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Research Article

Possibilities of coal−gas substitution in East Asia: A comparison among China, Japan and South Korea

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Abstract

Natural gas is currently playing an increasingly significant role in low carbon development, as it provides a credible pathway to meet rising energy demand while emitting fewer greenhouse gases than from using other fossil fuels such as coal and oil. In this paper, a log linear trans-log production function model is established to investigate inter-fuel elasticity of substitution between coal, oil, natural gas and electricity in China, Japan and South Korea, respectively. In order to overcome the problem of multicollinearity, the ridge regression approach is therefore adopted to estimate the parameters of the function. Results show elasticity estimates of both coal−gas substitution and coal−electricity substitution to be positive over 1985−2012, suggesting that these two energy input pairs are substitutes at least to some extent. It also reveals that relatively higher substitution possibilities between coal and natural gas, and less opportunities to substitute coal with other fuels in China. In addition, the model results also suggest the elasticities of coal−gas substitution in China are much larger than that in Japan and South Korea, indicating there is higher possibilities of coal−gas substitution in China.

Keywords: Substitution possibilities; Trans-log production function; Ridge regression; Natural gas

1. Introduction

1.1. China's natural gas market

China holds the largest natural gas reserves in the Asia−Pacific region. Its proved reserves of natural gas rank 13th in the world, with an amount of around 3.8 trillion cubic meters (tcm) in 2015.[1] What's more, according to the estimation of the U.S. Energy Information Administration (EIA), China holds the largest shale gas reserves in the world, with technically recoverable shale gas reserves of 31.57 tcm in 2014.[2] Though there is huge potential for the growth of China's shale gas industry, it stays in nascent stage facing various kinds of challenges. Both production and consumption have risen rapidly in China in recent years, as shown in the following Fig. 1.

In 2015, natural gas consumption in China rose to 197.3 bcm, ranking the third in the world, just after the U.S.

Abbreviation: bcf, billion cubic feet; bcm, billion cubic meters; GHG, greenhouse gas; LNG, liquefied natural gas; EIA, The U.S. Energy Information Administration; IEA, International Energy Agency; OECD, Organization for Economic Co-operation and Development; OLS, ordinary least squares; VIF, variance inflation factor.

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[1] Data Source: BP Statistical Review of World Energy 2016.
[2] U.S. Energy Information Administration, "Technically Recoverable Shale Oil and Shale Gas Resources: An Assessment of 137 Shale Formations in 41 Countries Outside the United States", June 10, 2013.

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and Russia. While natural gas production in China increased to 138.0 bcm in 2015, ranking the sixth worldwide. With rapidly increasing use of natural gas in China, it has become the third-largest natural gas consumer worldwide. Natural gas production keeps growing as well, but in a lower rate than that in consumption, causing an ever-increasing gap between natural gas consumption and production. As a result, China has sought to raise natural gas imports via pipeline and as liquefied natural gas (LNG) to fill the gap. Fig. 2 shows China's natural gas imports from 2006 to 2015.

China became a net importer of natural gas ever since 2007. Rapid growth in natural gas demand in recent years has led to an accelerating development of China's LNG and pipeline infrastructure. China's total natural gas imports ranked the 4th in the world, with an amount of 59.8 bcm in 2015. Also, it is now the third-largest LNG importer in the world, after Japan and South Korea.

Energy structure centering on coal as well as the rapidly increasing energy demands are main reasons why a large area of haze is seen in China. The effective haze treatments are largely depending on the optimization of energy mix, in other words, on reducing China's heavy use of coal. However, a huge amount of energy is needed to sustain its rapid economic growth. Under this background, China has to seek for alternate energies to offset the supply gap of reducing coal consumptions. The most practical alternate energy is natural gas within the short term in China. For the past few years, natural gas industry in China has developed fast and natural gas consumption has continuously maintained a double-digit growth rate.

As one of the largest natural gas consumers in the world, China's future demand for natural gas is of much concern. Though China is now the third-largest natural gas consumer, with natural gas consumption of 197.3 bcm in 2015. However, it only accounted for around 5 per cent of the country's total primary energy consumption in that year. According to China's development plan on natural gas, the share of natural gas consumption in its total energy use will rise up to 10 per cent

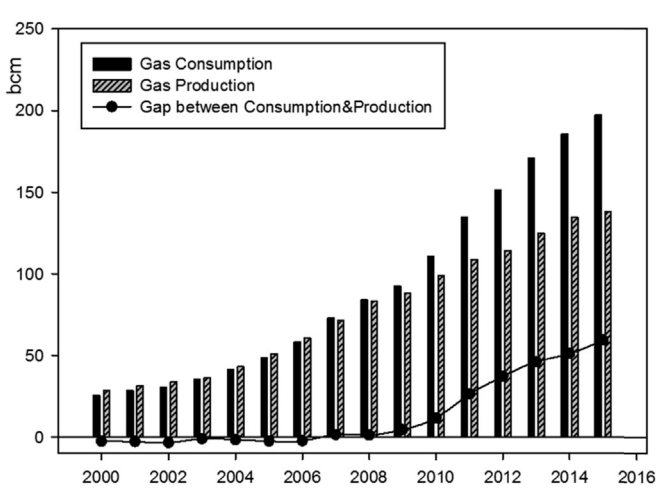

Fig. 1. Natural gas production & consumption in China. Data Source: BP Statistical Review of World Energy 2001−2016.

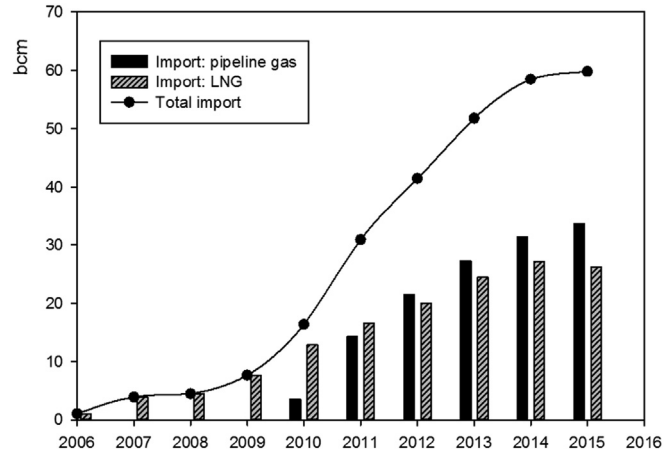

Fig. 2. Pipeline gas & LNG imports in China. Data Source: BP Statistical Review of World Energy 2001−2016.

by the year of 2020, in order to alleviate the serious pollution causing by the China's heavily use of coal. That is to say, future natural gas consumption in China is likely to maintain a rapid growth.

1.2. Natural gas market in Japan and South Korea

Both Japan and South Korea have limited domestic energy resources, and rely heavily on imported energy to meet their demands. As a result, both Japan and South Korea's domestic natural gas productions are negligible compared to their gas consumptions.

