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Substitution between Purchased Electricity and Fuel for Onsite Power Generation in the Manufacturing Industry: Plant level analysis in Japan[1]

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Abstract

Using plant level data, we investigate the substitution between purchased electricity and fuel usage for onsite power generation by estimating the cross price elasticities in Japan. We find that the sensitivity of the fuel demand for onsite power generation to the changes in the price of purchased electricity and the degree of sensitivity depend heavily on industrial characteristics. We also calculate the expenditure elasticities for the fuels and find that firms prefer to use electricity generated on site compared to purchased electricity. Furthermore, from the analysis of the preference for fuel types used in onsite generation, we find that coal, which is relatively inexpensive but has relatively high CO_2 emission, is increasingly preferred by firms across industries. Some industries indeed are contributing to the reduction of CO_2 emissions by either replacing oil with scrap materials as fuel and/or utilizing recovered fuel or byproducts to generate onsite power. The results indicate the effort capacity to reduce emissions appears to heavily depend on industrial characteristics.

Keywords: Substitution, Purchased electricity, Onsite power generation, Manufacturing industry
JEL classification: D22, D24, L61, L62, L65

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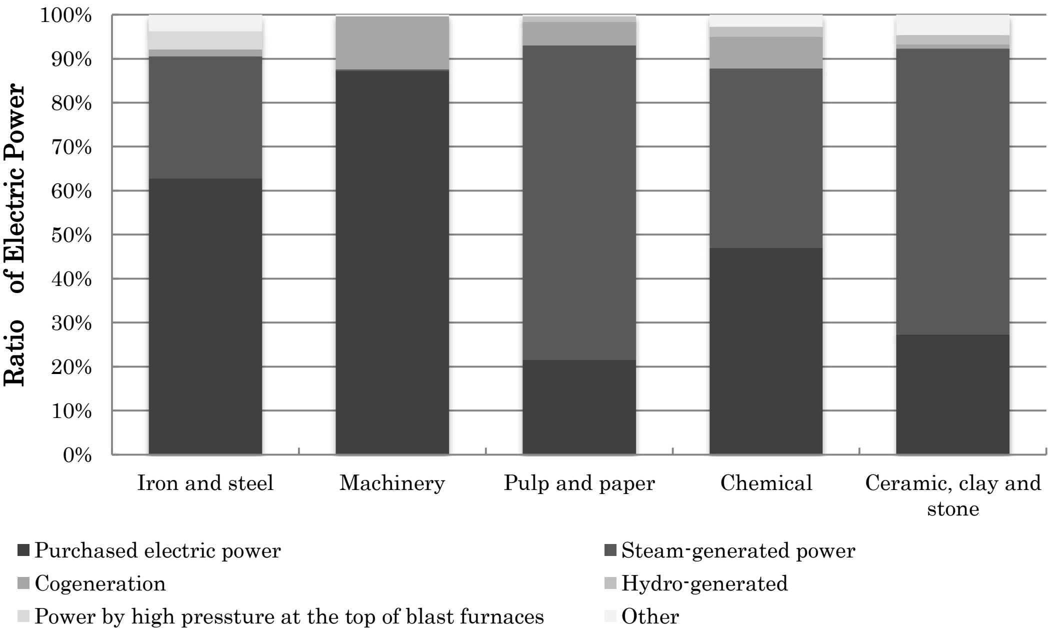
1. INTRODUCTION

Much of the literature has investigated energy demand by estimating the price elasticity of demand, which indicates the percentage change in the quantity of demand in response to a one percent change in price (e.g., Fuss, 1977; Pindyck, 1979; Considine, 1989; Serletis & Vasetsky, 2010; and Steinbuks, 2012). Stern (2012) showed that the levels of elasticities of the oil-electricity and gas-electricity are greater than unity by employing a meta-analysis of the interfuel substitutability. This result implies the substitution effect between purchased electricity and fuels do exist and should be integrated into the analysis of price elasticity.

Japanese researchers have been evaluating the substitution between fuels as well as between fuels and purchased electricity in the post oil crisis period by using aggregated data. Among the studies of the manufacturing industries in Japan, Matukawa et al. (1983) found substitution between purchased electricity and coal, mentioning the indication of coal‒fired generation. This implies that a study to understand substitution between purchased electricity and fuels for onsite power generation is needed.

Onsite power generation has become increasingly important,[5] and major power suppliers to manufacturing industry as plants can substitute it for purchased electricity. This implies the need to understand the substitution between fuel and electricity purchased in addition to the substitution between the fuels. Figure 1 shows the distribution of the purchased electricity and the electricity generated onsite by the industry. The figure indicates that onsite power accounts for a large portion of the electricity supply. In particular, onsite power accounts for 80 % of the power supply in the pulp, paper and paperboard industry.



Note: The distribution is calculated by using a unit ［kWh］ for electric power consumption.

Fig.1 Distribution of Electricity Supply in FY2012

While the importance of onsite power generation has been widely discussed, to our knowledge, there is no

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[5] The rise of electricity rates for power by about 28 % since 2010 (METI, 2014) and the shortage of power supply capacity of major electric utilities caused by the Great East Japan Earthquake called to public attention and provided an incentive to introduce an onsite power generator. This situation requires the elasticity of electricity demand to be investigated in addition to a whole energy demand by an establishment.

study that provides systematic analysis of the substitution between purchased electricity and onsite power generation (such as steam-generated power and cogeneration). This is primarily due to the use of aggregate data in the literature, where the substitution is hard to identify. We contribute to the understanding of energy demand by using the original plant level panel data to analyze the substitution between purchased electricity and onsite power generation[6][7].

In the analysis, we estimate both demand and expenditure elasticities of fuel types used for onsite generation. We calculate the elasticities for 5 different industries and for several fuel patterns for each industry. As a main result, we find through the calculation of demand elasticity whether the fuel demand for onsite power generation is sensitive to the changes of price of purchased electricity. Similarly when the fuel demand is sensitive to the price change, the degree of sensitivity depends on industrial characteristics. Also, from the calculated expenditure elasticities for various fuels used for onsite generation for the industries, we find that the establishments of all industries covered in this analysis prefer to use electricity generated on site compared to the purchased electricity.

In addition to the elasticity analysis, we estimate the basic CO_2 emission units for each fuel type used for the onsite power generation. The estimated results help to understand the environmental impact of the establishment's fuel selection and lead to providing the evidence needed to discuss the mitigation of negative externality from climate change. Keidanren (Japan Business Federation) announced the Keidanren Action Plan on Environment in 1997, and since then, the manufacturing industry in Japan has been taking a voluntary approach to reducing CO_2 emissions. However, the data shows that the level of effort depends on the industries. Some industries are indeed contributing to the reduction of CO_2 emissions by replacing oil with scrap materials as the fuel to generate onsite power. However, there are other industries that are replacing oil with relatively cheaper coal, which in turn increases CO_2 emissions. Thus, the capacity of the effort to reduce emissions appears to heavily depend on industrial characteristics.

This paper is structured as follows. Section 2 explains the theoretical model used to estimate the price elasticity and expenditure elasticity, which is based on the linear approximate almost ideal demand system (LA/AIDS) developed by Deaton and Muellbauer (1980). Section 3 provides a description of the data. Section 4 provides the estimation results of demand and expenditure elasticity. Section 5 concludes.

2. MODEL

We take the following function as a work function: $W = g(F_1, F_2, \cdots, F_n)$, ・・・(1)

where F_i is the amount of fuel i. The output is a scalar output and thermal energy for the heating process or electric power for driving machines. We consider electric power in this study. An indirect work function can be written in the form: $W = h(p_1/x, p_2/x, \cdots, p_n/x)$ ・・・(2)

where p_i and x are a unit price of fuel i and the total expenditure for energy consumed, respectively. Referring to the previous literature in total (Jorgenson & Lau, 1975; Deaton & Muellbauer, 1980), we take the translog function as the

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[6] In this analysis, electric power generated on site does not always indicate consumed power, because some firms sell electricity generated on site to an electric power company.

[7] Some literatures address economic incentive to stimulate electric power conservation during peak demand hours. Igarashi and Ohashi (2015) estimated the potential of industrial demand response by using the data of establishments who had a contract of adjusting demand and supply with an electric power company. Ito et al. (2013) investigated the effect of moral suasion and dynamic pricing during peak demand hours by using the household level data obtained from field experiment.

indirect work function as follows:

$$w = \alpha_0 + \sum_{i=1}^{n} \alpha_i log\left(\frac{p_i}{x}\right) + \frac{1}{2}\sum_{i=1}^{n}\sum_{j=1}^{n} \beta_{ij} log\left(\frac{p_i}{x}\right) log\left(\frac{p_j}{x}\right), \qquad \cdots(3)$$

where $\sum_{i=1}^{n} \alpha_i = -1$ and $\beta_{ij} = \beta_{ji}$ are chosen for normalization.

The work (w) is normalized between 0 and 1. The zero of w means the minimum quantity of work, and one of w does the maximum quantity of work given the fuel prices and the expenditure during the period of estimation. This is the same form as the indirect utility function from which Deaton and Muellbauer (1980) obtained a general form of the cost function. Following the study, a cost function defined for the minimum expenditure necessary to achieve a specific work level is chosen for as follows:

$$log\ c(w, \boldsymbol{p}) = log\ a(\boldsymbol{p}) + w\{log\ b(\boldsymbol{p}) - log\ a(\boldsymbol{p})\} \quad . \qquad \cdots(4)$$

We take

$$log\ a(\boldsymbol{p}) = \alpha_0 + \sum_{k=1}^{n} \alpha_k log\ p_k + \frac{1}{2}\sum_{k=1}^{n}\sum_{j=1}^{n} \gamma_{kj}^{*} log\ p_k log\ p_j \qquad \cdots(5)$$

$$log\ b(\boldsymbol{p}) = log\ a(\boldsymbol{p}) + \beta_0 \prod_{k=1}^{n} p_k^{\beta_k} \qquad \cdots(6)$$

Then, the AIDS cost function is expressed as follows:

$$log\ c(w,\boldsymbol{p}) = \alpha_0 + \sum_{k=1}^{n} \alpha_k log\ p_k + \frac{1}{2}\sum_{k=1}^{n}\sum_{j=1}^{n} \gamma_{kj}^{*} log\ p_k log\ p_j + w\beta_0 \prod_{k=1}^{n} p_k^{bk} . \qquad \cdots(7)$$

As a firm minimizes the cost, $c(w, p)$ is equal to expenditure x. By applying Shephard's Lemma (Shephard, 1953), the cost share equation is expressed imposing a condition for the cost function to be homogeneous of degree one in p as follows:

$$s_i = \alpha_i + \sum_{j=1}^{n} \gamma_{ij} log\ p_j + \beta_i log\left(\frac{x}{P}\right) \qquad \cdots(8)$$

where $\gamma_{ij} = 0.5(\gamma_{ij}^{*} + \gamma_{ji}^{*})$ and P is a price index:

$$log\ P = \alpha_0 + \sum_{k=1}^{n} \alpha_k log\ p_k + \frac{1}{2}\sum_{k=1}^{n}\sum_{j=1}^{n} \gamma_{kj} log\ p_k log\ p_j . \qquad \cdots(9)$$

The following conditions are imposed for summation, price homogeneity and symmetry:

$$\sum_{i=1}^{n} \alpha_i = 1, \quad \sum_{i=1}^{n} \gamma_{ij} = 0, \quad \sum_{i=1}^{n} \beta_i = 0 \ \text{ and } \ \gamma_{ij} = \gamma_{ji}. \qquad \cdots(10)$$

According to the study of Alston, Foster and Green (1994), the elasticity formula for the true AIDS model could result in poor estimates. In this study, the weighted average price index P^{*} is used for linear approximation instead of P where

$$logP^{*} = \sum_{i=1}^{n} s_i\ log\ p_i \qquad \cdots(11)$$

The partial price elasticity of demand is calculated as follows.

$$e_{ij}\big|_x = \frac{\partial log\ E_i}{\partial log\ p_j} \qquad \cdots(12)$$

$$= -\delta_{ij} + \frac{\gamma_{ij}}{s_i} - \frac{\beta_i s_j}{s_i}$$

where E_i is the energy of fuel i. This is conditional on the total expenditure.

