Allocative Efficiency, Potential Cost Savings, and Power Supply Price Markdown in Korean Electric Power Sector*

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Keywords: allocative efficiency for fuel inputs, parametric efficiency test, shadow price, supply relation, power supply markdown, cost saving effect, electric power sector

* This research was a part of the project titled ‘Manpower training program for ocean energy’, funded by the Ministry of Oceans and Fisheries, Korea.

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Abstract

As a publicly owned company, KEPCO monopolizes the electricity supply in the Korean power generation sector and, as a result, the power market has been distorted due to the government's top-down power supply planning, electricity price controls, bureaucracy, etc. Firms faced with constraints imposed by a regulatory environment are likely to fail to minimize their production costs subject to market prices, because of the divergence between the shadow prices and market prices due to the allocative inefficiency of inputs. In this paper, we test for the allocative efficiency of fuel inputs for the Korean electric power industry over the period of 1990-2015 by estimating a shadow cost function along with the unobservable shadow input prices jointly with the power supply relation. Then, the potential cost savings and maximum power supply price markdown are calculated by imposing the allocative efficiency. The empirical results indicate that the null hypothesis of allocative efficiency with respect to all fuel inputs is rejected, implying that the power plants could not achieve cost-minimization subject to market prices. The power plants could reduce their fuel costs by as much as 22.1% per year, on average, by efficiently allocating their fuel inputs. The attainment of allocative efficiency would make it possible to cut the power supply price by 7.6% a year.

I. Introduction

In 2017, Korea's new government unveiled a new energy policy that aims to move towards a country free of nuclear power plants and reduce coal-fired power plants, giving the top priority to public safety and environment. It will scrap existing plans for new nuclear plants without extending the life of existing ones and shut down old coal power plants, cancelling new coal projects. Meanwhile, the shares of renewable and natural gas energies should be raised.[1] The ratio of renewable energy (LNG) generation will be increased to 20% (27%) by 2030 from 4.7% (18%) in 2017; that of nuclear (coal) generation will drop to from 30% (40%) to 21.6% (21.8%) instead. The expansion of the share of renewable energy would contribute to the relatively high supply electricity price by increasing power generation costs, which places some cost burdens on the industrial sectors.

In the Paris Agreement adopted by the 21th COP of the UNFCCC in 2015, Korea, the 7th largest CO_2 emitter in the world, pledged to cut its GHG emissions to 37% below the BAU level by 2030. In achieving this target, in 2015, Korea launched a cap-and-trade scheme by allocating allowances to five sectors including the electricity generating/energy sector, so that the total amount of CO_2 emissions would be reduced to 1.69 billion tons over the period 2015–2017. Therefore, renewable energy will inevitably continue to increase its share in power generation, which exerts strong pressure for raising the supply price for electricity.

[1] Power plants of which generating capacity exceeds 500MW have faced with Renewable Energy Portfolio Standards (RPS) since 2012, so that they are required to supply a certain ratio of total power generation by relying on renewable energy. The ratio is scheduled to extend to 10% in 2024.

The Korea Electric Power Corporation (KEPCO), a publicly owned company, monopolizes the supply of electric power, which is purchased from its subsidiary power plants and private ones through KPX (Korea Power Exchange). There exist several types of factors that are likely to hinder efficient power generation in Korea, such as the government's top-down power supply planning, electricity price controls, the bureaucracy of KEPCO, etc. Particularly, the prices at which KEPCO purchases power through KPX are determined based on the cost-reimbursement principle; the prices of electricity, which are defined as public utility charges based on the price stabilization law, are controlled by the government.[2] As a result, the power plants would tend to maximize their capital assets or scale rather than pursuing cost-minimization. This is why the need for deregulation has been raised along with restructuring and privatization to promote competition in the Korean electricity industry.