For Japan, after the removal of nuclear power due to the Fukushima plant accident in 2011, Japan's energy self-sufficiency rate fell from 20% to no more than 9%. With its primary energy consumption ranking the fifth in the world, Japan has been seeking for reliable energy sources to meet its national energy demands. Japan's demand for natural gas maintains a comparatively fast growth ever since 2009, while its domestic production is just the opposite, leading to an ever higher gas dependency on foreign countries.

Fig. 3 shows natural gas consumptions and imports in Japan. Due to the geographical location as well as other factors, natural gas imports through pipeline to Japan presents serious difficulties. In 2015, Tokyo Gas showed interest in building a gas pipeline which would connect Russia's Sakhalin Island with Japan. However, it is believed that the construction of an underwater pipeline to Japan indicates great risks. As a result, all natural gas imports in Japan are imported as LNG, and it is currently the world's largest LNG importer.

Fig. 4 shows natural gas consumptions and imports in South Korea. Similar to Japan, South Korea has an even higher foreign dependency on natural gas and its domestic production of natural gas is very limited. What's more, South Korea does not have any international natural gas pipeline connections and must therefore import all gas via LNG tankers. As a result, although South Korea is not among the group of top natural gas-consuming countries, it is the second-largest importer of LNG in the world after Japan. Despite the recent lower natural

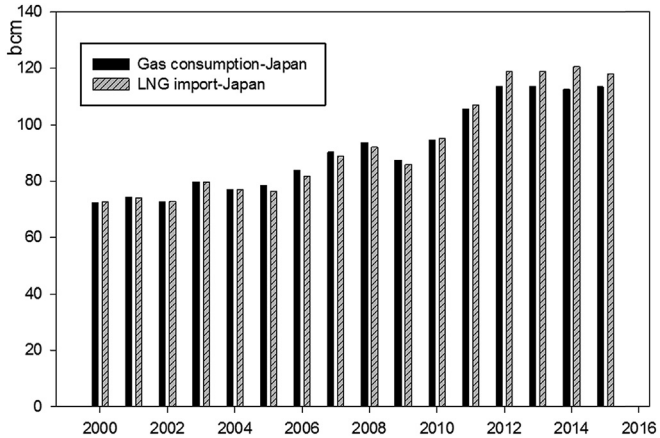

Fig. 3. Natural gas consumptions and imports in Japan. Data Source: BP Statistical Review of World Energy 2001–2016.

gas demand in 2015 (dropped by 8.8 per cent compared to 2014), the fuel remains a significant source of cleaner energy for the nation.

Natural gas demand in East Asia stays at a high level, especially LNG demands. Eastern Asian countries currently account for around three quarters of the global LNG consumption currently. Three final markets in particular provided the bulk of demand: Japan, South Korea and China (the top-three LNG importers worldwide) together took up 55.5% of the world's total LNG consumption in 2015. Future development of natural gas market in Asia is of much concern, due to their fast growing gas demand and high gas dependency on foreign countries.

2. Research method

2.1. Trans-log production function

The trans-log production function is one type of quadratic response surface models in terms of structure, and can be used to analyze the interaction of input factors in production function. This flexible function has both linear and quadratic terms with the ability of using more than two factor inputs. Introduced by [1], this function can be approximated by second order Taylor series, and can be expressed in a general functional form as follows:

$$\ln Y_t = \alpha_0 + \alpha_1 lnX_{1t} + \alpha_2 lnX_{2t} + \alpha_3 (lnX_{1t})^2 + \alpha_4 (lnX_{2t})^2 + \alpha_5 lnX_{1t} * lnX_{2t} \quad (1)$$

where Y_t represents output at time t; α_0 signifies the state of technical knowledge; X_{1t} and X_{2t} represent inputs 1 and 2 at time t, respectively; while α_1 and α_2 etc. are technologically determined parameters. According to [2], the use of this functional form permits one to avoid the imposition of assumptions such as perfect competition or perfect substitution among inputs. The presence of quadratic terms also allows for nonlinear relationships between the output and the inputs. These characteristics make the trans-log production function attractive to researchers due to its flexibility relative to other functional forms. In this manuscript, capital, labor, and four different types of energies: coal, oil, natural gas, and electricity are selected as inputs; thus the trans-log production function can be specified as follows:

$$\begin{aligned}\ln Y_t = {} & \alpha_0 + \alpha_K lnK_t + \alpha_L lnL_t + \alpha_C lnC_t + \alpha_O lnO_t + \alpha_{NG} lnNG_t \\ & + \alpha_E lnE_t + \alpha_{CO} lnC_t lnO_t + \alpha_{CNG} lnC_t lnNG_t \\ & + \alpha_{CE} lnC_t lnE_t + \alpha_{ONG} lnO_t lnNG_t + \alpha_{OE} lnO_t lnE_t \\ & + \alpha_{NGE} lnNG_t lnE_t + \alpha_{CC} (lnC_t)^2 + \alpha_{OO} (lnO_t)^2 \\ & + \alpha_{NGNG} (lnNG_t)^2 + \alpha_{EE} (lnE_t)^2\end{aligned} \quad (2)$$

In the above expression, Y_t represents the output (GDP); while K_t, L_t, C_t, O_t, NG_t, and E_t are inputs of capital, labor, coal, oil, natural gas and electricity respectively; α are the parameters of the inputs to be estimated.

Characterizing the economic region of a linear homogeneous production function, it is possible to calculate the output elasticity of each input from Eq. (2). Output elasticities of different energy inputs can be expressed as:

$$\begin{aligned}\rho_C &= \frac{dY/Y}{dC/C} = \frac{dlnY_t}{dlnC_t} \\ &= \alpha_C + \alpha_{CO} lnO_t + \alpha_{CNG} lnNG_t + \alpha_{CE} lnE_t + 2\alpha_{CC} lnC_t\end{aligned} \quad (3)$$

$$\begin{aligned}\rho_O &= \frac{dY/Y}{dO/O} = \frac{dlnY_t}{dlnO_t} \\ &= \alpha_O + \alpha_{CO} lnC_t + \alpha_{ONG} lnNG_t + \alpha_{OE} lnE_t + 2\alpha_{OO} lnO_t\end{aligned} \quad (4)$$

$$\begin{aligned}\rho_{NG} &= \frac{dY/Y}{dNG/NG} = \frac{dlnY_t}{dlnNG_t} \\ &= \alpha_{NG} + \alpha_{CNG} lnC_t + \alpha_{ONG} lnO_t + \alpha_{NGE} lnE_t + 2\alpha_{NGNG} lnNG_t\end{aligned} \quad (5)$$

$$\begin{aligned}\rho_E &= \frac{dY/Y}{dE/E} = \frac{dlnY_t}{dlnE} \\ &= \alpha_E + \alpha_{CE} lnC_t + \alpha_{OE} lnO_t + \alpha_{NGE} lnNG_t + 2\alpha_{EE} lnE_t\end{aligned} \quad (6)$$