The expenditure elasticity are calculated as follows:

$$e_{ix} = 1 + \frac{\beta_i}{s_i} \quad . \qquad \cdots(13)$$

We estimate the following equation as an empirical one:

$$s_{it}^{k} = \alpha_i + \sum_{j=1}^{n} \gamma_{ij} \, log \, p_{jt} + \beta_i \, log\left(\frac{x_t^k}{P_t^{*k}}\right) + \delta_i t + \xi_i t_{2011} \times D_{disaster} + \zeta_i^k D_k + \varepsilon_i \quad , \qquad \cdots(14)$$

where t, D_k, t_{2011}, $D_{disaster}$, ε are the time trend term to capture the effect of technical change, the dummy variable for an establishment, the dummy variable for the fiscal year 2011, the dummy variable for the damaged area by the Great East Japan Earthquake[8], and a random error, respectively. In addition to the equations in (10), the following conditions are imposed:

$$\sum_{i=1}^{n} \delta_i = 0 \ , \sum_{i=1}^{n} \xi_i = 0 \ \ and \ \ \sum_{i=1}^{n} \zeta_i^k = 0 \qquad \cdots(15)$$

Equation (14) is estimated, using the seemingly unrelated regression (Zellner, 1962). In the case of two fuel equations, they are estimated as a reduced equation by imposing the restrictions.

3. DATA

3.1 Data for electricity demand analysis

We use the monthly plant level survey data for the Yearbook of the Current Survey of Energy Consumption in the Selected Industries by the Ministry of Economy, Trade and Industry. Available variables include amounts of purchased electric power, electric power from onsite power generator and volume of fuel consumed for boiler use. The fuel prices except purchased electricity rate are drawn from the Handbook of Energy & Economic Statistics in Japan (EDMC, 2014). The purchased electricity price is calculated based on the annual reports of 10 major Japanese electricity suppliers. All prices are converted to real prices using the GDP implicit price deflator (2005=1.00). Note that the price paid may be different from that used in the study, because it is independently decided in a contract of each establishment. In the analysis, the fuel volume is converted to primary energy by using the values[9] in the guide for completing the questionnaire of the Current Survey of Energy Consumption.

The fuel consumption data for cogeneration are included in the survey for the yearbook. It is needed, however, to estimate the fuel consumption data for the steam-generated power[10], because they are not included in the survey. As the data of the amount of electric power by an onsite steam–generated power generator are included in it, we can estimate the volume of fuel for steam-generated power generation. We divide the amount of electric power generated by the electric power generation efficiency of a generator. We assume that electric power generation efficiency

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[8] The service area of the utilities damaged by the earthquake is decided as the area of the dummy variable $D_{disastor}$.

[9] We use a unit conversion constant 3.6 MJ/kWh to obtain the primary energy of the purchased electricity from the guide.

[10] The steam–generated power is generated by steam from a boiler. The electric power by the CHP with a backpressure turbine is classified as the steam–generated power.

is 35%[11]. It is difficult to distinguish the volume of steam for onsite generation by a specific fuel. The volume of fuel for onsite power generation is derived by the volume of fuel for boiler use in order from recovery fuels to purchased fuels

3.2 Solution for the conditional data set

Figures 6.1 to 6.5 in the APPENDIX show the estimated onsite power generator possession ratio. Not every firm possesses an onsite power generator. In addition, firms in larger scale of energy consumption possess an onsite power generator.

There are some fuel patterns among the onsite power generator owners. Not every establishment possessing an onsite power generator uses all types of fuels used in an industry. A large portion of zero demand of fuel should be included when economic models are applied to the entire data. The demand or cost share of zero is not allowed in the estimation because it causes some problems. In the previous literature, there are two approaches to the zero demand of a fuel in firms. One of them is that some types of fuels are not allowed by technological constraints. Woodland (1987) made the assumption and estimated the conditional production functions of manufacturing establishments in the Australian state of New South Wales. He estimated the models separately for each observed pattern of fuel use. Bjørner and Jensen (2002) took the same approach in the study of Danish industrial companies. Another assumption is that one factor is not economical to use all factors. Firms decide to use some of the different types of fuel deliberately. Lee and Pit (1987) developed the model and adapted it to the data of Indonesian firms. Bousque and Ivaldi (1998) followed the approach. Bousquet and Ladoux (2006) investigated two approaches through the case of three energy input types. The research showed that the prediction of the fuel pattern in the latter approach was globally acceptable in two inputs cases, but only 39% of firms were predicted in all three input cases. This implies that the estimated fuel pattern by the latter model does not address every fuel pattern change.

There may be three cases of fuel pattern change: (1) to introduce a new type of fuel, (2) to stop using a type of fuels, and (3) to use a type of fuel intermittently. No technical barrier could prevent an establishment from starting to use a new type of fuel for an electric power generator. In the first case, however, there are some constraints. First, it is costly to replace a generator with new fuel. The timing of replacement depends not only on fuel prices but also on the establishment's investment plan. Second, no town gas pipeline network near the land of an oil user prevents an establishment from using town gas. Those are the examples of the budget and time constraints and the physical constraint. In contrast, no additional cost is required in the case of demand for a fuel decreasing to zero. Considering the cases mentioned above, both of the two previously developed approaches fit the situations. Moreover, in addition to the factor price, firm's environmental policy could be important for a fuel switch. It is difficult to address all practical fuel switch causes.

Our approach is a conditional estimation. Estimation is conducted for the model separately for each observed fuel pattern. The establishments with multiple electric power generators using different types of fuels or with an electric power generator for dual types of fuel can use a type of fuel intermittently. It is expected that a few limited establishments have such a capacity for fuel selection. As the maintenance cost for a redundant power generating system is higher than that of simple one, the situation with multiple fuels may be a temporary one for transition from one fuel to

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[11] The electric power generation efficiency varies in accordance with operating condition. The assumed value is decided based on the examples (the Ministry of Environment, 2014; Yoshimura & Takagi, 2002; Miyamoto, 2002).

another. Selected fuels are primary ones in an industry and the amount of the fuel is expected to comprise a large portion of energy consumed in an establishment. Therefore, fuel pattern change implies discontinuity in the volume of fuel.

The procedure for our exogenous fuel pattern change model is as follows. Suppose the demand for each fuel is denoted by “1” and “0” to express fuel pattern j for three fuel inputs (f_1, f_2 and f_3) as an example. Let f_3 be the demand of purchased electricity, assuming that all establishments always use purchased electricity. There are 2^2 fuel patterns; $[f_1f_2f_3]$ is [111], [101], [011] or [001]. Our focus in this study is the substitution between the purchased electricity and the fuel for onsite power generation. Estimation is conducted in each pattern except [001]. The cost share equation is adopted for only positive demand in a fuel pattern.

We take the following steps to address the zero demand problems.

A panel data set S is defined.

$S = \{f^k_{it} \mid f^k_{it}$ is an element of the original panel data$\}$,

where f^k_{it} is quantity of fuel i for establishment k at time t.

A subset of S is defined as follows:

$P_j = \{f^k_{it} \in S \mid f^k_{it}$ is an element of the fuel pattern j$\}$.

The set S is a union of the disjoint sets of P_j: $S = \cup_i P_i,\ \forall i, j \in I (i \neq j \rightarrow P_i \cap P_j = \phi)$.

We assume that the number of fuel pattern changes monotonically during the period of estimation. No establishment changes its fuel pattern very often. Under this assumption, an establishment changes its fuel pattern one time at most. If an establishment changes its fuel pattern, the estimation for it should be conducted for each fuel pattern.

$P^k_j = \{f^k_{it} \in P_j \mid f^k_{it}$ is an element of a consecutive time series data for establishment k$\}$.

Set P^k_j includes a series of elements for the establishment k at successive times in the fuel pattern j. Set $P_j \setminus P^k_j$ includes intermittent time series data. The establishments in the set change their fuel pattern frequently. In this study, the conditional cost share equations for the fuel pattern j are calculated for the data set of $FP_j = \cup_k P^k_j$. The elements (observations) of $\cup_j FP_j$ cover 99% of $\cup_j P_j$ for the iron and steel industry, 94% for the machinery industry, 92% for the pulp, paper and paperboard products industry, 95% for the chemical industry, and 96% for the ceramic, clay and stone products industry. The exogenous fuel pattern change model will generate a selection bias. As a result of the observation coverage, we take the data set as being a practical.

4. RESULTS

4.1 Selection of fuel and model

The distribution of the estimated amount of primary energy of fuels is presented in Fig. 2. We chose the main fuels for the analysis in the order of largest amount of primary energy. There are, however, some fuels excluded from the analysis. In the pulp, paper and paperboard industry, black liquor is excluded from the analysis, because it is recovered fuel. Scrap material is excluded from the analysis too. In the chemical industry, hydrocarbon oil and petroleum hydrocarbon are excluded from the analysis for simplification. They are by-products or fuel bought from other establishments. In addition, the surveys for establishments manufacturing petrochemical products are not made for receipt, inventory, and use as materials because of the limitation of the survey. In the ceramic and stone products industry, heavy fuel oil type B･C is excluded from the analysis, as the volume decreased to a relatively low level at the beginning of the estimation period.

We examined the fuel patterns of the owners of onsite power generation based on the estimated volume of fuels for each industry. To estimate the cost share equations, we extracted the fuel patterns, which have enough data for statistic processing. The decided fuel patterns are presented in the tables showing the estimation results of demand and expenditure elasticities.

Tables 3.1 to 3.11 in the APPENDIX present the parameter estimates of equation (18). We use the results of the fixed effects model with a time variable to estimate the elasticities based on the significance level of the coefficients for two fuel patterns: heavy fuel oil type A and purchased electricity in the machinery industry; coal and purchased electricity in the pulp, paper and paperboard industry. Except for the fuel patterns, we choose the results of the fixed effects model without a time trend variable as long as the random effects model is resoundingly rejected by the Hausman's specification test.

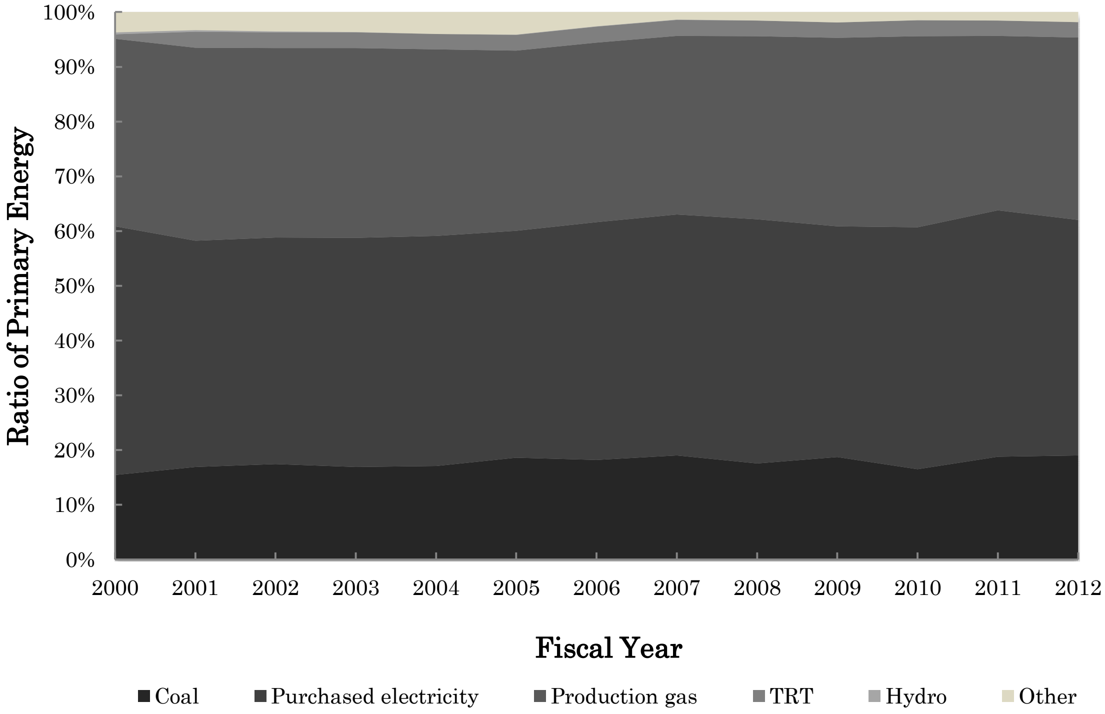

Fig. 2.1 Estimated Factor Distribution for Electricity Demand in the Iron and Steel Industry

