f(p_B,\ p_G,\ p_A,\ p_R) \tag{3}$$

where C_p is the purchase cost of power, p_i $(i = B, G, A, R)$ are the price of generated electricity generated from the corresponding types of power plants. Equation (3) is specified by the trans-log form as follows.

$$\ln C_p = \alpha_0 + \sum_{i=B,G,A,R} \alpha_i \ln p_i + \frac{1}{2} \sum_{i=B,G,A,R} \sum_{j=B,G,A,R} \alpha_{ij} \ln p_i \ln p_j \tag{4}$$

where α_0, α_i, and α_{ij} are the parameters to be estimated. From Shephard's lemma, the share of the cost of the ith power source is,

$$S_i = \alpha_i + \sum_{i=B,G,A,R} \alpha_{ij} \ln p_j \tag{5}$$

where $S_i = p_i x_i / (p_B x_B + p_G x_G + p_A x_A + p_R x_R)$ is the share of the cost of the ith power source. By definition, the cost function of purchasing electricity, equation (3), is homogeneous of degree one in p_B, p_G, p_A, and p_R. Thus, the following restrictions are needed.

$$\sum_{i=B,G,A,R} \alpha_i = 1 \quad \text{and} \quad \sum_{i=B,G,A,R} \alpha_{ij} = 0 \tag{6}$$

To estimate the parameters in equation (4), equations (4) and (5) are jointly estimated by the maximum likelihood method.[1]

The price elasticity of demand, η_{ij}, is,

$$\eta_{ij} = \alpha_{ij}/S_i + S_j \ ; \quad i \neq j, \ \ i, j = B, G, A, R \tag{7}$$

$$\eta_{ii} = \alpha_{ii}/S_i + S_i - 1 \ ; \quad i = j, \ \ i = B, G, A, R \tag{8}$$

The Hicks-Allen elasticity of substitution, σ_{ij}^{HA}, is derived from equations (7) and (8) as

$$\sigma_{ij}^{HA} = \alpha_{ij}/(S_i S_j) + 1 \ ; \quad i \neq j, \ \ i, j = B, G, A, R \tag{9}$$

$$\sigma_{ii}^{HA} = \left(\alpha_{ii} + S_i^2 - S_i\right) \Big/ S_i^2 \ ; \quad i = j, \ \ i = B, G, A, R \tag{10}$$

Finally, the Morishima elasticity of substitution, σ_{ij}^{M}, is derived from equations (7) and (8) as

$$\sigma_{ij}^{M} = \eta_{ji} - \eta_{ii} \ ; \quad i, j = B, G, A, R \tag{11}$$

The cross-price elasticity of demand $\eta_{ij}, \ i \neq j$ measures proportional change in demand for x_i responding to proportional change in price p_j. A positive cross-price elasticity η_{ij} implies that a decrease (increase) in x_j induced by rising (declining) p_j is accompanied by an increase (decrease) in x_i; namely, x_i and x_j are substitutes. A negative cross-price elasticity η_{ij} implies that a decrease (increase) in x_j is accompanied by a decrease (increase) in x_i (i.e., x_i. and x_j are complements). Since the Hicks-Allen elasticity has the same sign as the corresponding cross elasticity of demand, x_i and x_j, $i \neq j$, are judged to be substitutes if $\sigma_{ij}^{HA} > 0$ and complements if $\sigma_{ij}^{HA} < 0$.

On the other hand, the Morishima elasticity of substitution indicates whether the ratio of inputs increases or decreases as input prices change. Blackorby and Russell discuss that the Hicks-Allen elasticity of substitution becomes less insightful when the number of inputs is more than two because it adds little to the price elasticity of demand [21]. In this case, the Morishima elasticity of substitution is more informative. Following Blackorby and Russell [22], the Morishima elasticity of substitution as defined by the Morishima [23] can be written as

$$\sigma_{ij}^{M} = -\frac{\partial \log\left(C_i/C_j\right)}{\partial \log\left(p_i/p_j\right)} = -\frac{\partial \log x_i}{\partial \log\left(p_i/p_j\right)} + \frac{\partial \log x_j}{\partial \log\left(p_i/p_j\right)} \tag{12a}$$

where p_i and p_j are the prices of the ith and the jth input, respectively, and C_i and C_j are partial derivatives of the cost function for the ith and the jth input, respectively. Therefore, from Shephard's lemma, C_i and C_j give the optimal demand for x_i and x_j, respectively, while p_j remains fixed. Under fixed p_j, equation (11) is derived from equation (12). According to this definition, the Morishima elasticity of substitution, σ_{ij}^{M}, indicates that the proportional change in the ratio of demand for the ith to the jth input responds to the proportional change in the ith input price [21]. By definition, a positive σ_{ij}^{M} means that the increase in the ith input price, p_i, given $p_j, \ j \neq i$, declines the ratio of ith to the jth input, x_i/x_j. Conversely, a negative σ_{ij}^{M} means an increase in the ratio of the ith to the jth input, x_i/x_j, as p_i increases.