As Atkinson and Halvorsen (1984) demonstrated, firms faced with a set of regulations are likely to fail to achieve cost-minimization subject to market prices, because the marginal rates of technical substitution for each pair of inputs are not equal to the ratios of their market prices. That is, the divergence between the shadow prices and market prices of inputs could cause an increase in the costs incurred by the allocative inefficiency of inputs. Given the situation in which the government will likely try to refrain from hiking power prices to avoid a decline in price competition for domestic industries, this paper simulates the potential cost saving and power supply price markdown effects that would be obtainable by achieving allocative efficiency with respect to inputs in power generation. In order to test for the allocative efficiency with respect to inputs and create a simulation model for the Korean electric power

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[2] The electricity price for industrial use was raised by 61% over the period of 2000-2011, which is still only 52.6% of the OECD average in 2012 (KEPCO).

generation industry, a shadow cost function is estimated along with unobservable shadow input prices, jointly with a power supply relation.

Several previous studies conducted relative price efficiency tests for the electric power sector. Atkinson and Halvorsen (1980) developed a model based on the normalized profit function that allows testing all types of relative price inefficiency for regulated utilities; they confirmed the existence of the Averch-Johnson effect and rejected relative price efficiency with respect to fuel and labor using 1973 data.[3] Atkinson and Halvorsen (1984) performed a relative price efficiency test with the 1970 data for 123 U.S. electric power utilities utilizing a shadow cost function. The null hypothesis of relative price efficiency with respect to all inputs is rejected, implying that regulated utilities do not minimize their actual production costs subject to market prices; they found that the relative price inefficiency, on average, increased costs by 3.8%. Lee (2002) estimated the effects of SO_2 regulations on the U.S. electric power industry over the period of 1975-1990. He rejected the hypothesis of cost-minimization and found that the imposition of cost-minimization would yield an underestimation of the effects of sulfur regulations on the average cost increase by 1.1 percentage points. However, these studies did not consider the supply relation in the econometric model. As a result, the effects of allocative efficiency on the supply price were not analyzed.

The remainder of this paper is organized as follows. The econometric model is presented in the following section. The results of the hypothesis tests are described in section III and the

[3] Averch and Johnson (1962) showed that the effective rate of return constraint causes relative price inefficiency by inducing a profit-maximizing utility to use more capital relative to labor, compared to the cost-minimizing level.

empirical results are analyzed in section IV. Section V contains the conclusion.

II. The Model

Consider a production function for the representative power plant that generates electricity (Q) using capital (K) and three fossil fuels—coal (C), oil (O), and gas (G)—as follows:

$$Q = Q(K, \mathbf{F}, t), \tag{1}$$

where $\mathbf{F} \in R_3^+$ is the vector of fossil fuels and t is the time index allowing for technical change.

Given that K is quasi-fixed in the short-run, the shadow restricted cost function dual to Eq. (1) can be derived by solving the shadow cost-minimization problem subject to the shadow prices of fossil fuels as follows (Atkinson and Halvorsen, 1998):

$$RC^s = RC^s(K, \mathbf{W_F^s}, Q, t), \tag{2}$$

where $\mathbf{W_F^s} \in R_3^+$ is the vector of shadow fuel prices that reflect the possible existence of costs incurred by the allocative inefficiency of fuel inputs. Note that $RC^s = \sum_i W_i^s \cdot F_i$. On condition that K satisfies non-decreasing, concavity, and linear homogeneity, Eq. (2) can be rewritten as

$$RC^s = K \cdot FC^s(\mathbf{W_F^s}, Q, t), \tag{3}$$

where FC^s is the shadow fuel cost that satisfies regularity conditions.[4]

The distortion in the power market creates a divergence between the shadow and market prices of fuel inputs. Following Atkinson and Halvorsen (1984), the shadow price of fuel input F_i is expressed by using the input specific factor of proportionality as follows:

$$W_i^s = \delta_i W_i, \quad i = C, O, G, \tag{4}$$

where δ_i is defined as a distortion factor that measures the potential extent of divergence between the market price (W_i) and the shadow price of F_i, caused by the plant's regulatory environment and inefficient production. If the hypothesis of $\delta_i = 1$ is accepted, indicating that the shadow prices coincide with the market prices, then the plant's cost-minimization subject to market prices is guaranteed by achieving the allocative efficiency of fuel inputs.