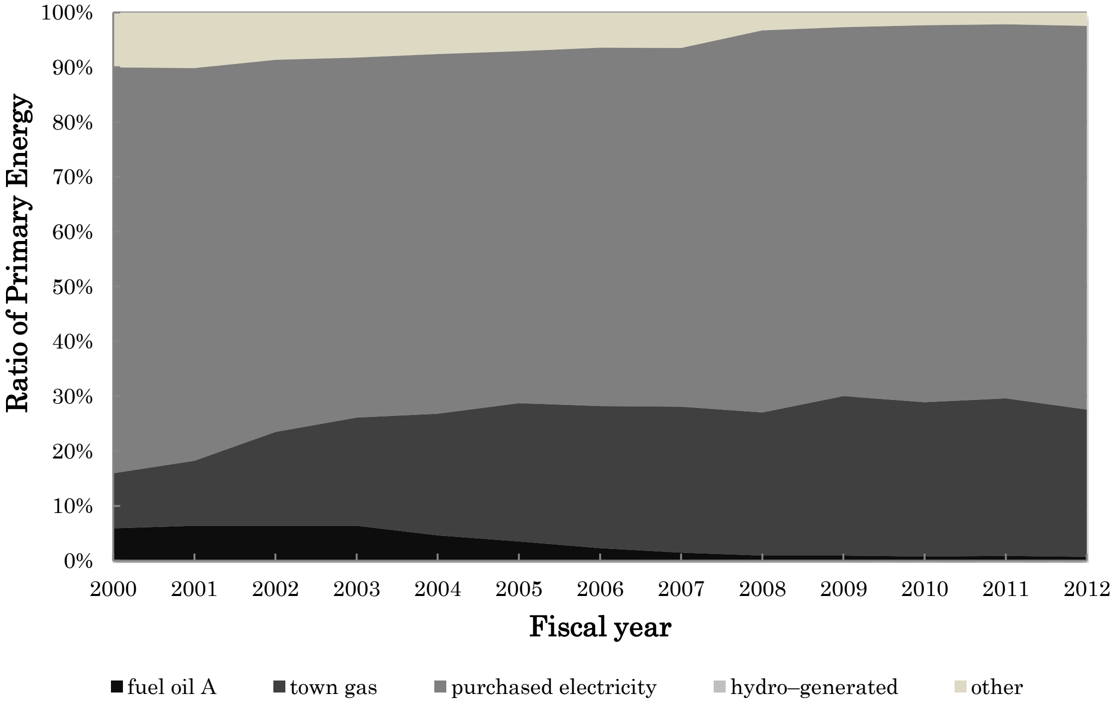

Fig. 2.2 Estimated Factor Distribution for Electricity Demand in the Machinery Industry

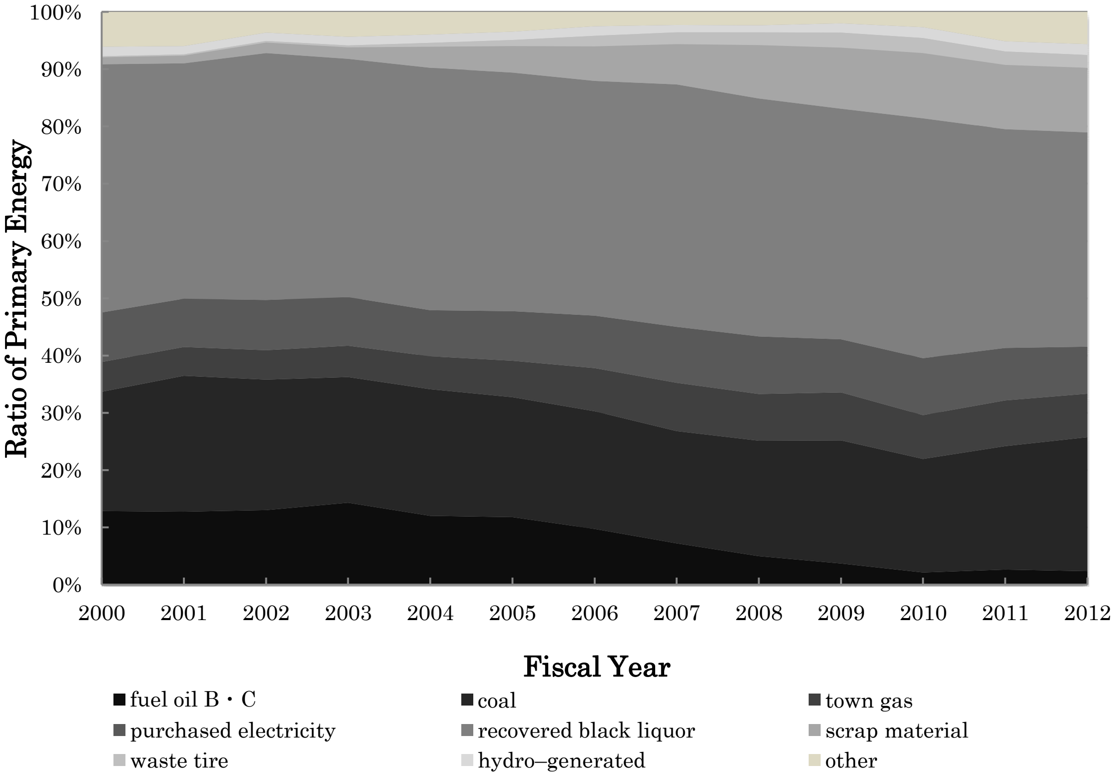

Fig. 2.3 Estimated Factor Distribution for Electricity Demand in the Pulp, Paper and Paperboard Industry

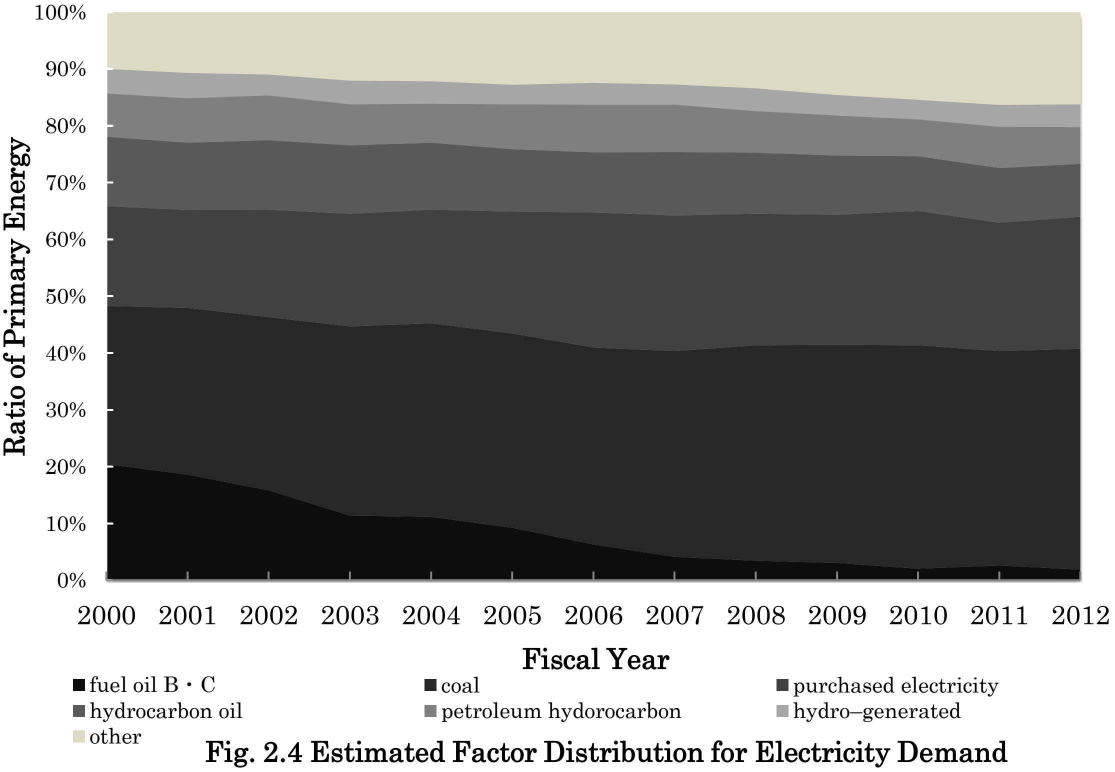

Fig. 2.4 Estimated Factor Distribution for Electricity Demand in the Chemical Industry

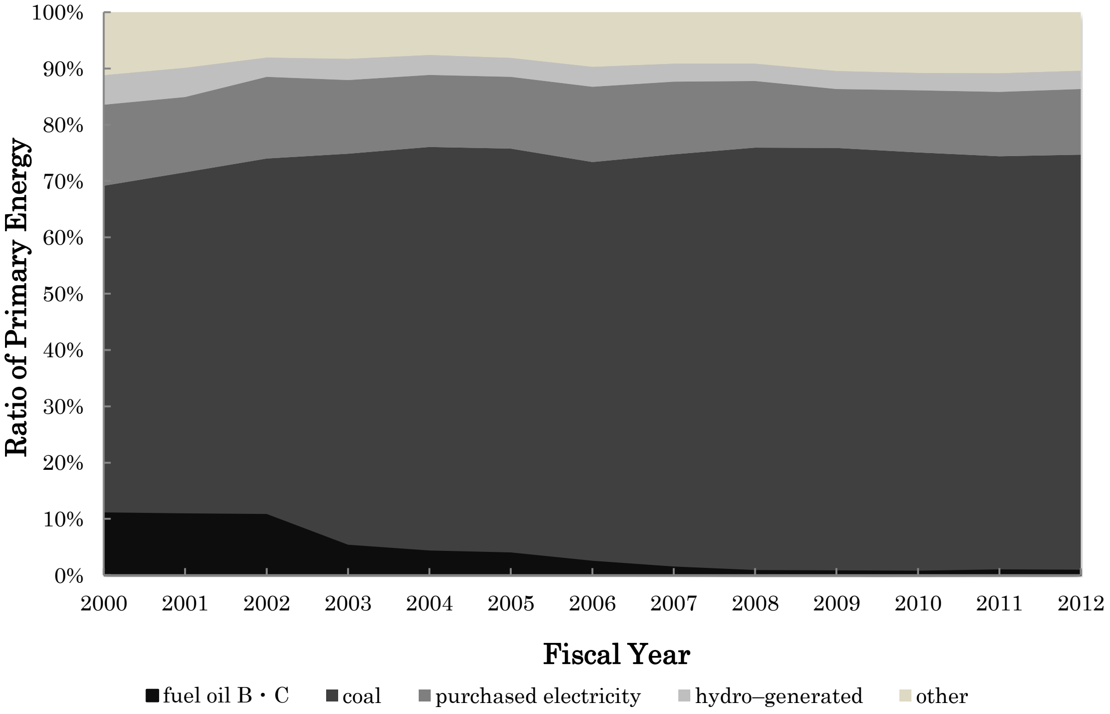

Fig. 2.5 Estimated Factor Distribution for Electric Demand in the Ceramics, Clay and Stone Products Industry

4.2 Price elasticities

Table 1 shows the estimated partial price elasticities[12] in each fuel pattern of the industries. Most of the industries' own-price elasticities are negative. These results indicate that a rise in the price of fuel lowers the demand as expected. An exception is the result of town gas in the machinery industry (0.04).

Electricity by onsite power generation can substitute for purchased electricity when purchased electricity rates increase. Therefore, the cross price elasticity for the fuel with respect to purchased electricity should be positive. Each industry, however, does not follow the previous explanation. Most of the cross price elasticities of fuel with respect to purchased electricity are negative. Understanding the unexpected results needs technical explanation.

In the machinery industry, all cross price elasticities in two factor cases are negative. Cogeneration (e.g., gas engine/turbine generators) is primary in onsite power generation in the industry. It delivers two forms of energy electricity and thermal energy as steam or hot water from a single fuel simultaneously. The energy efficiency of the rated power operation for cogeneration is the highest in operation conditions. If the price of purchased electricity increased, cogeneration system could not compensate the decline in the amount of purchased electricity because of the rated power operation. Thus the cross price elasticity for fuel with respect to purchased electricity should be zero or negative. The price increase of fuel for cogeneration system or a boiler could decrease steam supply to production process. If it led to the excess of the electricity supply, a firm would decrease the amount of purchased electricity. In those cases, the cross price elasticities are negative. Town gas is usually used for cogeneration. In the pulp, paper and paperboard industry, the cross price elasticity for town gas with respect to purchased electricity could be negative for the same reason mentioned above.