According to [3], elasticity of substitution can be described as the relative variation of input proportion of production factors caused by the changes of marginal rate of technical substitution (given the technology level and prices of input factors). In other words, it is a ratio between the percentage change of proportion of input factors and the percentage change of marginal rate of technical substitution. Degree of substitutability among factors can be described by the elasticity of substitution. It shows how will the substitution of one production factor to other production factor change when price of one production factor changes. Elasticity of substitution varies from zero to infinity. A substitution elasticity of zero indicates that these two kinds of production factors can't substitute each other at all, and this situation exists in production functions with fixed input proportion (the Leontief production function); a substitution elasticity of infinity

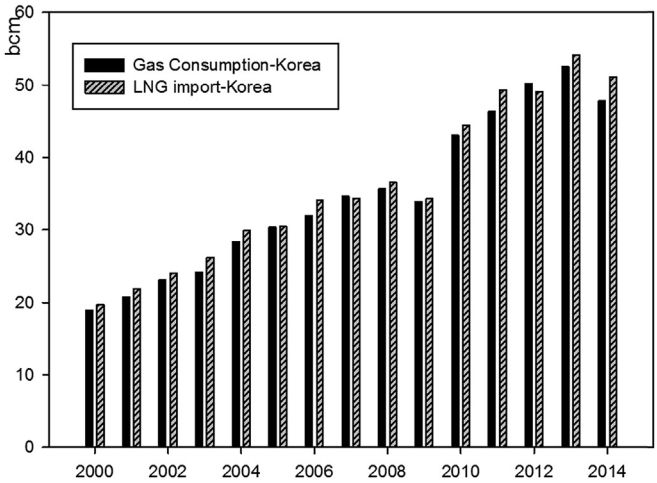

Fig. 4. Natural gas consumptions and imports in South Korea. Data Source: BP Statistical Review of World Energy 2001−2016.

indicates these two production factors can be totally substituted by each other. The elasticity of inter-energy substitution can thus be calculated as (take coal−gas substitution elasticity as an example):

$$\rho_{CNG} = \frac{d\left(\frac{C}{NG}\right)}{\left(\frac{C}{NG}\right)} \Bigg/ \frac{d\left(\frac{MP_{NG}}{MP_C}\right)}{\left(\frac{MP_{NG}}{MP_C}\right)} = \frac{d\left(\frac{C}{NG}\right)*\left(\frac{MP_{NG}}{MP_C}\right)}{d\left(\frac{MP_{NG}}{MP_C}\right)*\left(\frac{C}{NG}\right)} \tag{7}$$

Where MP_C and MP_{NG} represent for marginal product of coal and natural gas, respectively. From Eq. (7), the final formula used for calculating the substitution elasticities between coal and natural gas in this study becomes[3]:

$$\rho_{CNG} = \left[1 + \frac{-\alpha_{CNG} + 2*\frac{\rho_C}{\rho_{NG}}*\alpha_{NGNG}}{-\rho_C + \rho_{NG}}\right]^{-1} \tag{8}$$

Hence, the elasticity of inter-energy substitution can be obtained. In this article, ρ_{CO}, ρ_{CNG}, ρ_{CE}, ρ_{ONG}, ρ_{OE}, ρ_{NGE} indicate inter-fuel elasticities between coal and oil, coal and natural gas, coal and o electricity, oil and natural gas, oil and electricity and natural gas and electricity, respectively.

2.2. Ridge regression

Collinearity diagnostics provided by SPSS 22 suggests the trans-log model (2) suffers from severe multicollinearity − a statistical phenomenon in which two or more predictor variables in a multiple regression model are highly correlated, thereby violating a basic necessary condition for ordinary least squares (OLS) to be unbiased. To overcome the problem of multicollinearity, the ridge regression approach is therefore adopted, which was proposed by [4,5], for estimation, instead of the traditional OLS. For more detailed descriptions and explanations of ridge regression please refer to [6,7], etc.

2.3. Data processing

For output Y_t: data of GDP in constant 2005 U.S. dollar for China, Japan and South Korea, from 1985 to 2012, are collected from the International Comparison Program database of World Bank.

For capital K_t: data of capital stock at current purchasing power parities for China, Japan and South Korea, from 1985 to 2011, are based on the research of [8], which are also in constant 2005 U.S. dollars. Capital stock data after 2011 are not provided in their research, as a result, we refer to data of the percentage change of productive capital stock from the previous period, provided by the OECD Economic Outlook database. According to the percentage change rate of each year, data of capital stock for China, Japan and South Korea in 2012 can be obtained.

For labor L_t: data of employed persons for China, Japan and South Korea from 1985 to 2012 are collected from the China Statistical Yearbook, the Japan Statistical Yearbook and Statistics Korea,[4] respectively.

For energy inputs of coal C_t, oil O_t, natural gas NG_t, and electricity E_t: we aggregate final user energy consumptions used in different industries. However, there is obvious difference in statistic classification of industry sections among countries. For example, in China's official statistics yearbook, data of final user energy consumption are classified into 7 categories: 1) agriculture, forestry, animal husbandry, fishing; 2) industry; 3) construction; 4) transportation, storage and courier services; 5) commerce; 6) other industries; 7) residential. While data of final user energy consumption from IEA are classified into these following categories: 1) agriculture and forestry; 2) fishing; 3) industry; 4) transport; 5) commercial and public services; 6) other industries; 7) residential. In order to overcome the above problem, here in this paper we define productive use of energy as the difference of total final user energy consumption minus residential energy consumption, and regard it as energy inputs in our production function. Data of China's final user energy consumption for coal, oil, natural gas and electricity are collected from *China's statistics yearbook*; while data of Japan's and South Korea's final user energy consumption for coal, oil, natural gas and electricity are obtained from IEA Coal Information: OECD Coal Balance, IEA Oil Information: OECD Product Supply and Consumption, IEA Natural Gas Information: OECD Supply and Consumption by Sector, IEA Electricity Information: OECD Electricity and Heat Supply and Consumption, respectively.

2.4. Model results

The key issue for ridge regression is the selection of k (the ridge parameter). Ridge trace is a generally accepted approach for the determination of the value of k [9]. The selection of the k is also supported by the variance inflation factor (VIF), an

[3] For more details and full derivation of the substitution elasticity formula, please refer to the Appendix.

[4] Statistics Korea, http://kosis.kr/statHtml/statHtml.do?orgId=101&tblId=DT_1DA7024&language=en&conn_path=I3.