As the distortion factors are fuel input specific and vary over time, they can be specified as follows:

$$\delta_i = \exp(\mu_i + \mu_{it} t), \quad i = C, O, G \tag{5}$$

Considering that a plant's total revenue is generally influenced by the power market structure, the firm's perceived marginal revenue can be defined as follows (Atkinson and Halvorsen, 1998; Ellis and Halvorsen, 2002):

[4] Regularity requires that shadow fuel cost function be monotonically increasing and concave in shadow input prices. For the concavity, the Hessian matrix should be negative semi-definite.

$$MR^p = P + Q \cdot \frac{\partial P^p}{\partial Q}, \tag{6}$$

where P is the market price of electricity and the superscript p indicates the perceived situation. $\partial P^p/\partial Q$ represents the perceived price effect of the plant's power generation, reflecting the strategic behavior of power plants.

The profit-maximizing supply relation equation can be derived by equating the perceived marginal revenue to the shadow marginal restricted cost, as follows:

$$P = \frac{\partial RC^s}{\partial Q} - Q \cdot \frac{\partial P^p}{\partial Q}, \tag{7}$$

where $\partial RC^s/\partial Q$ is the shadow marginal restricted cost and $-Q \cdot \partial P^p/\partial Q$ measures the market power markup. If the perceived inverse demand equation is specified as $P^p(Q) = \rho(t) - \theta(t)Q$, following Diewert (1982), then the supply relation equation, Eq. (7), can be rewritten as follows:

$$P = \frac{\partial RC^s}{\partial Q} + \theta(t)Q, \tag{8}$$

where $\rho(t)$ and $\theta(t)$ are polynomial expressions in time.

For the estimation of the shadow restricted cost function, Eq. (3), the following translog functional form is used:

$$\ln RC^s = \ln K + \alpha_0 + \alpha_Q \ln Q + \alpha_t t + \frac{1}{2}\gamma_{QQ}(\ln Q)^2 + \sum_i \alpha_i \ln(\delta_i W_i)$$
$$+ \frac{1}{2}\sum_i \sum_j \gamma_{ij} \ln(\delta_i W_i) \ln(\delta_j W_j) + \sum_i \gamma_{iQ} \ln(\delta_i W_i) \ln Q,$$

$$\gamma_{ij} = \gamma_{ji}, \;\; i \neq j, \quad i,j = C,O,G, \tag{9}$$

where the time index, t, is a shift variable. Linear homogeneity of the shadow restricted cost function in the shadow prices of fuel inputs requires the following restrictions:

$$\sum_i \alpha_i = 1, \;\; \sum_i \gamma_{ij} = \sum_j \gamma_{ij} = \sum_i \sum_j \gamma_{ij} = \sum_i \gamma_{iQ} = 0. \tag{10}$$

The shadow cost share equations for the fuel inputs (M_i^s) are obtained by logarithmically differentiating Eq. (9) with respect to the shadow prices of fuel inputs and applying Shephard's lemma as follows:

$$\frac{\partial \ln RC^s}{\partial \ln(k_i W_i)} = \frac{k_i W_i}{RC^s} \cdot \frac{\partial RC^s}{\partial (k_i W_i)} = \frac{k_i W_i \cdot F_i}{RC^s} \equiv M_i^s = \alpha_i + \sum_j \gamma_{ij} \ln\left(\delta_j W_j\right) + \gamma_{iQ} \ln Q\,, i,j = C,O,G. \tag{11}$$

It is not possible to estimate Eq. (9) and Eq. (11) directly, because RC^s and M_i^s both are not observable, thus these data are unavailable. As a result, these should be expressed in terms of actual cost and its shares evaluated by market prices.