In the machinery industry, we find the positive cross price elasticity for oil with respect to purchased electricity in three factors case. There are two generators with different types of fuel for an establishment. There might be capacity room to compensate the decline in the amount of purchased electricity when purchased electricity rates increase. Additionally, the firms would possess two onsite power generators with different types of fuel for business continuity in case.

As seen in Table 1, we find the different sings of the cross price elasticities each other between purchased electricity and fuel. One of the possible explanations could attribute to the combined heat and power (CHP) using a backpressure turbine or a condensing turbine. We consider the case of the CHP with a backpressure turbine as an example. Steam from a boiler is used in production process after being used at the turbine to generate power. If the price of purchased electricity increased, the CHP could not compensate the decline in the amount of purchased electricity because of the rated power operation or the intended production output. On the other hand, the price increase of fuel could decrease the steam supply to production process and the amount of electricity generated by the CHP with a backpressure turbine. If it led to the shortage of electricity supply, a firm would purchase electricity from an electric power company increasingly. In those cases, it is possible for the two signs of cross price elasticities to be different. In the case of the CHP used by the iron and steel industry, the volume of production gases to generate power could be proportional to production output because they are by-products. If the price of purchased electricity increased, the CHP could not compensate the decline in the amount of purchased electricity because of the volume of production gases

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[12] In actual operation, both the complementarity and substitution between purchased electricity and onsite power generation may appear, depending on the demand of electric power and thermal energy used in production process. The results of estimated price elasticities indicate frequent demand change.

corresponding to the production output.

After the Great East Japan Earthquake, the electricity rates have increased because of the operation outage of the nuclear power plants. Onsite power is thought to be a solution to mitigate the increasing electricity rates. However, the results show that onsite power generators do not mitigate the impact of purchased electricity rate increase in all cases.

Turning to the level of demand elasticity, some of the industries' price elasticities are more than unity. In particular, the machinery industry has large demand elasticities, particularly in the three factors case. Thus, the industry is more sensitive to the change in the price of fuel or purchased electricity than other industries. This result is a surprise for us. The unit electricity cost for cogeneration is cheaper than purchased electricity. In addition, firms would like to keep the output power of cogeneration (e.g., gas engine/turbine generators) constant, as the total thermal efficiency of cogeneration is highest at the rated operation. Due to the above reasons, we had expected that the impact by price change either of the fuels of cogeneration or purchased electricity and the elasticities for the fuels could be small, contrary to the estimated results.

Table 1 Price elasticities for purchased electricity and fuels

Industry	Fuel pattern		Price elasticity		
Iron and Steel Industry	production gas (K)	e_{KK}	-0.81	***	(0.004)
	coal (C)	e_{KC}	-0.57	***	(0.005)
	purchased electricity (E)	e_{KE}	-0.26	***	(0.002)
		e_{CK}	-0.68	***	(0.005)
		e_{CC}	-0.91	***	(0.007)
		e_{CE}	-0.14	***	(0.002)
		e_{EK}	0.25	***	(0.001)
		e_{EC}	0.29	***	(0.001)
		e_{EE}	-0.77	***	(0.001)
	production gas (K)	e_{KK}	-1.57	***	(0.013)
	purchased electricity (E)	e_{KE}	-0.92	***	(0.014)
		e_{EK}	0.23	***	(0.005)
		e_{EE}	-0.63	***	(0.006)
Machinery	heavy fuel oil B･C (O)	e_{OO}	-2.59	***	(0.023)
	town gas (T)	e_{OT}	-1.42	***	(0.039)
	purchased electricity (E)	e_{OE}	1.60	***	(0.03)
		e_{TO}	-0.10	***	(0.003)
		e_{TT}	0.04	***	(0.008)
		e_{TE}	-1.62	***	(0.008)
		e_{EO}	0.10	***	(0.001)
		e_{ET}	-0.41	***	(0.003)
		e_{EE}	-1.18	***	(0.003)
	town gas (T)	e_{TT}	-0.41	***	(0.003)
	purchased electricity (E)	e_{TE}	-1.10	***	(0.003)
		e_{ET}	-0.26	***	(0.001)
		e_{EE}	-0.51	***	(0.001)
	heavy fuel oil A (o)	e_{oo}	-0.66	***	(0.005)
	purchased electricity (E)	e_{oE}	-1.34	***	(0.006)
		e_{Eo}	-0.10	***	(0.002)
		e_{EE}	-0.61	***	(0.002)
Pulp, Paper and Paperboard	coal (C)	e_{CC}	-1.44	***	(0.003)
	purchased electricity (E)	e_{CE}	-0.16	***	(0.003)
		e_{EC}	0.37	***	(0.002)
		e_{EE}	-0.86	***	(0.002)
	town gas (T)	e_{TT}	-0.99	***	(0.003)
	purchased electricity (E)	e_{TE}	-0.30	***	(0.003)
		e_{ET}	-0.01	***	(0.008)
		e_{EE}	-0.14	***	(0.008)
	heavy fuel oil B･C (O)	e_{OO}	-1.11	***	(0.019)
	purchased electricity (E)	e_{OE}	-0.52	***	(0.02)
		e_{EO}	0.07	***	(0.012)
		e_{EE}	-0.66	***	(0.013)
Chemical	heavy fuel oil B･C (O)	e_{OO}	-1.06	***	(0.002)
	purchased electricity (E)	e_{OE}	-0.31	***	(0.003)
		e_{EO}	0.03	***	(0.001)
		e_{EE}	-0.85	***	(0.001)

	coal (C) purchased electricity (E)	e_{CC}	-1.05	***	(0.001)
		e_{CE}	-0.25	***	(0.001)
		e_{EC}	0.09	***	(0.002)
		e_{EE}	-0.59	***	(0.001)
Ceramic, Clay and Stone Industry	coal (C) purchased electricity (E)	e_{CC}	-1.11	***	(0.001)
		e_{CE}	-0.20	***	(0.001)
		e_{EC}	0.28	***	(0.003)
		e_{EE}	-0.49	***	(0.002)

Notes: Simulation is conducted with sample means to obtain elasticities and standard errors (in parentheses) based on formula (12); *,**,and *** indicate significance levels of 10%, 5%, and 1%, respectively.

4.3 Expenditure elasticities

Table 2 shows the estimation results of the expenditure elasticities. All expenditure elasticities for the fuel are larger than those of purchased electricity and more than unity. The results indicate that establishments consume more electricity by onsite power generation than purchased electricity when the total expenditure to meet electricity demand increases. Figure 3.1 and Fig. 3.2 show the estimation results[13] of cost for mono–generation and cogeneration during the period of estimation. The generation costs are cheaper than purchased electricity rate except the mono-generation by oil. This is one of the reasons why establishments prefer onsite power generation to purchased electricity. Mono-generation by oil is a limited case, as cogeneration is energy efficient and popular in industries.

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[13] The power generation unit cost is written as follows:

$$Power\ Generation\ Unit\ Cost = \frac{I - S + CAP \cdot CF \cdot T \cdot \int_0^T \left(m + p_g\right) e^{-rt} dt}{CAP \cdot CF \cdot T}, \quad \cdots(16)$$

where I, S, CAP, CF, T, p_g, m and r are equipment cost, subsidy, equipment capacity, capacity factor, service life, fuel expense to generate one kWh, maintenance cost per kWh, and discount rate, respectively. We assume that firms operate power generators considering only the time of operation. Then, the power generation unit cost is written as follows:

$$PowerGeneration\ Unit\ Cost = i - s + m + p_g, \quad \cdots(17)$$

where i and s are capital cost per kWh and subsidy rate per kWh, respectively. We also assume that firms operate power generators, comparing the summation of maintenance cost and fuel expenses to generate a unit of electric power with purchased electricity rate at the time of operation. We take power generation unit cost as follows:

$$PowerGeneration\ Unit\ Cost = m + p_g. \quad \cdots(18)$$

The fuel expenses p_g for mono-generation and cogeneration are written as follows:

$$p_g = \frac{p_f}{\eta_{mgs\_e}} \quad \cdots(19)$$

and

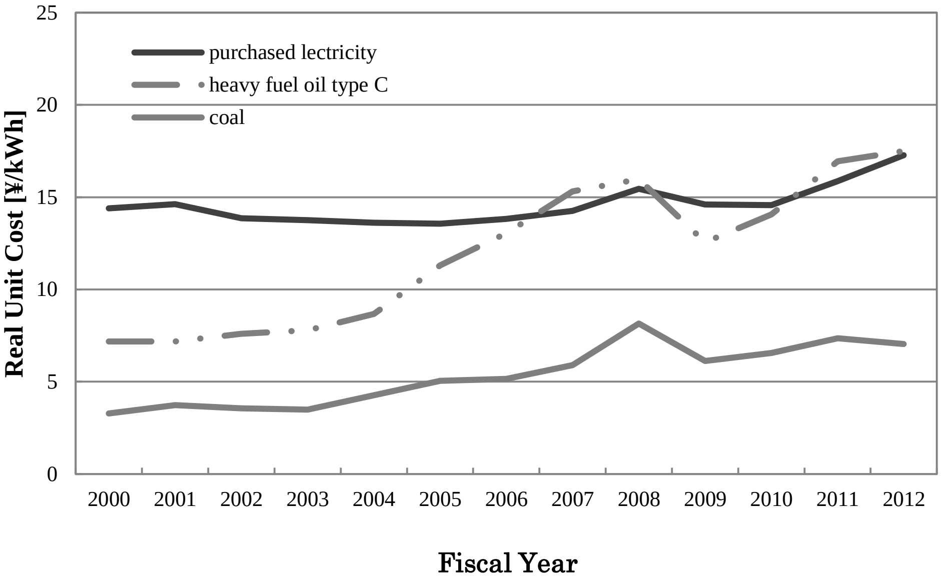
$$p_g = p_e - \left\{ \left(p_e \eta_{cgs\_e} + \frac{p_f \eta_{cgs\_t}}{\eta_b} \right) - p_f \right\}, \quad \cdots(20)$$

where p_f, η_{mgs_e}, p_e, η_{cgs_e}, η_{cgs_t}, η_b are a unit price of fuel, the generation efficiency for mono-generation, purchased electricity rate, the power generation efficiency and thermal recovery efficiency for cogeneration, and the thermal efficiency of a boiler for comparison with cogeneration, respectively. We use the numerical values for maintenance cost in the report concerning verification of power generation cost to the subcommittee for long-term energy supply-demand outlook by the working group under the advisory committee about energy problem (METI, 2015).