3. Data

This study uses monthly power data from January 2006 to December 2013 from the EPSIS of the KPX.[2] The data are obtained from the EPSIS website.[3] The power sources in the monthly EPSIS data are hydro, pumped-storage, anthracitic coal, bituminous coal (simply coal), oil, natural gas, nuclear power, and others. Renewable energy is included in the category “others” and thus, “others” is the proxy for renewable energy in this study. Note that hydro, pumped-storage, anthracitic coal, and oil are excluded, as these are assumed to be relatively less important. We should also note that there are many renewable energy sources in Korea (e.g. By-product, Bio gas, Small hydro, Landfill gas, Photovoltaic, Waste, Wind, Fuel cell, Marine), these renewable sources are aggregated as “Renewable energy” in this study.

The data includes the monthly generated electricity of each electrical power source (GWh), the monthly power exchange volume of each electrical power source (GWh), and the monthly calculated unit cost of each electrical power source (Won/kWh). This study regards the unit costs as the input prices. The mean and standard deviation of the variables used in the analysis are shown in Table 1.

Since the data are a monthly time-series for 96 months, the stationarity of the series is a relevant issue. Thus, the Phillips-Perron unit root test is performed to check whether the monthly time-series here are stationary.[4] The results of the unit root test shown in Table 2 indicate the null hypothesis of the test is rejected for all generated electricity, power transaction amounts, and price at the significance level of 1%.

4. Results and discussion

The estimated results, shown in Table 3,[5] are statistically significant at the 1% significance level entirely, implying that the trans-log model is appropriately estimated.

Tables 4–6 show the price elasticities, the Hicks-Allen elasticity

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[1] This is numerically equivalent with Zellner's seemingly unrelated regression [20] if the disturbances are distributed as multivariate normal.

[2] This study used data until December 2013 because the data after that were not opened and not available. If data after 2014 are published and the statistical method of data collection is continuous, it can be used to update the results of this study.

[3] http://epsis.kpx.or.kr/epsisnew/selectEkifBoardList.do?menuId=090140&boardId=003140.

[4] STATA 14 is used for the unit root test with Newey-West automatic lag selection [24].

[5] Monthly dummies are applied in estimation of the trans-log cost function to control seasonal variations.

Table 1
Description of the data.

	Generated Electricity (GWh)		Power Exchange Volume (GWh)		Price (Won/kWh)	
	Mean	Standard deviation	Mean	Standard deviation	Mean	Standard deviation
Coal	14588.9	2071. 2	14090.4	2024.5	55. 5	12.0
Natural Gas	7967.0	2525.2	6793.6	2222.2	135.3	27.1
Nuclear	12340.4	848.4	11767.7	810.3	38.7	7.2
Renewable	709.3	356.7	407.0	304.4	106.0	20.6

Table 2
Phillips-Perron unit root test.

		Coal	Natural Gas	Nuclear	Renewable
Generated Electricity (GWh)	Z (rho)	−33.473***	−57.854***	−94.298***	−30.421***
	Z (t)	−4.439***	−6.206***	−9.309***	−4.271***
Power Transaction Amounts (GWh)	Z (rho)	−46.993***	−58.299***	−66.317***	−51.254***
	Z (t)	−5.771***	−6.343***	−7.268***	−5.779***
Price (Won/kWh)	Z (rho)	−49.095***	−66.137***	−69.539***	−80.981***
	Z (t)	−5.795***	−8.441***	−6.947***	−9.907***

Note: The critical values of interpolated the Dickey-Fuller for Z (rho) are −27.230 at the 1% significance level, −20.610 at the 5% significance level, and −17.430 at the 10% significance level, respectively. The critical values of the interpolated Dickey-Fuller for Z (t) are −4.051 at the 1% significance level, −3.455 at the 5% significance level, and −3.153 at the 10% significance level, respectively. The Newey-West lags are 3. ***, **, and * indicate 1%, 5%, and 10% significance, respectively.

Table 3
Estimated coefficients.