The quantities of fuel inputs (F_i) are obtained from Eq. (11) as follows:

$$F_i = \frac{M_i^s \cdot RC^s}{k_i W_i}. \tag{12}$$

By defining the actual fuel costs (FC) and actual cost shares for fuel inputs (M_i), these actual variables can be expressed as a function of the shadow ones by substituting Eq. (12) for F_i as follows:

$$FC \;\equiv\; \sum_i W_i F_i = RC^s \sum_i M_i^s \cdot \delta_i^{-1}, \tag{13}$$

$$M_i \equiv \frac{W_i F_i}{FC} = \frac{RC^s M_i^S \cdot \delta_i^{-1}}{FC} = \frac{M_i^S \cdot \delta_i^{-1}}{\sum_i M_i^S \cdot \delta_i^{-1}}. \tag{14}$$

Substituting Eq. (9) and Eq. (11) into Eq. (13) and Eq. (14), the following equations to be estimated can be derived:

$$\begin{aligned}\ln FC = {} & \ln K + \alpha_0 + \alpha_Q \ln Q + \alpha_t t + \frac{1}{2}\gamma_{QQ}(\ln Q)^2 + \sum_i \alpha_i \ln(\delta_i W_i) \\ & + \frac{1}{2}\sum_i \sum_j \gamma_{ij} \ln(\delta_i W_i) \ln(\delta_j W_j) + \sum_i \gamma_{iQ} \ln(\delta_i W_i) \ln Q \\ & + \ln[\sum_i (\alpha_i + \sum_j \gamma_{ij} \delta_j W_j + \gamma_{iQ} \ln Q)/\delta_i], \\ & \gamma_{ij} = \gamma_{ji},\ \ i \neq j, \quad i,j = C,O,G,\end{aligned} \tag{15}$$

$$M_i = \frac{[\alpha_i + \sum_j \gamma_{ij} \ln(\delta_j W_j) + \gamma_{iQ} \ln Q]/k_i}{\sum_i [\alpha_i + \sum_j \gamma_{ij} \ln(\delta_j W_j) + \gamma_{iQ} \ln Q]/k_i},\ \ i,j = C,O,G. \tag{16}$$

By substituting $\partial RC^s/\partial Q$, derived from Eq. (9), into Eq. (8), the following estimable form of the supply relation equation is obtained:

$$\begin{aligned}P = {} & (\alpha_Q + \sum_i \gamma_{iQ} \ln(\delta_i W_i) + \gamma_{QQ} \ln Q) \times \exp(\ln K + \alpha_0 + \alpha_Q \ln Q + \alpha_t t + \frac{1}{2}\gamma_{QQ}(\ln Q)^2 \\ & + \sum_i \alpha_i \ln(\delta_i W_i) \quad + \frac{1}{2}\sum_i \sum_j \gamma_{ij} \ln(\delta_i W_i) \ln(\delta_j W_j) \\ & + \sum_i \gamma_{iQ} \ln(\delta_i W_i) \ln Q)/Q + \theta(t) \cdot Q, \\ & \gamma_{ij} = \gamma_{ji},\ \ i \neq j, \quad i,j = C,O,G,\end{aligned} \tag{17}$$

where the degree of the polynomial $\theta(t)$ is determined, depending on the empirical results.

The system of equations consisting of Eq. (15) and Eq. (16), as well as Eq. (17), are simultaneously estimated along with the restrictions (10) by using the iterative Zellner method.[5] Since it is not possible to estimate the absolute value of δ_i for each input, due to the linear homogeneity of degree zero of Eq. (15) and Eq. (16), proved by Atkinson and Halvorsen (1998), one of the distortion factors should be normalized to unity. In this study, $\delta_G = 1$ is imposed, indicating that $\mu_G = \mu_{Gt} = 0$ from Eq. (5).

III. Hypothesis Tests

The relative price efficiency between a pair of fuel inputs is attained if the marginal rate of technical substitution is equal to the ratio of their market prices, which is tested by imposing the restriction $\delta_i = \delta_j$ in Eq. (4). The relative price efficiency with respect to all pairs of fuel inputs implies the minimization of the fuel costs by achieving the allocative efficiency of fuel inputs.