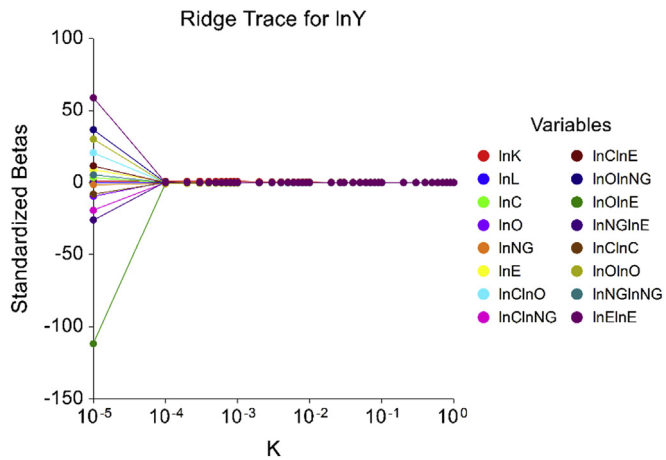

Fig. 5. Ridge trace for the selection of k.

index that measures how much the variance (the square of the estimate's standard deviation) of an estimated regression coefficient is increased due to collinearity (for more details, please refer to [10−12], etc.). Although one may expect small positive values of the ridge parameter to improve the conditioning of collinearity and reduce the variance of the estimates, sensitivity analysis show that the results are not very sensitive to how the value of the ridge parameter is selected. For this reason, this paper relies on the ridge trace plot and VIF ploy together to determine the best value of k. In addition, econometric software package of NCSS 11 is adopted for the ridge regression analysis, which can provide an optimum value of k initiatively. Figs. 5 and 6 are ridge trace and VIF plot of parameter estimates of China's trans-log production model (similar procedures have also been applied to trans-log production models of Japan and South Korea).

The value of 0.026631 is chosen by NCSS 11, as the optimum value of k. Based on the ridge trace and VIF plot, k = 0.026631 is considered to be reasonable, since at this value on one hand that all the coefficients of the variables appear to have stabilized (Fig. 5), on the other hand the values of VIF of the variables are within an acceptable range: generally, would

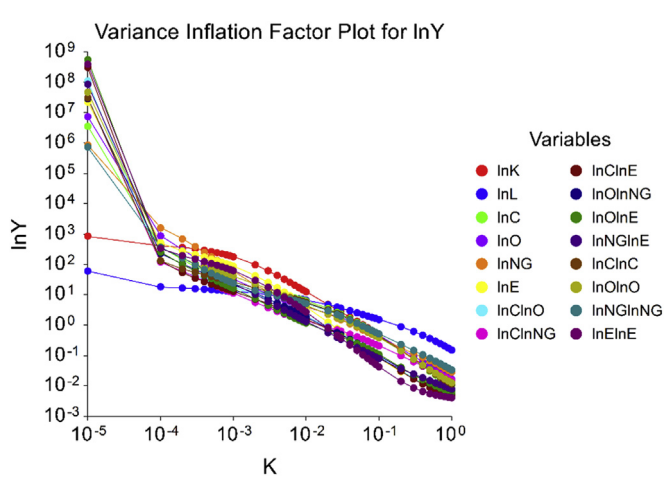

Fig. 6. VIF plot for the selection of k.

Table 1
The selection of k.

k Analysis section					
k	R2	Sigma	B'B	Ave VIF	Max VIF
0.000000	0.9999	0.0114	20076.4246	100297251.7127	547255397.4086
0.000100	0.9992	0.0355	2.3479	389.2166	1605.7037
0.000200	0.9990	0.0393	1.5792	183.5638	699.0153
0.000300	0.9988	0.0419	1.2986	121.2470	392.7372
0.000400	0.9987	0.0440	1.1407	92.0323	294.8952
0.000500	0.9986	0.0458	1.0321	75.0232	267.4410
0.000600	0.9985	0.0474	0.9491	63.7559	243.9519
0.000700	0.9984	0.0489	0.8817	55.6429	223.6378
0.000800	0.9983	0.0501	0.8249	49.4604	205.9175
0.000900	0.9982	0.0513	0.7760	44.5559	190.3464
0.001000	0.9982	0.0524	0.7332	40.5488	176.5762
0.002000	0.9976	0.0602	0.4802	21.0719	95.9354
0.003000	0.9972	0.0652	0.3653	13.9473	61.3126
0.004000	0.9968	0.0689	0.3016	10.3345	43.1000
0.005000	0.9966	0.0719	0.2620	8.1902	32.2731
0.006000	0.9963	0.0744	0.2354	6.7846	25.2793
0.007000	0.9961	0.0767	0.2163	5.7968	20.4795
0.008000	0.9959	0.0787	0.2020	5.0657	17.0293
0.009000	0.9957	0.0805	0.1909	4.5027	14.4569
0.010000	0.9955	0.0823	0.1820	4.0553	12.4811
0.020000	0.9939	0.0955	0.1400	2.0406	4.7607
0.026631	0.9930	0.1022	0.1277	1.5214	3.9042
0.030000	0.9926	0.1052	0.1232	1.3421	3.6144
0.040000	0.9914	0.1133	0.1133	0.9825	2.9746
0.050000	0.9903	0.1204	0.1065	0.7648	2.5409
…	…	…	…	…	…
1.000000	0.9249	0.3355	0.0587	0.0208	0.1512

be no larger than 10 (Fig. 6). In addition, Table 1 shows main test statistics with different values of k, indicating 0.026631 is a reliable value for the ridge parameter (as shaded in the table). Results of the ridge regression can therefore be obtained.

2.4.1. China

Based on the selection of k, ridge regression coefficients of the variables are showed in Table 2, from which China's trans-log production model can be obtained as:

$$\begin{aligned}\ln Y = &-2.629042 + 0.1962253*\ln K + 0.6362945*\ln L \\ &+ 0.01164311*\ln C + 0.2300488*\ln O \\ &- 0.01940903*\ln NG + 0.110079*\ln E \\ &+ 0.007820168*\ln ClnO - 0.001150404*\ln ClnNG \\ &+ 0.003819649*\ln ClnE + 0.005167123*\ln OlnNG \\ &+ 0.01035886*\ln OlnE + 0.002384198*\ln NGlnE \\ &- 0.0005551324*\ln ClnC + 0.01776127*\ln OlnO \\ &- 0.001357602*\ln NGlnNG + 0.005933656*\ln ElnE \end{aligned} \tag{9}$$

In order to test the fitting accuracy and stability of the model, historical data of the variables are substituted into Eq. (9) and thus fitted values of Y (GDP) are obtained and compared with the actual value, as shown in Fig. 7.

Table 2
Model results for China.