Parameters	Estimated coefficients	Parameters	Estimated coefficients
α_B	0.536*** (0.015)	α_{GG}	0.255** (0.017)
α_G	0.223*** (0.019)	α_{GA}	−0.005 (0.009)
α_A	0.243*** (0.011)	α_{GR}	0.030*** (0.005)
α_R	−0.002 (0.003)	α_{AA}	0.140*** (0.008)
α_{BB}	0.409*** (0.017)	α_{AR}	−0.013*** (0.002)
α_{BG}	−0.280*** (0.015)	α_{RR}	−0.011** (0.004)
α_{BA}	−0.122*** (0.009)	Constant	10.550*** (0.036)
α_{BR}	−0.006** (0.002)		

Note: The numbers in parentheses are standard errors. ***, **, and * indicate significance level of 1%, 5%, and 10%, respectively.

of substitution, and the Morishima elasticity of substitution, respectively. All values in parentheses are t-statistics. As shown in the tables, the results are entirely statistically significant at the 1% level.

Table 4 shows that the own-price elasticities of coal and natural gas are positive. This contradicts demand theory and means that the model is unstable. Mathematically speaking, the instability of the model stems from the unsatisfied concavity of the cost function. For the appropriate analysis of the substitutability of renewable energy for other power sources, we impose local concavity on the original trans-log function and investigate the relationship among the power sources.

Concerning the concavity problem, Ryan and Wales show that concavity of the entire cost function can be satisfied by locally imposed concavity at a reference time point [25]. Here, we use their method to improve the concavity of the model and show the change in the results. First, following Ryan and Wales [25], we substitute α_{ij} in our equations (4) and (5) (see Section 2) with the following equation (12), by citing Diewert and Wales [26].

$$\alpha_{ij} = -\left(DD'\right)_{ij} + \alpha_i\delta_{ij} - \alpha_i\alpha_j, \qquad i,j = B,G,A,R \tag{12b}$$

where D is the triangular matrix of order 4, and δ_{ij} is one when $i = j$, or zero otherwise. Ryan and Wales [25] show that local concavity is imposed at a reference time point when all the prices and the

Table 4
Price elasticity of demand η_{ij}.

i	j			
	Coal (C)	Natural Gas (G)	Nuclear (A)	Renewable (R)
Coal (C)	0.533*** (0.013)	−0.400*** (0.010)	−0.133*** (0.008)	−0.000 (0.001)
Natural Gas (G)	−0.358*** (0.011)	0.057*** (0.006)	0.207*** (0.007)	0.095*** (0.001)
Nuclear (A)	−0.271*** (0.030)	0.381*** (0.007)	−0.061** (0.027)	−0.049*** (0.002)
Renewable (R)	−0.262*** (0.058)	3.370*** (0.265)	−1.063*** (0.111)	−2.045*** (0.097)

Note: The numbers in parentheses are standard errors. ***, **, and * indicate significance level of 1%, 5%, and 10%, respectively.

Table 5
Hicks-Allen elasticity of substitution σ_{ij}^{HA}.

i	j			
	Coal (C)	Natural Gas (G)	Nuclear (A)	Renewable (R)
Coal (C)	1.592*** (0.063)	−1.017*** (0.032)	−0.829*** (0.110)	−0.832*** (0.183)
Natural Gas (G)	–	0.173*** (0.024)	0.939*** (0.002)	9.051*** (0.781)
Nuclear (A)	–	–	0.270 (0.430)	−4.224*** (0.328)
Renewable (R)	–	–	–	−283.46*** (46.943)

Note: The numbers in parentheses are standard errors. ***, **, and * indicate significance level of 1%, 5%, and 10%, respectively.

Table 6
Morishima elasticity of substitution σ_{ij}^{M}.

i	j			
	Coal (C)	Natural Gas (G)	Nuclear (A)	Renewable (R)
Coal (C)	–	-0.891^{***} (0.015)	-0.804^{***} (0.037)	-0.795^{***} (0.063)
Natural Gas (G)	-0.457^{***} (0.011)	–	0.324^{***} (0.012)	3.313^{***} (0.264)
Nuclear (A)	-0.072^{**} (0.034)	0.268^{***} (0.032)	–	-1.002^{***} (0.103)
Renewable (R)	2.045^{***} (0.096)	2.140^{***} (0.097)	1.996^{***} (0.098)	–

Note: The numbers in parentheses are standard errors. ***, **, and * indicate significance level of 1%, 5%, and 10%, respectively.

output are normalized to one; here by replacing α_{ij} in equations (4) and (5) with the right-hand-side of (12). we chose January 2006 as the reference point and normalized all prices and the output of the observations at that time. By this re-parametrization, the parameters to be estimated are α_i and the elements of D.