Table 2 Expenditure elasticities of purchased electricity and fuels

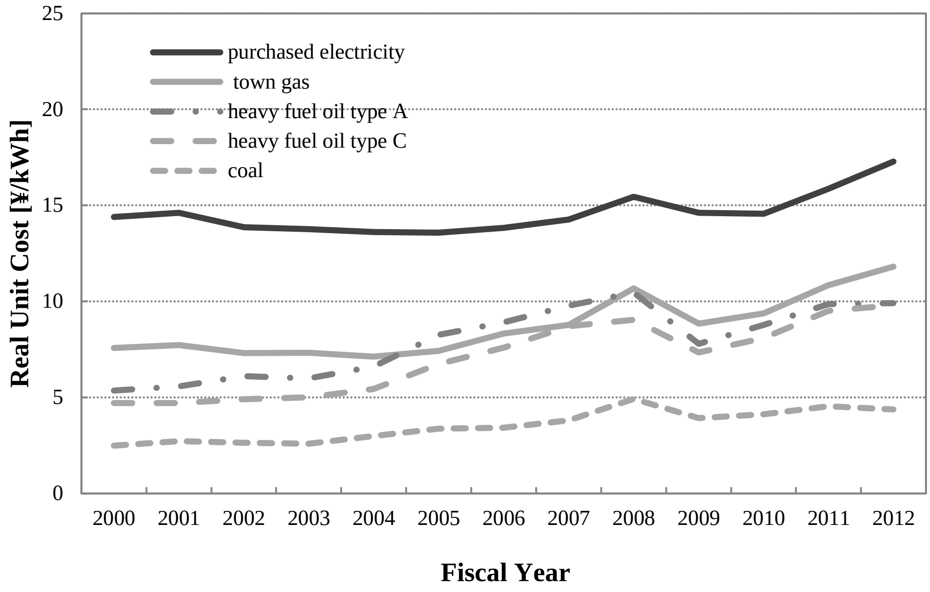
Industry	Fuel pattern	Expenditure elasticity			
Iron and Steel	production gas (K)	e_{Kx}	1.65	***	(0.002)
	coal (C)	e_{Cx}	1.72	***	(0.002)
	purchased electricity (E)	e_{Ex}	0.23	***	(0.001)
	production gas (K)	e_{Kx}	1.86	***	(0.003)
	purchased electricity (E)	e_{Ex}	0.52	***	(0.002)
Machinery	heavy fuel oil type B･C (O)	e_{Ox}	2.45	***	(0.019)
	town gas (T),	e_{Tx}	1.66	***	(0.004)
	purchased electricity (E)	e_{Ex}	0.66	***	(0.001)
	town gas (T)	e_{Tx}	1.51	***	(0.001)
	purchased electricity (E)	e_{Ex}	0.77	***	(0.001)
	heavy fuel oil type A (o)	e_{ox}	2.01	***	(0.004)
	electricity (E)	e_{Ex}	0.71	***	(0.001)
Pulp Paper and Paperboard	coal (C)	e_{Cx}	1.61	***	(0.002)
	purchased electricity (E)	e_{Ex}	0.50	***	(0.001)
	town gas (T)	e_{Tx}	1.31	***	(0.001)
	purchased electricity (E)	e_{Ex}	0.09	***	(0.003)
	heavy fuel oil type B･C (O)	e_{Ox}	1.65	***	(0.002)
	purchased electricity (E)	e_{Ex}	0.58	***	(0.002)
Chemical	heavy fuel oil type B･C (O)	e_{Ox}	1.37	***	(0.003)
	purchased electricity (E)	e_{Ex}	0.82	***	(0.001)
	coal (C)	e_{Cx}	1.30	***	(0.002)
	purchased electricity (E)	e_{Ex}	0.50	***	(0.003)
Ceramic, Clay and Stone Products	coal (C)	e_{Cx}	1.31	***	(0.001)
	purchased electricity (E)	e_{Ex}	0.21	***	(0.003)

Notes: Simulation is conducted with sample means to obtain elasticities and standard errors (in parentheses) based on formula (13); *,**,and *** indicate significance levels of 10%, 5%, and 1%, respectively.



Note: Estimation is conducted based on the data of the HANDBOOK of ENERGY & ECONOMIC STASTICS in JAPAN (MDMC, 2014). Price of electricity is estimated by using the data in the annual reports of ten Japanese utilities. The generation efficiency is assumed to be 35%.

Fig. 3.1 Estimated Electricity Cost of Monogeneration



Notes: Estimation is conducted based on the data of the HANDBOOK of ENERGY & ECONOMIC STASTICS in JAPAN (MDMC, 2014). Price of electricity is estimated by using the data in the annual reports of 10 Japanese utilities. The generation efficiency and thermal recovery efficiency are assumed to be 25 % and 40 % for town gas, 40 % and 35 % for heavy fuel oil, respectively. The generation efficiency and thermal recovery efficiency for coal are assumed to be 35% and 40 %.

Fig.3.2 Estimated Electricity Cost of Cogeneration (CHP)

4.4 Fuel selection

The Japanese manufacturing industry has been reducing oil consumption after the oil crisis of the 1970’s and 1980’s. In regards to energy security, the oil crisis has been the driving force for the oil reduction. The trend of replacing oil with other fuels under the circumstances depends on the industries; energy-intensive industries use coal or other fuels, and non-energy intensive industry uses town gas replacing oil.

As seen in Fig. 3.1 and Fig. 3.2, the unit electricity cost by using coal is cheaper than others. However, Fig.4 shows that the basic CO_2 unit of onsite power generation by using coal is larger than others[14]. Using coal for onsite power generation reduces cost and increases the environmental burden.

Figure 5 shows the passage of the ratio of some fuels to the total consumed energy for electricity demand. In the iron and steel industry, the ratio of coal to the total energy has been leveled off because no fuel replaces coal from manufacturing restrictions. Utilizing production gases, however, contributes to energy saving because they are by-products. In the pulp, paper and paperboard industry, the ratio of coal has been leveled off as scrap material has compensated for the decline in the amount of oil. In the chemical industry and the ceramic, clay and stone products industry, coal has replaced oil. Coal is essential for cost reduction by energy-intensive establishments. No establishments have enough fuel to replace coal to reduce the environmental burden, suppressing cost increases. Establishments must reduce the environmental burden by measures other than fuel conversion.

Figure 5 also shows that town gas has replaced oil in the machinery industry. As seen in Fig. 3.2, the unit

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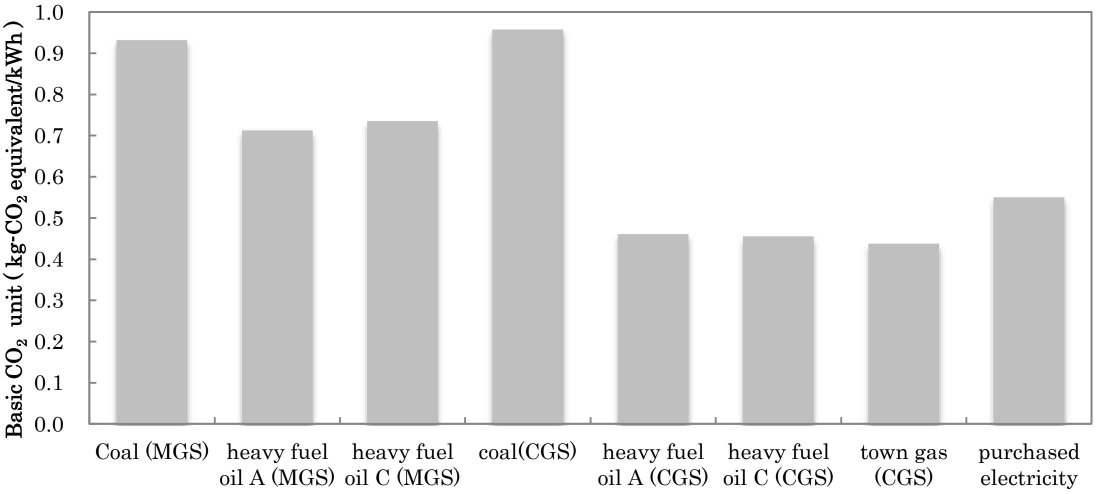
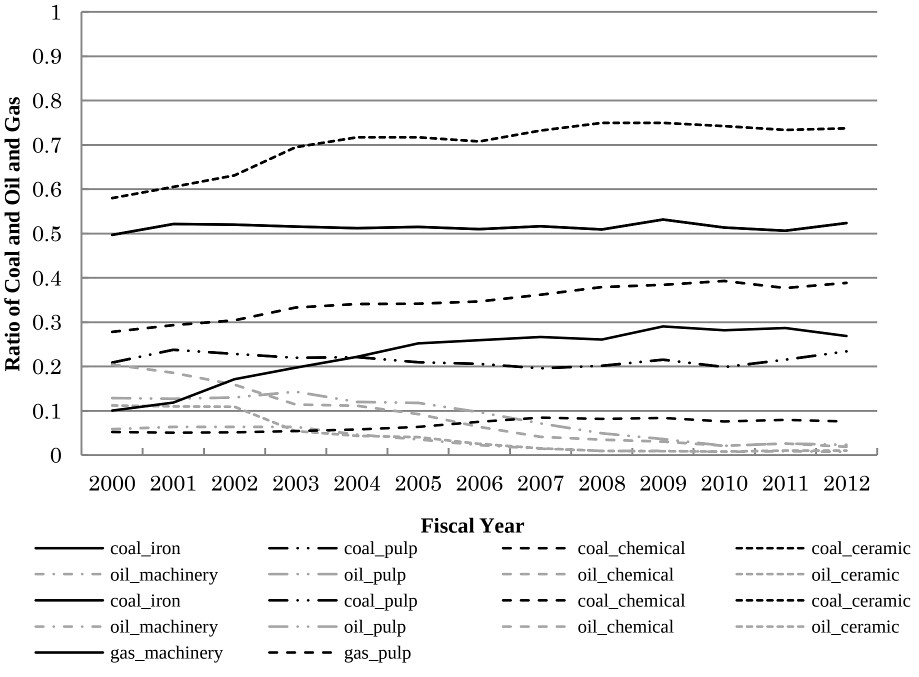
[14] The basic emission unit of purchased electricity varies in accordance with composition of electrical source for each utility. In this study, the value 0.55 kg−CO_2/kWh for purchased electricity is used in Fig. 4. The basic CO_2 unit of the Japanese Electric Utility Industry has been in the range between 0.354 and 0.571 kg−CO_2/kWh (Kyoto Mechanism credit is not reflected in the numerical values.) during the estimation period (FEPC, 2014).

electricity cost of onsite power generation by using town gas does not differ from oil. Additionally, the basic CO_2 unit of onsite power generation by using town gas is lower than others. The machinery industry has reduced CO_2 emissions with fuel conversion as oppose to energy-intensive industries. It might be deduced that the machinery industry has an environmental policy for fuel conversion.



Note: Estimation is conducted based on the data of the manual about basic CO_2 units (MoE & METI, 2015). The generation efficiency and the thermal efficiency are assumed to be 40 % and 35 % for the CGS with oil, 25 % and 50 % for the CGS with town gas, and 35 % and 40 % for the CGS with coal, respectively. The generation efficiency for MGS is assumed to be 35%.

Fig. 4 Estimated Basic CO_2 Units of Onsite Power Generation



Note: Coal_iron shows the summension of production gas and coal.

Fig. 5 Estimated Ratio of Coal, Oil and Gas to Total Energy for Electricity Demand

5. CONCLUSION

Using plant level panel data of various Japanese industries, we have analyzed the electricity demand focusing on the substitution between purchased electricity and onsite power generation. The results indicate that the fuel demand and its degree of sensitivity for onsite power generation with respect to the price changes of the fuels depend on the industrial characteristics. Additionally, the estimated expenditure elasticity indicates establishments prefer to use electricity generated on site compared to purchasing electricity.

In addition, we find that the coal, which is relatively cheaper but with relatively high CO_2 emissions, is preferred by establishments. Some industries are contributing to the reduction in CO_2 emissions by replacing oil with scrap materials as fuel or utilizing recovered fuel or by-products to generate electricity on site. However, there are other industries that are replacing oil with relatively cheaper coal, which in turn increases CO_2 emissions in the situations, where manufacturing industries have been reducing consumed oil after the oil crisis.

The implication from the results of the demand elasticities is quite striking. Introducing an onsite power generator reduces the utility cost of electric power. Therefore, we may expect to see a rise in usage of onsite power generation when the price of purchased electricity increases. However, from the results of elasticity estimations, we find that the price increase of purchased electricity is not always accompanied by substitution between purchased electricity and onsite generation. This indicates complementary effect between purchased electricity and onsite generation. Although substituting purchased electricity with onsite power generation is relatively cost effective, not all industries end up substituting because they differ in onsite generation capacity as well as in available low cost fuels that can be recycled. Therefore, considering industrial variation and characteristics is important in the analysis of electricity demand.

Under the circumstance that CO_2 reduction has been an important environmental policy for the manufacturing industries in Japan, some industries are using recovered fuel or by-products for onsite power generation. However, some industries cannot help using coal for onsite power generation because of manufacturing restrictions or fuel cost as a large percentage of product price in some energy-intensive industries such as the iron and steel industry and the ceramics, clay and stone products industry. In those industries, coal as fuel for onsite power generation accounts for the majority of the consumed energy to meet electricity demand. Thus, the energy−intensive industries have to pursue reducing CO_2 emissions by measures other than fuel conversion from coal to other fuel types.

The policy implication from the demand elasticities is that the Carbon Tax may be effective to reduce CO_2 emissions by electricity consumption generated on site, because we find the sensitivity of the fuel demand for onsite power generation to changes in fuel prices. We had expected no change in demand of the fuel to its price increase because of the cost saving effect by usage of onsite power generators.