The constant terms in Eq. (5) representing the distortion factors are the same across fuel inputs if the following restrictions are satisfied:

$$\mu_C = \mu_O = \mu_G \ (= 0). \qquad (18)$$

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[5] Inclusion of the cost share equations, Eq. (16), into the system of equations to be estimated makes it possible to obtain additional the degrees of freedom.

The null hypothesis of the time-invariant distortion factors is tested by imposing the following restrictions:

$$\mu_{Ct} = \mu_{Ot} = \mu_{Gt} (= 0). \tag{19}$$

To test for the allocative efficiency of fuel inputs, the following restrictions are imposed, so that $\delta_i = 1, C, O, G$:

$$\mu_C = \mu_{Ct} = \mu_O = \mu_{Ot} = 0 (= \mu_G = \mu_{Gt}). \tag{20}$$

If this hypothesis is not rejected, then the power plants are successful in minimizing their fuel costs subject to market prices.

The allocative efficiency between each pair of fuel inputs is tested by imposing the following restrictions, so that $\delta_i = \delta_j$:

$$\mu_i = \mu_j,\ \mu_{it} = \mu_{jt}, \quad i, j = C, O, G. \tag{21}$$

For all hypothesis tests, a Wald test is used at the 0.01 significance level. The test statistic is distributed asymptotically as χ^2 with degrees of freedom equal to the number of restrictions.

IV. Empirical Results

The econometric model is estimated with the annual time series data for KEPCO and its subsidiary power plants over the period of 1990-2015. The power generation (Q) is drawn from the *Statistics of Electric Power in Korea* (published annually by KEPCO) and the capital stock (K) is measured as the capacity of the power generating facilities. The quantity of coal (C) is the sum of the bituminous coal and anthracite used; the price of coal (W_C) is calculated by averaging the price of anthracite used for power generation (from the *Business Statistics* published by KEPCO) and import price of bituminous coal (the *Yearbook of Energy Statistics* published by Korea Energy Economics Institute) weighted by the consumption of each type of coal. The quantity of oil (O) is the heavy oil used; the price of oil (W_O) is the price of bunker-C oil used for power generation. The quantity of gas (G) and its price (W_G) are the amount of LNG used and its import price, respectively. The supply price of power (P) is measured as the average revenue per kWh. The descriptive statistics for these variables are presented in Table 1.

Table 1: Descriptive statistics (sample size = 26)

Variables	Units	Average	Standard deviation	Maximum	Minimum
Q	TWh	295.23	118.61	448.76	103.19
K	GW	48.805	17.312	73.282	19.783
W_C	KRW/kg	70.10	37.76	152.86	35.77
W_O	KRW/l	326.51	256.29	858.33	71.41
W_G	KRW/kg	404.46	261.43	891.34	128.82
FC	10^{12}KRW	8.275	7.523	24.517	0.924
M_C	-	0.439	0.088	0.594	0.301
M_O	-	0.217	0.125	0.433	0.069
M_G	-	0.344	0.066	0.487	0.255
P	KRW/kWh	76.43	16.40	111.57	52.94

Table 2 reports the results of the hypothesis tests conducted by imposing the corresponding restrictions on the distortion factors for each fuel input in Eq. (5). The same constant terms across fuel inputs, Eq. (18), and no time varying distortion factors, Eq. (19), are both rejected. The null hypothesis that the power plants achieve allocative efficiency with respect to all fuel inputs, Eq. (20), is rejected. This finding suggests that the plants fail to attain cost-minimization subject to market prices through the optimal allocation of each fuel input, due to several types of inefficiency in the power generation sector. The achievement of allocative efficiency for all pairs of fuel inputs (i.e., coal-oil, oil-gas, and coal-gas) is also rejected.