The results of price elasticity with locally imposed concavity are shown in Tables 7–9. As shown in Table 7, the own-price elasticity of coal and natural gas turns out to be negative as expected by demand theory.

The Hicks-Allen elasticities of substitution in Table 8 show that the primary relationship among the power sources in Korea is substitute. The only exception is the relationship between nuclear power and renewable electricity, which shows complementarity. This implies that renewable electricity cannot be an alternative to nuclear power. Therefore, to make appropriate policy concerning renewable energy, we need more detailed information about the effect of each price on the change in the ratio of renewable electricity and another power source.

Table 9 shows that σ_{AR}^{M} is negative while σ_{RA}^{M} is positive. As mentioned, the negative σ_{AR}^{M} indicates that an increase in the price of nuclear power, p_A, induces an increase in the ratio of nuclear power to renewable electricity, x_A/x_R. Based on demand theory, an increase in p_A induces a decrease in x_A. An increase in the ratio x_A/x_R, therefore, means a more rapid decrease in x_R than in x_A. The rapid decrease in renewable electricity responding to the rise in the price of nuclear power is due to the complementarity between nuclear power and renewable electricity as suggested by the measurement of the Hicks-Allen elasticity of substitution in Table 8. On the other hand, it is paradoxical that the positive σ_{RA}^{M} in Table 9 indicates an increase in the price of renewable electricity, p_R, which leads to a decrease in x_R/x_A. This means that the decrease in x_R dominates the change in x_R/x_A. Fig. 1 in Section 1 shows that the share of power generation of renewable electricity is much lower than that of nuclear power. This implies that the impact of a change in renewable electricity on the entire electricity sector would be very small. Namely, x_A is not driven by a change in p_R, while x_R decreases with an increase in p_R. In sum, the asymmetric signs of the Morishima elasticity of substitution between nuclear power and renewable electricity show that the response of renewable energy to a change in the price of nuclear power is more prominent than that of nuclear power to a change in the price of renewable electricity. This indicates that nuclear power responds imperceptibly to a change in the price of renewable electricity but renewable energy acts as a complement to nuclear power, as suggested by the Hick-Allen elasticity of substitution in Table 8.

Table 9 also shows that the Morishima elasticities of substitution are positive between renewable electricity and fossil-fuel electricity based on coal and natural gas. These results indicate that an increase in the price of fossil-fuel electricity leads to a decrease in the ratio of fossil-fuel electricity to renewable electricity, while an increase in the price of renewable electricity induces a decrease in the ratio of renewable electricity to fossil-fuel electricity. These are consistently interpretable results for the substitutability of fossil-fuel electricity and renewable electricity, implied by the Hicks-Allen elasticity of substitution. This substitutability may reflect the fact that fossil-fuel electricity is used to backup volatile renewable electricity.

To enhance renewable energy use, we can put forth three related policy instruments based on the results; 1) reducing the price of renewable electricity through subsidies; 2) decreasing the price of nuclear power by relaxing the safety standard to leverage its complementarity; and 3) increasing the price of fossil fuels by

Table 7
Price elasticity of demand η_{ij}.

i	j			
	Coal (C)	Natural Gas (G)	Nuclear (A)	Renewable (R)
Coal (C)	-0.170^{***} (0.002)	0.098^{***} (0.006)	0.060^{***} (0.007)	0.125^{***} (0.002)
Natural Gas (G)	0.084^{***} (0.005)	-0.724^{***} (0.010)	0.535^{***} (0.012)	0.149^{***} (0.002)
Nuclear (A)	0.073^{***} (0.015)	1.042^{***} (0.035)	-1.104^{***} (0.021)	-0.332^{***} (0.015)
Renewable (R)	4.031^{***} (0.332)	5.480^{***} (0.456)	-6.485^{***} (0.602)	-3.027^{***} (0.186)

Note: The numbers in parentheses are standard errors. ***, **, and * indicate significance level of 1%, 5%, and 10%, respectively.

Table 8
Hicks-Allen elasticity of substitution σ_{ij}^{HA}.

i	j			
	Coal (C)	Natural Gas (G)	Nuclear (A)	Renewable (R)
Coal (C)	-0.481^{***} (0.005)	0.230^{***} (0.012)	0.173^{***} (0.050)	11.875^{***} (1.087)
Natural Gas (G)	–	-1.897^{***} (0.066)	2.545^{***} (0.044)	14.783^{***} (1.337)
Nuclear (A)	–	–	-6.109^{***} (0.509)	-26.312^{***} (1.716)
Renewable (R)	–	–	–	-455.321^{***} (82.428)

Note: The numbers in parentheses are standard errors. ***, **, and * indicate significance level of 1%, 5%, and 10%, respectively.