APPENDIX

Table 3.1 Parameter Estimates of Iron and Steel Industry
Fuel pattern : production gas(K), coal (C), purchased electricity (E)

	(1) Pooled		(2) FE		(3) Pooled with a time var.		(4) FE with a time var.	
Parameter	coef.	s.e.	coef.	s.e.	coef.	s.e.	coef.	s.e.
α_K	0.5304	(0.8313)	-2.7156 ***	(0.3649)	1.2339	(27.8168)	3.5305	(5.1875)
γ_{KK}	0.1450	(0.1995)	0.1054 ***	(0.3411)	0.1462	(0.2083)	0.1202 ***	(0.037)
γ_{KC}	-0.1269	(0.2466)	-0.1176 ***	(0.0407)	-0.1257	(0.2491)	-0.1127 ***	(0.0406)
γ_{KE}	-0.0181	(0.0699)	0.0122	(0.0135)	-0.0205	(0.1165)	-0.0075	(0.0206)
β_K	-0.0138	(0.0466)	0.1815 ***	(0.0214)	-0.0137	(0.0466)	0.1844 ***	(0.0214)
t					-0.0003	(0.0138)	-0.0031	(0.0026)
$t_{2011}D_{disaster}$	-1.13E-16	(omitted)	-2.95E-17	(omitted)	-3.10E-17	(omitted)	4.34E-17	(omitted)
α_C	-0.9832	(0.8682)	-2.6771 ***	(0.2760)	-0.0333	(28.9947)	0.8874	(3.9518)
γ_{CK}	-0.1269	(0.2466)	-0.1176 ***	(0.0407)	-0.1257	(0.2491)	-0.1127 ***	(0.0406)
γ_{CC}	0.0964	(0.3129)	0.0684	(0.0516)	0.0986	(0.3332)	0.0761	(0.0533)
γ_{CE}	0.0305	(0.0848)	0.0492 ***	(0.0141)	0.0271	(0.1408)	0.0366 *	(0.0203)
β_C	0.0714	(0.0475)	0.1784 ***	(0.0159)	0.0714	(0.0476)	0.1796 ***	(0.0158)
t					-0.0005	(0.0143)	-0.0018	(0.002)
$t_{2011}D_{disaster}$	0.0000	(omitted)	0.0000	(omitted)	0.0000	(omitted)	0.0000	(omitted)
α_E	1.4528	(1.0994)	6.3927 ***	(0.3587)	-0.2006	(37.9271)	-3.4179	(5.1204)
γ_{EK}	-0.0181	(0.0699)	0.0122	(0.0135)	-0.0205	(0.1165)	-0.0075	(0.0206)
γ_{EC}	0.0305	(0.0843)	0.0492 ***	(0.0141)	0.0271	(0.1408)	0.0366 *	(0.0203)
γ_{EE}	-0.0124	(0.0713)	-0.0614 ***	(0.0115)	-0.0065	(0.1519)	-0.0291	(0.0202)
β_E	-0.0576	(0.0625)	-0.3600 ***	(0.021)	-0.0577	(0.0626)	-0.3606 ***	(0.0207)
t					0.0008	(0.0187)	0.0049 *	(0.0025)
$t_{2011}D_{disaster}$	1.13E-16	(1.49E-16)	2.95E-17	(5.03E-18)	3.10E-17	(3.88E-16)	-4.34E-17	(1.65E-16)
Obs	87							
R-sq								
oil	0.0134		0.9639		0.0134		0.9644	
town gas	0.0297		0.9815		0.0297		0.9818	
LL	21		344		21		346	
AIC	-27		-650		-23		-650	
BIC	-10		-603		-1		-598	
df	7		19		9		21	

Note: *, ** and *** indicate significance levels of 10%, 5%, and 1%, respectively; dummy variables in the fixed effects model are not reported.

Table 3.2 Parameter estimates of Iron and Steel Industry
Fuel pattern : production gas (K) and purchased electricity (E)

	(1) RE		(2) FE		(3) RE with a time var.		(4) FE with a time var.	
Parameter	coef.	s.e.	coef.	s.e.	coef.	s.e.	coef.	s.e.
α_K	-6.003 *	(0.517)	-6.527 ***	(0.492)	12.314 **	(5.749)	11.969 **	(5.41)
γ_{KK}	-0.031 **	(0.013)	-0.041 ***	(0.012)	0.023	(0.021)	0.015	(0.02)
γ_{KE}	0.031 **	(0.013)	0.041 ***	(0.012)	-0.023	(0.021)	-0.015	(0.02)
β_K	0.392 ***	(0.031)	0.426 ***	(0.03)	0.401 ***	(0.029)	0.428 ***	(0.028)
T					-0.009 ***	(0.003)	-0.009 ***	(0.003)
$t_{2011}D_{disaster}$	-0.061 *	(0.032)	-0.056 *	(0.03)	-0.050	(0.03)	-0.046	(0.029)
Obs	115							
R-sq								
Within	0.7306		0.7316		0.7589		0.7597	
Between	0.0229		0.0231		0.0230		0.0231	
Overall	0.0003		0.0003		0.0002		0.0002	
	Wald χ^2(3) =225.36***		F(3,102)=92.70***		Wald χ^2(4) =268.74***		F(4,101)=79.81***	
Hausman statistics								
	χ^2(3) =65.76***(p=0.0000)				χ^2(4) =106.34***(p=0.0000)			

Note: *,**,and *** indicate significance levels of 10%, 5%, and 1%, respectively.

Table 3.3 Parameter Estimates of Machinery Industry
Fuel pattern : heavy fuel oil type B･C (O), town gas (T), purchased electricity (E)

	(1) Pooled		(2) FE		(3) Pooled with a time var.		(4) FE with a time var.	
Parameter	coef.	s.e.	coef.	s.e.	coef.	s.e.	coef.	s.e.
α_O	0.0111 ***	(0.0887)	-0.4390 **	(0.1724)	16.9509 ***	(5.5714)	7.9909 ***	(3.0888)
γ_{OO}	-0.0638 **	(0.0272)	-0.0377 **	(0.0182)	-0.0252	(0.0274)	-0.0264	(0.0181)
γ_{OT}	0.0147	(0.049)	-0.0251	(0.0291)	0.1119 ***	(0.0614)	0.0166	(0.0333)
γ_{OE}	0.0491	(0.0356)	0.0629 ***	(0.0208)	-0.0866	(0.06)	0.0098	(0.0295)
β_O	-0.0038	(0.0056)	0.0344 **	(0.0145)	-0.0036	(0.0052)	0.0319 **	(0.0142)
t					-0.0084 ***	(0.0027)	-0.0042 ***	(0.0015)
$t_{2011}D_{disaster}$	-0.0051	(0.0416)	0.0043	(0.024)	0.0059	(0.0388)	0.0135	(0.0235)
α_T	1.0004 ***	(0.2874)	-1.6988 ***	(0.3861)	-52.3465 *	(21.331)	-37.4172 ***	(8.7287)
γ_{TO}	0.0147	(0.049)	-0.0251	(0.0291)	0.1119 ***	(0.0614)	0.0166	(0.0333)
γ_{TT}	0.5763 ***	(0.1419)	0.3662 ***	(0.0715)	-0.1292	(0.2663)	-0.0148	(0.1108)
γ_{TE}	-0.5910 ***	(0.1223)	-0.3411 ***	(0.0565)	0.0173	(0.2572)	-0.0018	(0.0999)
β_T	-0.0025	(0.0177)	0.1974 ***	(0.0326)	-0.0054	(0.0176)	0.1936 ***	(0.0316)
t					0.0263 ***	(0.0105)	0.0176 ***	(0.0043)
$t_{2011}D_{disaster}$	-0.1337	(0.1317)	0.0106	(0.0553)	-0.1390	(0.1303)	-0.0076	(0.0533)
α_E	-0.0116	(0.2909)	3.1378 ***	(0.3861)	36.3956 *	(22.1553)	30.4263 ***	(8.6266)
γ_{EO}	0.0491	(0.0356)	0.0629 ***	(0.0208)	-0.0866	(0.06)	0.0098	(0.0295)
γ_{ET}	-0.5910 ***	(0.1223)	-0.3411 ***	(0.0565)	0.0173	(0.2572)	-0.0018	(0.0999)
γ_{EE}	0.5419 ***	(0.1189)	0.2782 ***	(0.0517)	0.0693	(0.2616)	-0.0080	(0.0978)
β_E	0.0063	(0.018)	-0.2318 ***	(0.0301)	0.0090	(0.0177)	-0.2255 ***	(0.0295)
t					-0.0179	(0.0109)	-0.0135 ***	(0.0042)
$t_{2011}D_{disaster}$	0.1388	(0.1336)	-0.0150	(0.0512)	0.1331	(0.1312)	-0.0059	(0.0496)
Obs	182							
R-sq								
oil	0.0663		0.6757		0.0883		0.6849	
town gas	0.128		0.8634		0.178		0.8755	
LL	250		528		258		538	
AIC	-482		-935		-493		-951	
BIC	-453		-739		-458		-749	
df	9		61		11		63	

Note: *, ** and *** indicate significance levels of 10%, 5%, and 1%, respectively; dummy variables in the fixed effects model are not reported.

Table 3.4 Parameter Estimates of Machinery Industry
Fuel pattern: town gas (T) and purchased electricity (E)

	(1) RE		(2) FE		(3) RE with a time var.		(4) FE with a time var.	
Parameter	coef.	s.e.	coef.	s.e.	coef.	s.e.	coef.	s.e.
α_T	-1.1445 ***	(0.1444)	-1.4910 ***	(0.1674)	-26.0649 ***	(4.6516)	-27.2121 ***	(4.6257)
γ_{TT}	0.2345 ***	(0.0285)	0.2311 ***	(0.0284)	-0.0252	(0.0559)	-0.0360	(0.0554)
γ_{TE}	-0.2345 ***	(0.0285)	-0.2311 ***	(0.0284)	0.0252	(0.0559)	0.0360	(0.0554)
β_T	0.1316 ***	(0.0106)	0.1573 ***	(0.0124)	0.1361 ***	(0.0105)	0.1624 ***	(0.0122)
t					0.0122 ***	(0.0023)	0.0126	(0.0023)
$t_{2011}D_{disaster}$	0.0176	(0.0248)	0.0178	(0.0246)	0.0125	(0.0242)	0.0125 ***	(0.024)
Obs	665							
R-sq								
within	0.2876		0.2899		0.3233		0.326	
between	0.1515		0.1488		0.1543		0.1515	
overall	0.1557		0.1507		0.166		0.1602	
	Wald $\chi^2(3)$ =232.53***		F(3,582)=79.21***		Wald $\chi^2(4)$ =272.71***		F(4,581)=70.21***	
Hausman statistics								
	$\chi^2(2)$ =14.31***(p=0.0025)				$\chi^2(3)$ =14.31***(p=0.0018)			

Note: *, ** and *** indicate significance levels of 10%, 5%, and 1%, respectively.

Table 3.5 Parameter Estimates of Machinery Industry

Fuel pattern: heavy fuel oil type A (o) and purchased electricity (E)

	(1) RE		(2) FE		(3) RE with a time var.		(4) FE with a time var.	
Parameter	coef.	s.e.	coef.	s.e.	coef.	s.e.	coef.	s.e.
α_O	-0.3292	(0.2199)	-2.8391***	(0.3199)	43.0711***	(8.303)	30.10266***	(7.5917)
γ_{OO}	0.0232	(0.0283)	-0.0062	(0.0256)	0.1965***	(0.0428)	0.1253***	(0.0391)
γ_{OE}	-0.0232	(0.0283)	0.0062	(0.0256)	-0.1965***	(0.0428)	-0.1253***	(0.0391)
β_O	0.0472***	(0.0176)	0.2521***	(0.026)	0.0365***	(0.0175)	0.2262**	(0.0258)
t					-0.0215***	(0.0041)	-0.0162***	(0.0037)
$t_{2011}D_{disaster}$	-0.0827	(0.0514)	-0.0807*	(0.0452)	-0.0332	(0.0498)	-0.0453	(0.0444)
Obs	309							
R-sq								
Within	0.1754		0.2792		0.1931		0.329	
Between	0.1833		0.187		0.1307		0.1823	
Overall	0.1176		0.1269		0.0303		0.1134	
	Wald $\chi^2(3)=10.37^{*}$		$F(3,254)=32.79^{***}$		Wald $\chi^2(4)=40.25^{***}$		$F(4,253)=31.03^{***}$	
Hausman statistics								
	$\chi^2(3)=115.44^{***}$(p=0.0000)				$\chi^2(4)=99.72^{***}$(p=0.0000)			

Note: *, ** and *** indicate significance levels of 10%, 5%, and 1%, respectively.