Table 3 presents the parameter estimates for the model. The empirical results indicate that $\theta(t)$ in the supply relation, Eq. (17), should be second order in time.[6] Twenty-one out of twenty-three of the estimated parameters are statistically significant at the 1% level; the values of R^2 range from 0.58 to 0.99. Regularity conditions are checked; monotonicity is satisfied for all observations and seven observations violate concavity.

Table 2: Results of hypothesis tests

Restrictions	Wald statistic	Critical value (1% significance level)	Degree of freedom
$\mu_C = \mu_O = 0$	294.88	9.21	2
$\mu_{Ct} = \mu_{Ot} = 0$	160.26	9.21	2
$\delta_C = \delta_O = \delta_G\ (= 1)$	662.58	9.21	2
$\delta_C = \delta_O$	534.43	6.63	1
$\delta_C = \delta_G\ (= 1)$	279.43	6.63	1
$\delta_O = \delta_G\ (= 1)$	377.47	6.63	1

[6] That is, $\theta(t) = \theta_0 + \theta_t t + \theta_{tt} t^2$.

Table 3: Parameter estimates

Parameters	Estimates	Parameters	Estimates
α_0	-22.8740 (2.9529)**	γ_{CO}	-0.0011 (0.0003)**
α_Q	7.6867(1.0948)**	γ_{CG}	-0.0012 (0.0005)**
α_t	-0.0856(0.0063)**	γ_{OO}	0.0733 (0.0172)**
α_C	0.0025 (0.0043)	γ_{OG}	-0.0722 (0.0172)**
α_O	-0.3997 (0.2426)	γ_{GG}	0.0734 (0.0170)**
α_G	1.3972 (0.2406)**	γ_{CQ}	0.0030 (0.0009)**
μ_C	-6.2317 (0.3860)**	γ_{OQ}	0.1641 (0.0478)**
μ_{Ct}	0.0712 (0.0108)**	γ_{GQ}	-0.1671 (0.0477)**
μ_O	-2.1918 (0.3686)**	γ_{QQ}	-1.3115 (0.2013)**
μ_{Ot}	0.2365 (0.0192)**	θ_0	0.4915 (0.0148)**
μ_G	0[a]	θ_t	-0.0273 (0.0022)**
μ_{Gt}	0[a]	θ_{tt}	0.0006 (0.0001)**
γ_{CC}	0.0023 (0.0007)**		

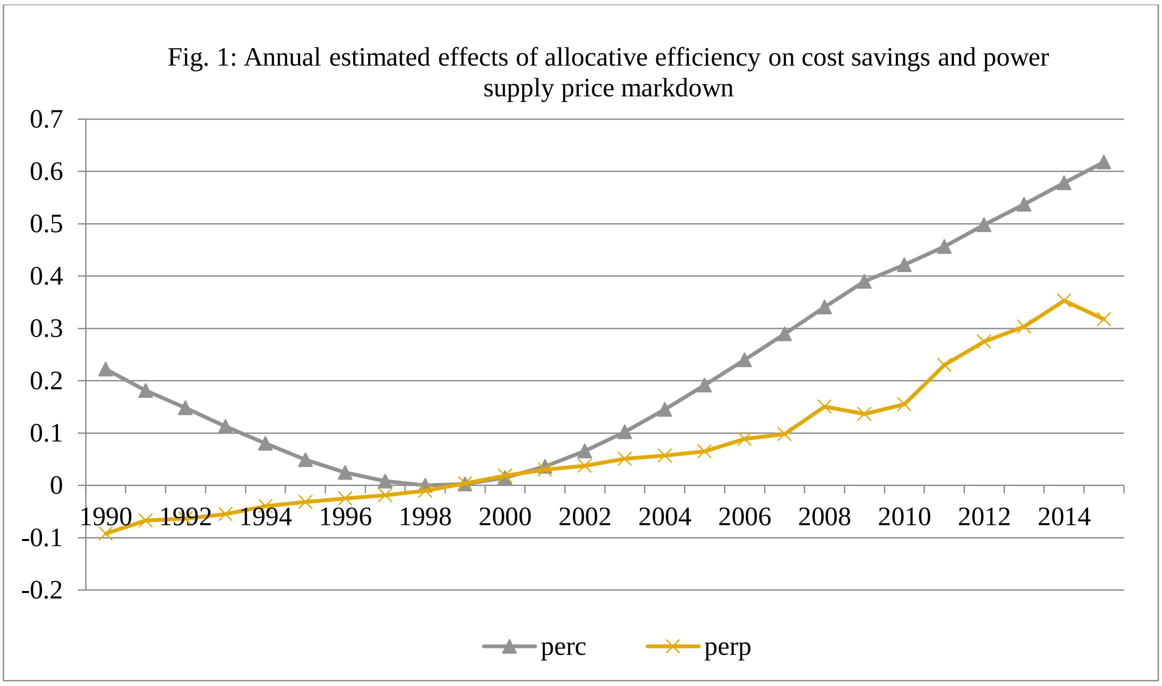
[a] The restrictions are imposed, so that $\delta_G = 1$.
Note: the numbers in parenthesis are the standard errors; ** indicates the significance at the 1% level.