Ridge regression coefficient section for k = 0.026631				
Independent variable	Regression Coefficient	Standard error	Stand'zed regression coefficient	VIF
Intercept	−2.629042			
lnK	0.1962253	0.04344026	0.2035	3.2069
lnL	0.6362945	0.3050798	0.1037	3.9042
lnC	0.01164311	0.05891147	0.0080	2.6204
lnO	0.2300488	0.05410343	0.1465	1.8756
lnNG	−0.01940903	0.03585772	−0.0178	1.7142
lnE	0.110079	0.02338931	0.1039	0.7695
lnClnO	0.007820168	0.002396893	0.0652	0.6311
lnClnNG	−0.001150404	0.001501348	−0.0161	0.6937
lnClnE	0.003819649	0.00156278	0.0457	0.5511
lnOlnNG	0.005167123	0.001672733	0.0586	0.5693
lnOlnE	0.01035886	0.001810745	0.0991	0.4742
lnNGlnE	0.002384198	0.0009713027	0.0389	0.3973
lnClnC	−0.0005551324	0.003821583	−0.0057	2.4259
lnOlnO	0.01776127	0.00499164	0.1198	1.7912
lnNGlnNG	−0.001357602	0.001964351	−0.0261	2.2488
lnElnE	0.005933656	0.00126796	0.0806	0.4685

Analysis of variance section for k = 0.026631					
Source	DF	Sum of squares	Mean square	F-ratio	Prob level
Intercept	1	1427.712	1427.712		
Model	16	16.3804	1.023775	98.0428	0.000000
Error	11	0.1148634	0.01044213		
Total (adjusted)	27	16.49526	0.6109357		
Mean of dependent		7.140708			
Root mean square error		0.1021867			
R-Squared		0.9930			
Coefficient of variation		0.01431045			

2.4.2. Japan

Based on the selection of k, ridge regression coefficients of the variables are showed in Table 3, from which Japan's trans-log production model can be obtained as:

$$\begin{aligned}\ln Y = {} & 4.387963 + 0.05435068*\ln K + 0.3267217*\ln L \\ & + 0.02087492*\ln C - 0.0148409*\ln O \\ & + 0.02508416*\ln NG + 0.1011789*\ln E \\ & - 0.0005324596*\ln ClnO + 0.004647474*\ln ClnNG \\ & + 0.008892847*\ln ClnE + 0.002813931*\ln OlnNG \\ & + 0.004124776*\ln OlnE + 0.002732879*\ln NGlnE \\ & + 0.002427701*\ln ClnC - 0.002682942*\ln OlnO \\ & + 0.001288896*\ln NGlnNG + 0.007116192*\ln ElnE \end{aligned} \tag{10}$$

In order to test the fitting accuracy and stability of the model, historical data of the variables are substituted into Eq. (10) and thus fitted values of Y (GDP) are obtained and compared with the actual value, as shown in Fig. 8.

2.4.3. South Korea

Based on the selection of k, ridge regression coefficients of the variables are showed in Table 4, from which South Korea's trans-log production model can be obtained as:

$$\begin{aligned}\ln Y = {} & 2.836826 + 0.09240083*\ln K + 0.5305287*\ln L \\ & - 0.01822554*\ln C - 0.02682192*\ln O \\ & + 0.01418954*\ln NG + 0.09311763*\ln E \\ & - 0.00272178*\ln ClnO + 0.002748111*\ln ClnNG \\ & + 0.00737951*\ln ClnE + 0.002173664*\ln OlnNG \\ & + 0.0088275*\ln OlnE + 0.003845131*\ln NGlnE \\ & - 0.002637475*\ln ClnC - 0.003228154*\ln OlnO \\ & + 0.001631602*\ln NGlnNG + 0.01086178*\ln ElnE \end{aligned} \tag{11}$$

In order to test the fitting accuracy and stability of the model, historical data of the variables are substituted into Eq. (11) and thus fitted values of Y (GDP) are obtained and compared with the actual value, as shown in Fig. 9.

All statistical testing indicators in Tables 2–4, such as the value of R-squared (very closed to 1), standard error (most of them are smaller than 0.01), VIF (most of them are smaller than 1), as well as significance level of regression equation, reflect that the above three models are reliable. More importantly, the accuracy of these models indicates the ridge regression has overcome the multi-collinearity problem efficiently and also all the estimated parameters are statistically significant.

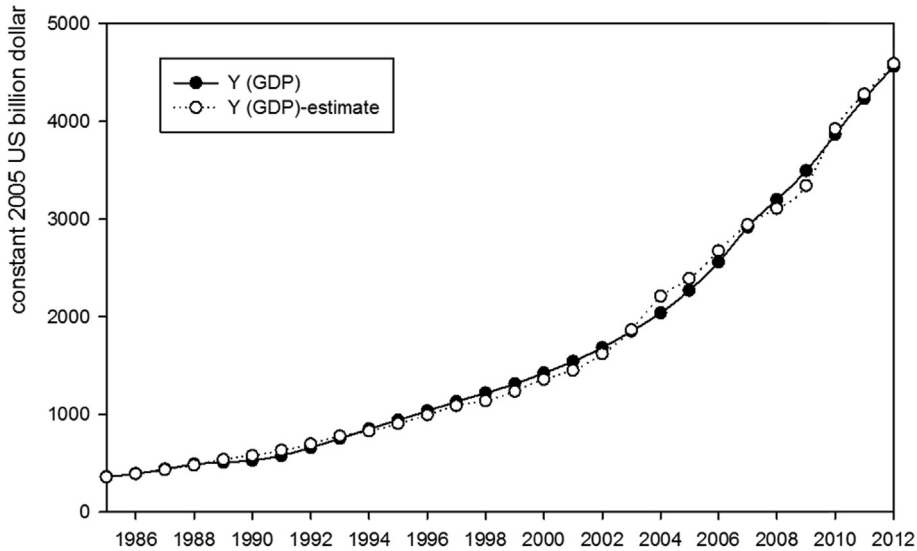

Fig. 7. Model fitting accuracy: China.

3. Possibilities of coal–gas substitution in China, Japan and South Korea

Combine trans-log production functions of (9–11) with Eq. (8), elasticities of coal–gas substitution in China, Japan and South Korea can therefore be obtained.

3.1. Coal–gas substitution in China

Fig. 10 reveals elasticities of coal–gas substitution and coal–electricity substitution in China. The results from Fig. 10 show elasticity estimates of both coal–gas substitution and coal–electricity substitution to be positive over 1985–2012, suggesting that these two energy input pairs are substitutes at least to some extent. It also indicates that relatively higher substitution possibilities between coal and natural gas, and less opportunities to substitute coal with electricity in China. Similar findings are concluded by [13] in Chinese iron and steel sector [7], in Chinese transport sector [14], in Chinese chemical industry, etc.

Under the background of climate change and environmental protection, China has to seek for alternate energies to offset the supply gap of reducing coal consumptions. The transition to renewables is unlikely to happen in decades, considering supply security and affordability of renewable energy sources. As a result, as the 'cleanest' fossil fuel, natural gas has gained increasing attention under the global warming background, and it is the most practical alternate energy within the short term in China.

Different from OECD countries where natural gas consumption took up 19.8% in total final consumption in 2012, the number was merely 5.6% in China. China's energy structure is now dominated by coal, with a proportion of 70.6% in total final consumption in 2012. However, with the West–East Gas Pipeline as well as foreign-connected gas pipelines being put into operation, China's natural gas consumption in recent years has grown rapidly. Its average annual growth rate reached 7.46% from 1980 to 2011, while the figure from 2002 to 2011 was as high as 16.08%.[5]

3.2. Coal–gas substitution in Japan

Fig. 11 shows elasticities of coal–gas substitution and coal–electricity substitution in Japan, indicating these two energy input pairs are substitutes over 1985–2012. Similar to China, elasticities of coal–gas substitution are found larger than elasticities of coal–electricity substitution in Japan, suggesting higher opportunities to substitute natural gas for coal in the country.