Table 3.6 Price Elasticities of Pulp and Paper and Paperboard Industry

Fuel pattern: coal (C) and purchased electricity (E)

	(1) RE		(2) FE		(3) RE with a time var.		(4) FE with a time var.	
Parameter	Coef.	s.e.	coef.	s.e.	coef.	s.e.	coef.	s.e.
α_C	-2.4522***	(0.2983)	-3.1873***	(0.34)	-36.9519***	(8.7037)	-40.4339***	(8.4308)
γ_{CC}	0.0794***	(0.0182)	0.0680***	(0.0179)	-0.0536	(0.0377)	-0.0747**	(0.0366)
γ_{CE}	-0.0794***	(0.0182)	-0.0680***	(0.0179)	0.0536	(0.0377)	0.0747**	(0.0366)
β_C	0.2159***	(0.0209)	0.2681***	(0.024)	0.2252***	(0.0205)	0.2750***	(0.023)
t					0.0171***	(0.0043)	0.0184***	(0.0184)
$t_{2011}D_{disaster}$	0.2504***	(0.0534)	0.2473***	(0.0517)	0.2197***	(0.0518)	0.2138***	(0.05)
Obs	222							
R-sq								
Within	0.5266		0.5324		0.5703		0.575	
Between	0.1877		0.1886		0.1706		0.1736	
Overall	0.2028		0.1948		0.2002		0.1934	
	Wald $\chi^2(3)=195.23^{***}$		$F(3,194)=73.63^{***}$		Wald $\chi^2(4)=228.40^{***}$		$F(4,193)=65.39^{***}$	
Hausman statistics								
	$\chi^2(3)=19.79^{***}$(p=0.0002)				$\chi^2(4)=21.91^{***}$(p=0.0002)			

Note: *, ** and *** indicate significance levels of 10%, 5%, and 1%, respectively.

Table 3.7 Price Elasticities of Pulp and Paper and Paperboard Industry

Fuel pattern : town gas (T) and purchased electricity (E)

	(1) RE		(2) FE		(3) RE with a time var.		(4) FE with a time var.	
Parameter	coef.	s.e.	coef.	s.e.	coef.	s.e.	coef.	s.e.
α_T	-1.9806***	(0.2992)	-2.1729***	(0.351)	-16.9276*	(9.6234)	-22.3973**	(9.336)
γ_{TT}	0.1668***	(0.0607)	0.1731***	(0.0613)	0.0049	(0.1193)	-0.0392	(0.1152)
γ_{TE}	-0.1668***	(0.0607)	-0.1731***	(0.0613)	-0.0049	(0.1193)	0.0392	(0.1152)
β_T	0.2178***	(0.0214)	0.2331***	(0.025)	0.2092***	(0.0208)	0.2279***	(0.0249)
t					0.0074	(0.0048)	0.0100**	(0.0046)
$t_{2011}D_{disaster}$	-0.0500	(0.0369)	-0.0475	(0.037)	-0.0534	(0.0381)	-0.0500	(0.0366)
Obs	222							
R-sq								
Within	0.3584		0.3585		0.3736		0.374	
Between	0.4148		0.4146		0.394		0.3886	
Overall	0.3223		0.3219		0.32		0.3184	
	Wald $\chi^2(3)=122.94^{***}$		$F(3,186)=34.64^{***}$		Wald $\chi^2(4)=126.22^{***}$		$F(4,185)=27.67^{***}$	
Hausman statistics								
	$\chi^2(3)=3.79^{***}$(p=0.2855)				$\chi^2(4)=28.63^{***}$(p=0.0002)			

Note: *, ** and *** indicate significance levels of 10%, 5%, and 1%, respectively.

Table 3.8 Price Elasticities of Pulp, Paper and Paperboard Industry
Fuel pattern : heavy fuel oil type B･C (O) and purchased electricity (E)

	(1) RE		(2) FE		(3) RE with a time var.		(4) FE with a time var.	
Parameter	coef.	s.e.	coef.	s.e.	coef.	s.e.	coef.	s.e.
α_O	-1.2716 ***	(0.2287)	-2.7623 ***	(0.3678)	23.2971	(14.5762)	4.4212	(14.7349)
γ_{OO}	0.0477 **	(0.0243)	0.0547 **	(0.0236)	0.1372 **	(0.0583)	0.0805	(0.0579)
γ_{OE}	-0.0477 **	(0.0243)	-0.0547 **	(0.0236)	-0.1372 **	(0.0583)	-0.0805	(0.0579)
β_O	0.1348 ***	(0.0174)	0.2531 ***	(0.0286)	0.1314 ***	(0.0176)	0.2488 ***	(0.03)
t					-0.0122 *	(0.0072)	-0.0035	(0.0072)
$t_{2011}\times D_{disaster}$	-0.0754	(0.0673)	-0.0592	(0.0645)	-0.0494	(0.0687)	-0.0522	(0.0662)
Obs	270							
R-sq								
Within	0.2661		0.2748		0.2545		0.276	
Between	0.2571		0.2574		0.2556		0.2572	
Overall	0.175		0.1719		0.1746		0.1721	
	Wald $\chi^2(3)=66.39^{***}$		$F(3,223)=28.17^{***}$		Wald $\chi^2(4)=69.81^{***}$		$F(4,222)=21.11^{***}$	
Hausman statistics								
	$\chi^2(3)=27.22^{***}$(p=0.0000)				$\chi^2(4)=23.24^{***}$(p=0.0001)			

Note: *, ** and *** indicate significance levels of 10%, 5%, and 1%, respectively.

Table 3.9 Price Elasticities of Chemical Industry
Fuel pattern : heavy fuel oil type B･C (O) and purchased electricity (E)

	(1) RE		(2) FE		(3) RE with a time var.		(4) FE with a time var.	
Parameter	coef.	s.e.	coef.	s.e.	coef.	s.e.	coef.	s.e.
α_O	-1.3026 ***	(0.3838)	-1.8936 ***	(0.4334)	5.0274	(12.179)	0.0719	(12.317)
γ_{OO}	0.0178	(0.0199)	0.0183	(0.0198)	0.0410	(0.0489)	0.0255	(0.049)
γ_{OE}	-0.0178	(0.0199)	-0.0183	(0.0198)	-0.0410	(0.0489)	-0.0255	(0.049)
β_O	0.1205 ***	(0.0276)	0.1635 ***	(0.0316)	0.1173 ***	(0.0289)	0.1618 ***	(0.0334)
t					-0.0031	(0.006)	-0.0010	(0.006)
$t_{2011}D_{disaster}$	-0.0594	(0.1009)	-0.0530	(0.0997)	-0.0522	(0.1018)	-0.0508	(0.1009)
Obs	201							
R-sq								
within	0.1396		0.1403		0.1384		0.140	
between	0.0011		0.0011		0.0012		0.0012	
overall	0.0038		0.0036		0.0036		0.0036	
	Wald $\chi^2(3)=19.69^{***}$		$F(3,168)=9.14^{***}$		Wald $\chi^2(3)=20.14^{***}$		$F(4,167)=6.82^{**}$	
Hausman statistics								
	$\chi^2(3)=7.84^{**}$(p=0.0493)				$\chi^2(3)=32.56^{***}$(p=0.0000)			

Note: *, ** and *** indicate significance levels of 10%, 5%, and 1%, respectively.

Table 3.10 Price Elasticities of Chemical Industry
Fuel pattern: coal (C) and purchased electricity (E)

	(1) RE		(2) FE		(3) RE with a time var.		(4) FE with a time var.	
Parameter	coef.	s.e.	coef.	s.e.	coef.	s.e.	coef.	s.e.
α_C	-2.0572 ***	(0.4962)	-2.2616 ***	(0.5263)	-9.3174 *	(5.7708)	-9.8237	(5.8626)
γ_{CC}	0.0844 ***	(0.0125)	0.0846 ***	(0.0127)	0.0575 **	(0.0247)	0.0567 **	(0.025)
γ_{CE}	-0.0844 ***	(0.0125)	-0.0846 ***	(0.0127)	-0.0575 **	(0.0247)	-0.0567 **	(0.025)
β_C	0.1871 ***	(0.0319)	0.1985 ***	(0.0351)	0.1925 ***	(0.0321)	0.2045 ***	(0.0353)
t					0.0036	(0.0028)	0.0037	(0.0029)
$t_{2011}D_{disaster}$	0.0134	(0.0527)	0.0132	(0.0533)	0.0086	(0.0526)	0.0083	(0.0532)
Obs	114							
R-sq								
Within	0.4265		0.4268		0.4361		0.437	
Between	0.2598		0.2594		0.2595		0.2591	
Overall	0.2048		0.2041		0.2047		0.2039	
	Wald $\chi^2(3)=77.50^{***}$		$F(3,99)=24.57^{***}$		Wald $\chi^2(4)=79.76^{***}$		$F(4,98)=18.98^{***}$	
Hausman statistics								
	$\chi^2(3)=0.61$(p=0.8948)				$\chi^2(4)=0.67$(p=0.9545)			

Note: *, ** and *** indicate significance levels of 10%, 5%, and 1%, respectively.

Table 3.11 Price Elasticities of Ceramics, Clay and Stone Products Industry

Fuel pattern: coal (C) and purchased electricity (E)

	(1) RE		(2) FE		(3) RE with a time var.		(4) FE with a time var.	
Parameter	coef.	s.e.	coef.	s.e.	coef.	s.e.	coef.	s.e.
α_C	-2.4100 ***	(0.3874)	-2.8689 ***	(0.4298)	-25.8877 ***	(9.2605)	-28.1693 ***	(8.8506)
γ_{CC}	0.0808 ***	(0.02)	0.0688 ***	(0.0205)	-0.0063	(0.0408)	-0.0297	(0.0397)
γ_{CE}	-0.0808 ***	(0.02)	-0.0688 ***	(0.0205)	0.0063	(0.0408)	0.0297	(0.0397)
β_C	0.2233 ***	(0.0236)	0.2509 ***	(0.0264)	0.2176 ***	(0.0225)	0.2573 ***	(0.0257)
t					0.0116 **	(0.0046)	0.0124 ***	(0.0043)
$t_{2011}D_{disaster}$	0.0644	(0.05)	0.0664	(0.0493)	0.0479	(0.0505)	0.0499	(0.0482)
obs	131							
R-sq								
within	0.6403		0.6423		0.6616		0.666	
between	0.3934		0.3967		0.3859		0.3914	
overall	0.3789		0.3765		0.3775		0.3745	
	Wald $\chi^2(3)$ =204.15***		F(3,117)=70.03***		Wald $\chi^2(4)$ =210.39***		F(4,116)=57.80***	
Hausman statistics								
	$\chi^2(3)$ =5.32(p=0.1497)				$\chi^2(4)$ =9.89***(p=0.0423)			

Note: *, ** and *** indicate significance levels of 10%, 5%, and 1%, respectively.