Table 9
Morishima elasticity of substitution σ_{ij}^{M}.

i	*j*			
	Coal (C)	Natural Gas (G)	Nuclear (A)	Renewable (R)
Coal (C)	–	0.254^{***} (0.006)	0.243^{***} (0.016)	4.201^{***} (0.331)
Natural Gas (G)	0.822^{***} (0.007)	–	1.766^{***} (0.027)	6.204^{***} (0.461)
Nuclear (A)	1.164^{***} (0.014)	1.639^{***} (0.012)	–	-5.381^{***} (0.615)
Renewable (R)	3.152^{***} (0.186)	3.176^{***} (0.186)	2.694^{***} (0.194)	–

Note: The numbers in parentheses are standard errors. ***, **, and * indicate significance level of 1%, 5%, and 10%, respectively.

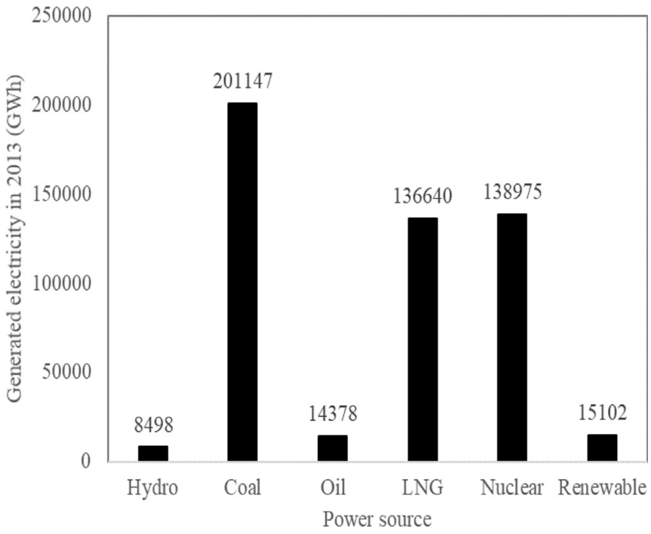

Fig. 1. Total electricity generated in Korea in 2013.

imposing carbon tax. The own-price elasticity of renewable electricity shown in Table 7 suggests that a subsidy for renewable electricity will be effective. Finally, carbon taxation could induce the substitution of renewable electricity for fossil-fuel power generation. Therefore, the effective policies to enhance renewable energy growth would be a combination of renewable electricity subsidy and carbon taxation. Most importantly, substituting renewable energy for nuclear power generation will be ineffective because of their complementarity.

5. Conclusion and policy implications

This study investigates the substitutability of renewable energy for nuclear power. We use the monthly data from January 2006 to December 2013 from the EPSIS of the KPX. To estimate the elasticities of substitution among four power sources (i.e., coal, natural gas, nuclear power, and renewable energy), the trans-log cost function model is used, with local concavity restrictions imposed. The Hicks-Allen and Morishima elasticity of substitution estimations show that renewable electricity and nuclear power are complements. The results also provide evidence that renewable electricity and fossil-fuel thermal power generation are substitutes. By implication, this shows that low carbon policy would be more effective than regulating nuclear power to enhance renewable energy use.

Renewable energy attracted attention in the aftermath of the oil crisis of the 1970s [27]. Since then, control of climate change and energy security have played roles in driving investment in renewable energy [28]. Recently, renewable energy has been pointed to as a substitute for nuclear power due to the safety concern around nuclear energy. However, based on the results here, replacing nuclear power with renewable electricity is not viable yet. A more realistic policy would be to facilitate renewable energy through carbon tax while preserving nuclear power as the base load electricity.

We have some challenges that should deal with further work. First, because of limitation on data, this study does not concern externalities of nuclear power (e.g. the cost of radioactive waste disposal) and thermal power (e.g. the environmental cost of CO_2 emission). The results may become quite different with the reflection of conventional power sources' externalities in unit costs. Second, the data used in this study does not include the potential of prospective technological progress of renewable energy efficiency, grid stabilization, and the additional utility (e.g. Energy Storage System). These challenges stem from the lack of available data. Above all, taking account all these externalities in calculating of the power generation price is a hard work and this is occasionally seemed arbitrary.

Despite these challenges, the suggested model of this study is still valuable. We can use the framework of this study even if the potential benefits and externalities of all power sources are considered when we calculate the unit cost of power generation.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.net.2019.04.005.

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