3.3. Coal–gas substitution in South Korea

Fig. 12 reveals elasticities of coal–gas substitution and coal–electricity substitution in South Korea, from which a conclusion can be made that both coal–natural gas and coal–electricity are substitutes, since their substitution elasticities are found to be positive over 1985–2012. Though the results indicate that elasticity of coal–electricity substitution is higher, elasticity of coal–gas substitution is however, increasing steadily.

4. Conclusions

Sustained focus on rising concerns about climate change have resulted in a proliferation of energy analysis for decades, among which, inter-fuel substitution has caught growing attention of researches and policymakers [15] first analyzed inter-fuel substitution and the industrial demand for energy [16] suggested substitution of natural gas for coal is one means of reducing carbon dioxide emissions. Relevant researches also have been done by [17,18], etc.

[5] Data Source: China energy statistical yearbook 2013.

Table 3
Model results for Japan.

Ridge regression coefficient section for k = 0.061436					
Independent variable	Regression coefficient	Standard error	Stand'zed regression coefficient	VIF	
Intercept	4.387963				
lnK	0.05435068	0.01928369	0.1596	1.4985	
lnL	0.3267217	0.2871653	0.0868	2.7179	
lnC	0.02087492	0.02774506	0.0149	0.1841	
lnO	−0.0148409	0.03553747	−0.0127	0.4308	
lnNG	0.02508416	0.00514064	0.1105	0.2398	
lnE	0.1011789	0.03835851	0.1140	0.8723	
lnClnO	−0.0005324596	0.003810533	−0.0030	0.2111	
lnClnNG	0.004647474	0.0009153499	0.0907	0.1492	
lnClnE	0.008892847	0.003437612	0.0657	0.3010	
lnOlnNG	0.002813931	0.0009395969	0.0739	0.2844	
lnOlnE	0.004124776	0.002088606	0.0426	0.2170	
lnNGlnE	0.002732879	0.0003349221	0.1038	0.0756	
lnClnC	0.002427701	0.003807013	0.0126	0.1816	
lnOlnO	−0.002682942	0.00356319	−0.0234	0.4525	
lnNGlnNG	0.001288896	0.0002483968	0.1079	0.2021	
lnElnE	0.007116192	0.003074447	0.1019	0.9066	
Analysis of variance section for k = 0.061436					
Source	DF	Sum of squares	Mean square	F-ratio	Prob level
Intercept	1	1941.036	1941.036		
Model	16	0.4168237	0.02605148	28.5199	0.000001
Error	11	0.01004794	0.0009134492		
Total (Adjusted)	27	0.4268716	0.01581006		
Mean of dependent		8.326026			
Root mean square error		0.03022332			
R-Squared		0.9765			
Coefficient of variation		0.003629982			

In this paper, a log linear trans-log production function model is established to investigate inter-fuel elasticity of substitution between coal, oil, natural gas and electricity in China, Japan and South Korea, respectively. A ridge regression approach is applied to estimate the parameters of the function. Results and priorities for energy development in China, Japan and South Korea are drawn as follows:

1) Reducing greenhouse gas (GHG) emissions and environmental pollutions require a credible pathway to meet the growing energy demands without increasing coal use, including much more renewable energies of different types, as well as affordable and stable supplies of natural gas. Change, however, cannot come at the cost of economic growth. The results from Figs. 10−12 show all elasticities of coal−gas substitution and coal−electricity substitution in China, Japan, and South Korea to be positive, indicating these two energy input pairs are substitutes. This means it is possible to substitute among different types of energies in these three countries without impacting on the output.
2) The elasticities of coal−gas substitution in China are much larger than that in Japan and South Korea, suggesting there is higher possibilities of coal−gas substitution in China. This is in accordance with economic reality, especially when taking into account the differences of current structure of the energy mix in primary energy consumption among China, Japan and South Korea. Currently natural gas consumption merely takes up 5.6% in total primary energy consumption in China in 2014; while the proportion is 22.2% and 15.7% in Japan and South Korea, respectively.[6] Taking into consideration of China's international environmental commitments, its pollution problems as well as national natural gas development plan, China could potentially

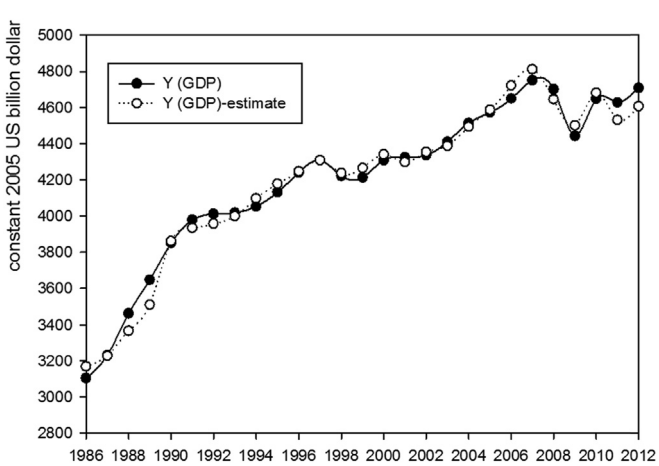

Fig. 8. Model fitting accuracy: Japan.

[6] Data Source: BP Statistical Review of World Energy 2015.

Table 4
Model results for South Korea.

Ridge regression coefficient section for k = 0.074304				
Independent variable	Regression coefficient	Standard error	Stand'zed regression coefficient	VIF
Intercept	2.836826			
lnK	0.09240083	0.01839357	0.1315	0.6148
lnL	0.5305287	0.1450132	0.1538	1.5852
lnC	−0.01822554	0.02418599	−0.0195	0.6010
lnO	−0.02682192	0.03204896	−0.0244	0.7637
lnNG	0.01418954	0.008856485	0.0570	1.1347
lnE	0.09311763	0.01191782	0.1424	0.2976
lnClnO	−0.00272178	0.003730837	−0.0155	0.4063
lnClnNG	0.002748111	0.001066658	0.0397	0.2128
lnClnE	0.00737951	0.002232963	0.0593	0.2886
lnOlnNG	0.002173664	0.0008423224	0.0455	0.2785
lnOlnE	0.0088275	0.001502576	0.0881	0.2017
lnNGlnE	0.003845131	0.0005381598	0.1142	0.2291
lnClnC	−0.002637475	0.007878128	−0.0106	0.9015
lnOlnO	−0.003228154	0.00438246	−0.0222	0.8153
lnNGlnNG	0.001631602	0.000425721	0.0859	0.4499
lnElnE	0.01086178	0.001536334	0.1649	0.4879

Analysis of variance section for k = 0.074304					
Source	DF	Sum of squares	Mean square	F-ratio	Prob level
Intercept	1	1152.058	1152.058		
Model	16	6.112334	0.3820209	55.3492	0.000000
Error	11	0.07592219	0.006902018		
Total (Adjusted)	27	6.188257	0.2291947		
Mean of Dependent		6.414432			
Root Mean Square Error		0.08307838			
R-Squared		0.9877			
Coefficient of Variation		0.01295179			

be a much larger consumer of natural gas than it is now. According to [19], natural gas demand of 330−370 bcm in the medium-term and 500−590 bcm in the long-term should be expected in China, based on logistic modelling approach. Similar conclusions are also made by [20,21], etc.