The potential cost savings ($perc$) obtainable by achieving the allocative efficiency of the fuel inputs can be estimated by comparing the fitted actual fuel costs ($\widehat{FC}$) with what they would have been if allocative efficiency had been attained ($\widehat{FC}^*$), as follows:

$$perc = \left|\frac{\widehat{FC}^* - \widehat{FC}}{\widehat{FC}}\right|, \quad (22)$$

where $\widehat{FC}$ is calculated by substituting the parameter estimates in Table 3 into Eq. (15) and $\widehat{FC}^*$ is calculated by setting the restrictions (20).

Though exhibiting a decreasing trend in the early phase for a short period of time, as shown in Fig. 1, the time path of $perc$ turns around after 1998 and increases continuously to 61.8% in 2015. This implies that the allocative inefficiency of fuel inputs starts to increase substantially beginning in 1999. An OLS regression of the values of $perc$ over time indicates that $perc$ increased annually by an average of 2.1% (4.1%) over the period of 1990-2015 (1999-2015). The power plants, on the average, could have reduced their fuel costs by as much as 22.1% per year by achieving the allocative efficiency of fuel inputs over the sample period.



The percentage changes for the quantity of each fuel required to achieve allocative efficiency ($perf_i$) can be estimated by comparing the fitted quantities ($\widehat{F_i}$) with the quantities that would have been demanded had allocative efficiency been attained ($\widehat{F_i^*}$), as follows:

$$perf_i = \frac{\widehat{F_i^*} - \widehat{F_i}}{\widehat{F_i}}, \quad i = C, O, G, \tag{23}$$

where $\widehat{F_i}$ are calculated using the fitted values of M_i^s and RC^s, which are obtained by substituting the parameter estimates into Eq. (9) and Eq. (11), in Eq. (12); $\widehat{F_i^*}$ are calculated by setting the restrictions (20). As presented in Table 4, the power plants could have achieved the allocative efficiency of fuel inputs by decreasing the quantities of coal and gas demanded, on average, by 98.3% and 27.2%, respectively, while increasing the quantity of oil demanded by 25.5% over the sample period. During 1990-1998, however, gas was demanded more, and oil was demanded less compared with their optimal quantities.