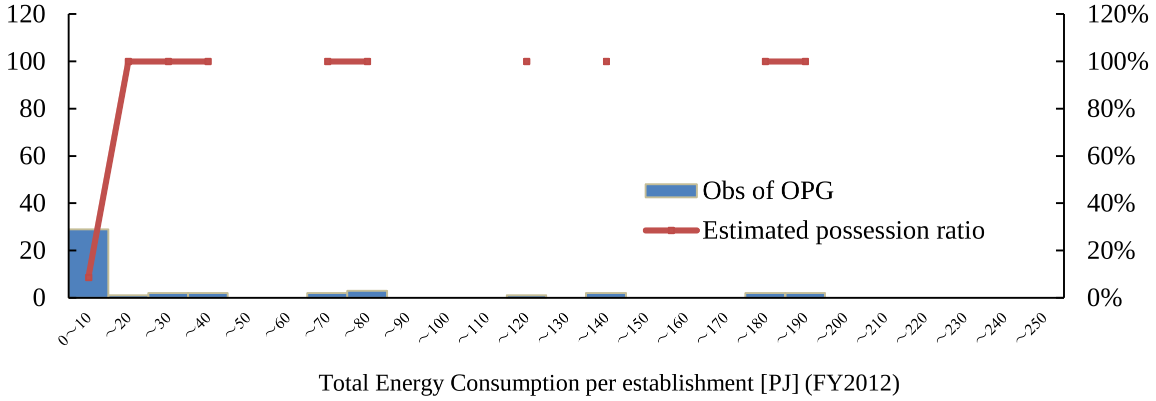


Fig. 6.1 Estimated Onsite Power Possession Ratio in the Iron and Steel Industry

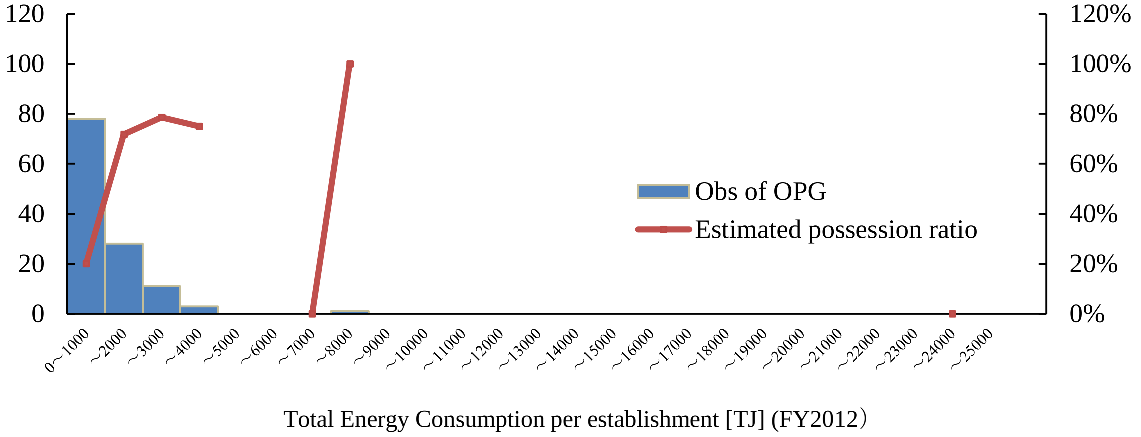


Fig. 6.2 Estimated Onsite Power Possesion Ratio in the Machinery Industry

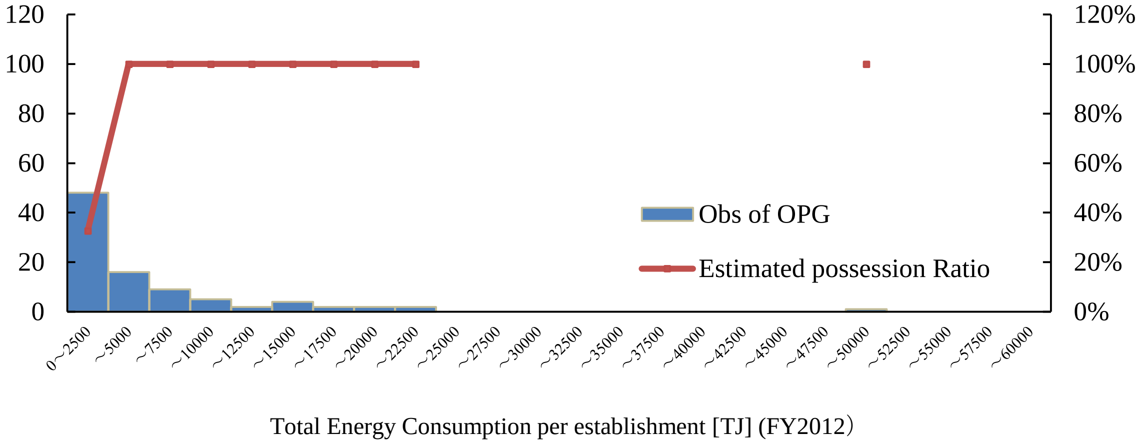


Fig. 6.3 Estimated Onsite Power Possesion ratio in the Pulp, Paper and Paperboard Industry

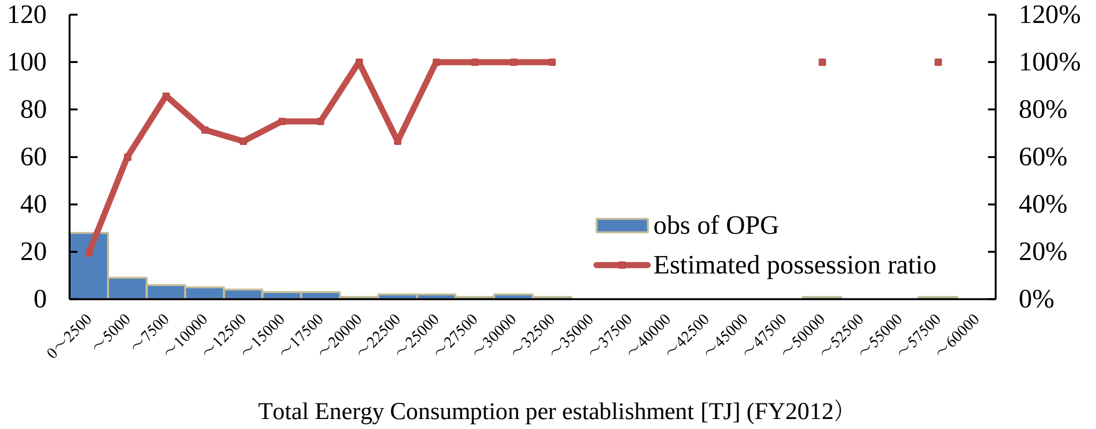


Fig. 6.4 Estimated Onsite Power Possession Ratio in the Chemistry Industry

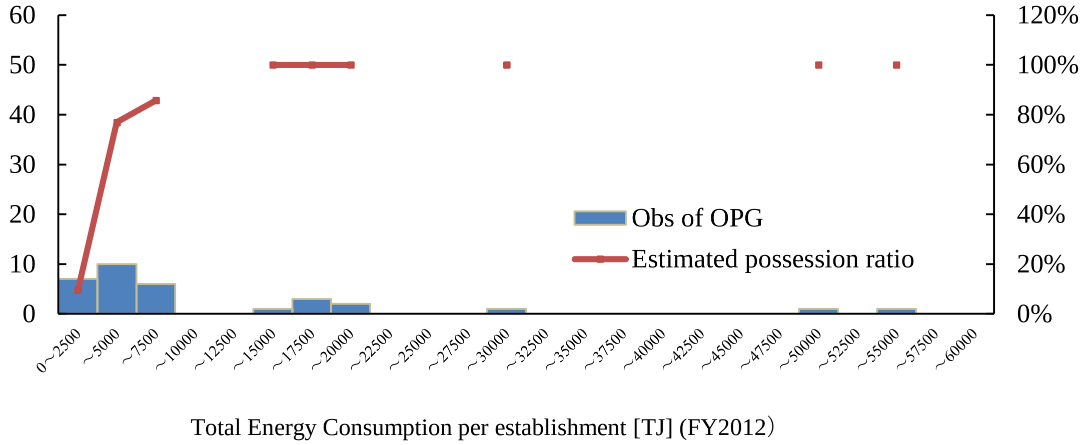


Fig. 6.5 Estimated Onsite Power Possession Ratio in the Ceramic, Clay and Stone Products Industry

REFERENCES

Alston, J. M., Foster, K. A., & Gree, R. D. (1994). Estimating elasticities with the linear approximate almost ideal demand system: some Monte Carlo results. *The review of economics and statistics*, 351-356.

Barnett, A. H., Reutter, K., & Thompson, H. (1998). Electricity substitution: some local industrial evidence. *Energy Economics, 20*(4), 411-419.

Berndt, E. R., & Wood, D. O. (1979). Engineering and econometric interpretations of energy-capital complementarity. *The American economic review*, 342-354.

Berndt, E. R., & Wood, D. O. (1981). Engineering and econometric interpretations of energy-capital complementarity: reply and further results. *The American economic review*, 1105-1110.

Bjørner, T. B., & Jensen, H. H. (2002). Interfuel substitution within industrial companies: an analysis based on panel data at company level. *The Energy Journal*, 27-50.

Bousquet, A., & Ivaldi, M. (1998). An individual choice model of energy mix. *Resource and Energy Economics, 20*(3), 263-286.

Bousquet, A., & Ladoux, N. (2006). Flexible versus designated technologies and interfuel substitution. *Energy Economics, 28*(4), 426-443.

Caves, D. W., & Christensen, L. R. (1980). Econometric analysis of residential time-of-use electricity pricing experiments. *Journal of Econometrics, 14*(3), 287-306.

Considine, T. J. (1989). Separability, functional form and regulatory policy in models of interfuel substitution. *Energy Economics, 11*(2), 82-94.

Deaton, A., & Muellbauer, J. (1980). An almost ideal demand system. *The American economic review*, 312-326.

Fuss, M. A. (1977). The demand for energy in Canadian manufacturing: An example of the estimation of production structures with many inputs. *Journal of Econometrics, 5*(1), 89-116.

Ida, T., Ito, K., & Tanaka, M. (2013). Using dynamic electricity pricing to address energy crises: Evidence from randomized field experiments. *36th Annual NBER Summer Institute, Cambridge, MA, USA.*

Jorgenson, D. W., & Lau, L. J. (1975). The structure of consumer preferences *Annals of Economic and Social Measurement, Volume 4, number 1* (pp. 49-101): NBER.

Igarashi, O. & Ohashi, H. (2015). Potential estimation of industrial demand response : Analysis for adjusting demand and supply contracts considering factory attribute, *RIETI Discussion Paper Series 15-J-053*, Research Institute of Economy, Trade & Industry, IAA.. (in Japanese)

Koetse, M. J., De Groot, H. L. F., & Florax, R. J. G. M. (2008). Capital-energy substitution and shifts in factor demand: A meta-analysis. *Energy Economics, 30*(5), 2236-2251.

Lee, L.-F., & Pitt, M. M. (1987). Microeconometric models of rationing, imperfect markets, and non-negativity constraints. *Journal of Econometrics, 36*(1), 89-110.

Matsukawa, I., Fujii, Y., & Madono, S. (1993). Price, environmental regulation, and fuel demand: econometric estimates for Japanese manufacturing industries. *The Energy Journal*, 37-56.

Ministry of Environment & Ministry of Economy and Trade and Industry (2015). *Manual for Accounting and Reporting of Green Gas Emissions*. (in Japanese)

Ministry of Economy, Trade and Industry (2014). Energy White Paper 2014, 22. (in Japanese)

Ministry of Economy, Trade and Industry (2015). *Report concerning verification of power generation cost to the subcommittee for long-term energy supply-demand outlook*, the working group under the Advisory Committee about Energy Problem (2015). (in Japanese)

Miyamoto, Y.(2002). *Senario for Saving Energy in Pulp Industry*, Environmental Harmony Type Energy System, The Society of Chemical Engineers, Japan ,63-72. (in Japanese)

Pindyck, R. S. (1979). Interfuel substitution and the industrial demand for energy: an international comparison. *The review of economics and statistics*, 169-179.

Serletis, A., Timilsina, G. R., & Vasetsky, O. (2010). Interfuel substitution in the United States. *Energy Economics, 32*(3), 737-745.

Shephard, R. W. (1953). *Cost and production functions*, Princeton.

Steinbuks, J. (2010). Interfuel substitution and energy use in the UK manufacturing sector.

Stern, D. I. (2012). Interfuel Substitution: A Meta ‐ Analysis. *Journal of Economic Surveys, 26*(2), 307-331.

The Energy Data and Modelling Center, IEEJ (2014), *HANDBOOK of ENERGY & ECONOMICS STATISTICS in JAPAN*, The Energy Conservation Center, Japan. (in Japanese)

The Federation of Electric Power Companies of Japan (2014), *Environmental Action Plan by the Japanese Electric Utility Industry*, 50.

Wales, T. J., & Woodland, A. D. (1983). Estimation of consumer demand systems with binding non-negativity constraints. *Journal of Econometrics, 21*(3), 263-285.

Woodland, A. D. (1993). A micro-econometric analysis of the industrial demand for energy in NSW. *The Energy Journal*, 57-89.

Yoshimura, N. & Takagi, N.(2002). *Energy System of Iron and Steel Industry*, Environmental Harmony Type Energy System, The Society of Chemical Engineers, Japan ,73-81. (in Japanese)

Zellner, A. (1962). An efficient method of estimating seemingly unrelated regressions and tests for aggregation bias. *Journal of the American statistical Association, 57*(298), 348-368.