3) Results also indicate relatively higher substitution possibilities between coal and natural gas, and less opportunities to substitute coal with other fuels in China [22] argued that the strong constraint on coal use results in substitution toward other energy sources in China. In order to promote the use of natural gas as a substitute fuel for coal, the Chinese government targeted to increase the share of natural gas in total primary energy consumption up to 10% by 2020. Though [21] argued that this target is unlikely to complete, as China's natural gas consumption market is sluggish currently. However, increasing the ratio of natural gas consumption in China and substituting coal with natural gas are still the optimal approaches to deal with air pollution and smog issues in China. And it is predicted by [23−25], etc., that another round of faster development for natural gas will arrive in China after 2020.
4) Possibilities of coal−gas substitution are also found in Japan and South Korea, though may not as high as China. However, this substitution of natural gas for coal would also raise great concern on energy security in these two countries. China hold the largest natural gas reserves in the East Asia, and it is the world's sixth largest natural gas producer in 2014. In contrast, both Japan and South Korea are lack of gas reserves and therefore have limited domestic natural gas production. The research on security analysis of natural gas supply in East Asia has vastly increased, for example [26], raised the question of whether gas supplies can respond to expanding demand for the cleanest fossil fuel in East Asia, and [27] analyzed indicators of security of natural gas supply in Asia. The heavy reliance on LNG imports in Japan and South Korea

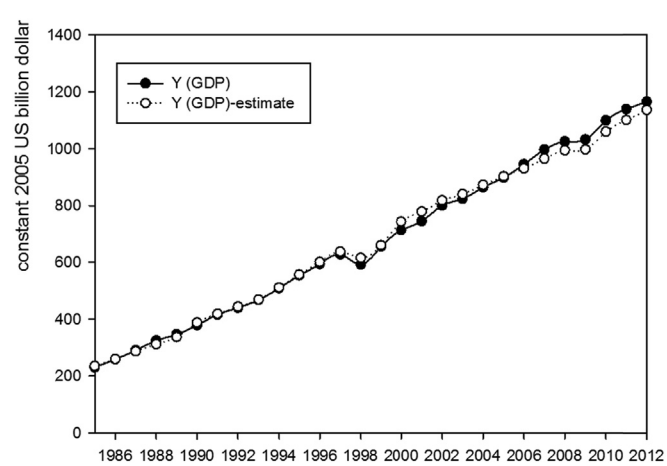

Fig. 9. Model fitting accuracy: South Korea.

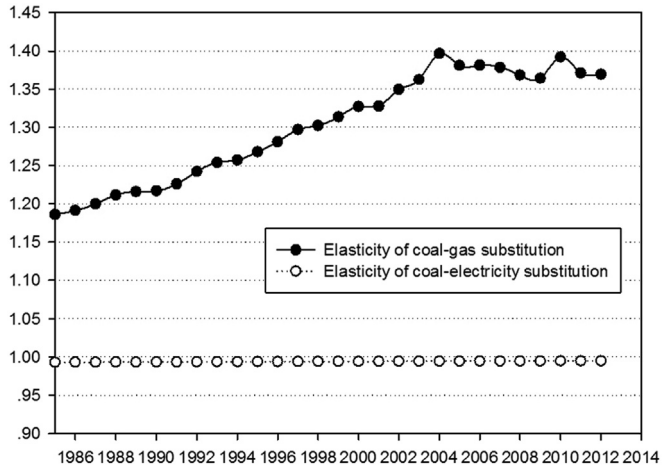

Fig. 10. Elasticity of coal−gas substitution in China.

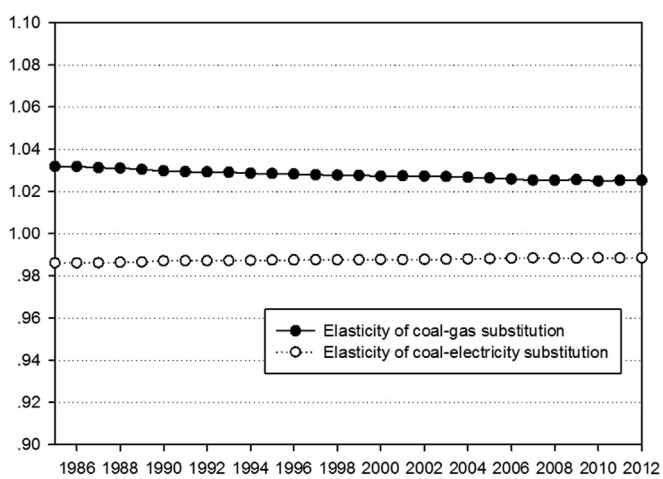

Fig. 11. Elasticity of coal−gas substitution in Japan.

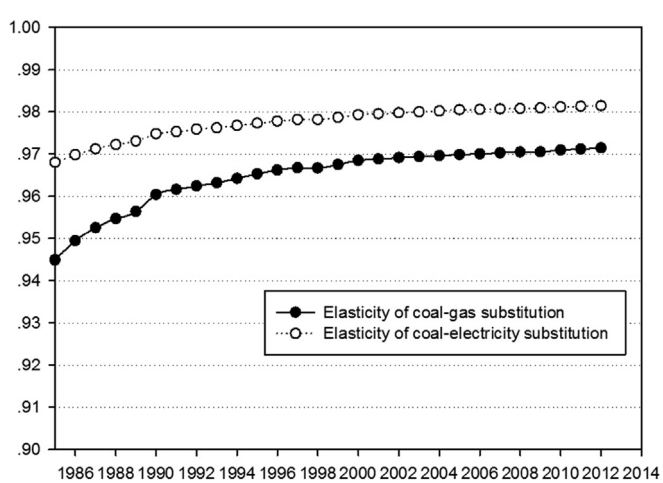

Fig. 12. Elasticity of coal−gas substitution in South Korea.

has become a major uncertainty to their national energy security. As a result, Unlike China, who would pay much attention to reducing the use of coal, Japan and South Korea should focus more on securing their natural gas supplies through means of supply diversification, free market competition and so on.

Appendix.