Table 4: Annual trend of the percentage changes for the quantity of each fuel input required to achieve allocative efficiency

Year	$perf_C$	$perf_O$	$perf_G$
1990	-0.971	-0.600	0.349
1991	-0.977	-0.556	0.317
1992	-0.977	-0.504	0.309
1993	-0.977	-0.442	0.287
1994	-0.978	-0.367	0.271
1995	-0.977	-0.291	0.216
1996	-0.978	-0.208	0.156
1997	-0.978	-0.123	0.085
1998	-0.980	-0.038	0.007
1999	-0.979	0.053	-0.069
2000	-0.972	0.140	-0.148
2001	-0.976	0.234	-0.220

2002	-0.979	0.314	-0.296
2003	-0.978	0.394	-0.366
2004	-0.985	0.478	-0.428
2005	-0.986	0.546	-0.489
2006	-0.985	0.602	-0.545
2007	-0.987	0.647	-0.595
2008	-0.990	0.728	-0.635
2009	-0.991	0.783	-0.673
2010	-0.993	0.698	-0.710
2011	-0.994	0.694	-0.736
2012	-0.993	0.748	-0.759
2013	-0.992	0.804	-0.780
2014	-0.991	0.892	-0.799
2015	-0.993	1.004	-0.816
Average	-0.983	0.255	-0.272

The potential power supply price markdown obtained by achieving the allocative efficiency of fuel inputs can be estimated by comparing the fitted power supply price ($\hat{P}$) with what it would have been had allocative efficiency been attained ($\widehat{P^*}$), as follows:

$$perp = -\left(\frac{\widehat{P^*} - \hat{P}}{\hat{P}}\right), \tag{24}$$

where $\hat{P}$ is calculated by substituting the parameter estimates in Table 3 into Eq. (17) and $\widehat{P^*}$ is calculated by setting the restrictions (20).

As shown in Fig. 1, the values of $perp$are estimated to be negative over the period of 1990-1998, indicating that the achievement of the allocative efficiency of fuel inputs has unexpectedly led to a rise in fuel costs, pushing up the power supply price. This is because the adjustment costs incurred in allocating fuel inputs appear to outweigh the relatively lower potential cost savings ($perc$) during that period. Not until $perc$ starts to gradually increase in 1999 do the values of $perp$ become positive and exhibit an overall upward trend, varying from a low of 0.3% to a high of 31.8%. An OLS regression of the values of $perp$ over time indicates that $perp$ increased has been increasing by 1.6% (2.2%) per year, on average, over the period of 1990-2015 (1999-2015). The achievement of the allocative efficiency of fuel inputs would make it possible for the power plants to reduce their power supply price by an average of 7.6% per year over the sample period.

V. Conclusion

There exist several types of factors causing distortion in the Korean power market, in which the publicly owned KEPCO monopolizes the electricity supply. These include the government's top-down power supply planning, electricity price controls, the bureaucracy of KEPCO, etc. Firms subject to regulatory environment are likely to fail to achieve cost-minimization with respect to market prices, because the divergence between the shadow prices and market prices of inputs could cause allocative inefficiency costs. In this paper, we test for the allocative efficiency of fuel inputs for the Korean electric power generation industry over the period of 1990-2015 by estimating a shadow cost function along with the unobservable shadow prices jointly with the power supply relation. Then, we calculate the potential cost savings and maximum power supply price markdown obtained by imposing allocative efficiency.

The null hypothesis of allocative efficiency with respect to all fuel inputs is rejected, implying that the power plants could not achieve cost-minimization subject to market prices.

The time path of the potential cost savings showed a decreasing trend for the period from 1990 to 1998, but turned around after 1998 and increased continuously to as much as 61.8% in 2015. The potential cost savings increased by an annual average of 2.1% over the period of 1990-2015. On average, the power plants could have reduced their fuel costs by as much as 22.1% per year by reducing their demands for coal and gas by 98.3% and 27.2%, respectively, and increasing their oil demand by 25.5%over the sample period.

The achievement of the allocative efficiency of fuel inputs led to a rise in fuel costs, pushing up the power supply price over the period of 1990-1998, because the adjustment costs incurred in allocating fuel inputs likely exceeded the potential cost savings. The potential power supply price markdown shows an overall upward trend from 0.3% in 1999 to 31.8% in 2015.On average, the potential power supply price markdown increased annually by 1.6% and the attainment of allocative efficiency would have made it possible to lower the power supply price by 7.6% a year over the period of 1990-2015.

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