The trans-log production function in this manuscript is specified as follows:

$$\begin{aligned}\ln Y_t = {} & \alpha_0 + \alpha_K lnK_t + \alpha_L lnL_t + \alpha_C lnC_t + \alpha_O lnO_t + \alpha_{NG} lnNG_t \\ & + \alpha_{OT} lnOT_t + \alpha_{CO} lnC_t lnO_t + \alpha_{CNG} lnC_t lnNG_t \\ & + \alpha_{COT} lnC_t lnOT_t + \alpha_{ONG} lnO_t lnNG_t + \alpha_{OOT} lnO_t lnOT_t \\ & + \alpha_{NGOT} lnNG_t lnOT_t + \alpha_{CC}(lnC_t)^2 + \alpha_{OO}(lnO_t)^2 \\ & + \alpha_{NGNG}(lnNG_t)^2 + \alpha_{OTOT}(lnOT_t)^2\end{aligned} \tag{1}$$

In the above expression, Y_t represents the output (GDP); while K_t, L_t, C_t, O_t, NG_t, and OT_t are inputs of capital, labor, coal, oil, natural gas and electricity respectively; α are the parameters of the inputs to be estimated.

Characterizing the economic region of a linear homogeneous production function, it is possible to calculate the output elasticity of each input from Eq. (1). Output elasticities of inputs K and L can be expressed as:

$$\rho_K = \frac{dY/Y}{dK/K} = \frac{dlnY_t}{dlnK_t} = \alpha_K + 2\alpha_{KK} lnK_t + \alpha_{KL} lnL_t + \alpha_{KE} lnE_t \tag{2}$$

$$\rho_L = \frac{dY/Y}{dL/L} = \frac{dlnY_t}{dlnL_t} = \alpha_L + 2\alpha_{LL} lnL_t + \alpha_{KL} lnK_t + \alpha_{LE} lnE_t \tag{3}$$

Elasticity of substitution can be described as the relative variation of input proportion of production factors caused by the changes of marginal rate of technical substitution (given the technology level and prices of input factors). The elasticity of substitution between two inputs can thus be calculated as (take elasticity of substitution between capital and labor as an example):

$$\rho_{KL} = \frac{d\left(\frac{K}{L}\right)}{\left(\frac{K}{L}\right)} \Bigg/ \frac{d\left(\frac{MP_L}{MP_K}\right)}{\left(\frac{MP_L}{MP_K}\right)} = \frac{d\left(\frac{K}{L}\right) * \left(\frac{MP_L}{MP_K}\right)}{d\left(\frac{MP_L}{MP_K}\right) * \left(\frac{K}{L}\right)} \tag{4}$$

where MP_K and MP_L represent for marginal product of capital and labor, respectively. Given that,

$$\frac{MP_L}{MP_K} = \frac{\frac{\partial Y}{\partial L}}{\frac{\partial Y}{\partial K}} = \frac{\rho_L}{\rho_K} * \frac{K}{L} \tag{5}$$

Combine (4) with (5), then:

$$\rho_{KL}=\frac{d\left(\frac{K}{L}\right)}{d\left(\frac{MP_L}{MP_K}\right)}*\frac{\rho_L}{\rho_K}=\frac{\rho_L}{\rho_K}*\left[\frac{d\left(\frac{MP_L}{MP_K}\right)}{d\left(\frac{K}{L}\right)}\right]^{-1}=\frac{\rho_L}{\rho_K}*\left[\frac{d\left(\frac{\rho_L}{\rho_K}*\frac{K}{L}\right)}{d\left(\frac{K}{L}\right)}\right]^{-1} \tag{6}$$

Given that,

$$\frac{d\left(\frac{\rho_L}{\rho_K}*\frac{K}{L}\right)}{d\left(\frac{K}{L}\right)}=\frac{\rho_L}{\rho_K}+\frac{K}{L}*\frac{d\left(\frac{\rho_L}{\rho_K}\right)}{d\left(\frac{K}{L}\right)} \tag{7}$$

$$d\left(\frac{\rho_L}{\rho_K}\right)=-\frac{\rho_L}{\rho_K^2}d(\rho_K)+\frac{1}{\rho_K}d(\rho_l) \tag{8}$$

$$d\left(\frac{K}{L}\right)=-\frac{K}{L^2}d(L)+\frac{1}{L}d(K) \tag{9}$$

Thus,

$$\begin{aligned}\frac{d\left(\frac{\rho_L}{\rho_K}*\frac{K}{L}\right)}{d\left(\frac{K}{L}\right)}&=\frac{\rho_L}{\rho_K}+\frac{K}{L}*\frac{-\frac{\rho_L}{\rho_K^2}d(\rho_K)+\frac{1}{\rho_K}d(\rho_l)}{-\frac{K}{L^2}d(L)+\frac{1}{L}d(K)}\\&=\frac{\rho_L}{\rho_K}+\frac{K}{L}*\frac{-\frac{\rho_L}{\rho_K^2}*\frac{d(\rho_K)}{d(L)}+\frac{1}{\rho_K}*\frac{d(\rho_l)}{d(L)}}{-\frac{K}{L^2}+\frac{1}{L}*\frac{d(K)}{d(L)}}\end{aligned} \tag{10}$$

Combine (6) with (10), then:

$$\rho_{KL}=\left[1+\frac{\rho_K}{\rho_L}*\frac{K}{L}*\frac{-\frac{\rho_L}{\rho_K^2}*\frac{d(\rho_K)}{d(L)}+\frac{1}{\rho_K}*\frac{d(\rho_l)}{d(L)}}{-\frac{K}{L^2}+\frac{1}{L}*\frac{d(K)}{d(L)}}\right]^{-1} \tag{11}$$

From (2) and (3), then:

$$\frac{d(\rho_K)}{d(L)}=\frac{\alpha_{KL}}{L} \tag{12}$$

$$\frac{d(\rho_L)}{d(L)}=\frac{2\alpha_{LL}}{L} \tag{13}$$

$$\frac{\rho_K}{\rho_L}=\frac{K}{L}*\frac{dL}{dK} \tag{14}$$

Combine (12–14) with (11), then:

$$\begin{aligned}\rho_{KL}&=\left[1+\frac{\rho_K}{\rho_L}*\frac{K}{L}*\frac{-\frac{\rho_L}{\rho_K^2}*\frac{\alpha_{KL}}{L}+\frac{1}{\rho_K}*\frac{2\alpha_{LL}}{L}}{-\frac{K}{L^2}+\frac{1}{L}*\frac{d(K)}{d(L)}}\right]^{-1}\\&=\left[1+\frac{-\frac{\rho_L}{\rho_K}*\frac{K}{L}*\frac{dL}{dK}*\alpha_{KL}+2*\frac{K}{L}*\frac{dL}{dK}*\alpha_{LL}}{-\rho_L*\frac{K}{L}*\frac{dL}{dK}+\rho_L}\right]^{-1}\\&=\left[1+\frac{-\alpha_{KL}+2*\frac{\rho_K}{\rho_L}*\alpha_{LL}}{-\rho_K+\rho_L}\right]^{-1}\end{aligned} \tag{15}$$

Elasticity of substitution between other input factors can be calculated similarly.

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