China's Energy Economy: Technical Change, Factor Demand and Interfactor/Interfuel Substitution

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Abstract:

With its rapid economic growth, China's primary energy consumption has exceeded domestic energy production since 1994, leading to a substantial expansion in energy imports, particularly of oil. China's energy demand has an increasingly significant impact on global energy markets. In this paper Allen partial elasticities of factor and energy substitution, and price elasticities of energy demand, are calculated for China using a two-stage translog cost function approach. The results suggest that energy is substitutable with both capital and labour. Coal is significantly substitutable with electricity and complementary with diesel while gasoline and electricity are substitutable with diesel. China's energy intensity is increasing during the study period (1995-2004) and the major driver appears to be due to the increased use of energy intensive technology.

Keywords: China; Interfactor/interfuel substitution; Technology; Energy intensity decomposition

JEL classifications: D24, O33, Q41

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1. Introduction

China's demand for energy has surged to fuel both its growing industrial and commercial sectors and the rapid rise in households' living standards (Crompton and Wu, 2005). China consumed 1.39 billion tonnes of oil equivalent primary energy and accounted for 13.6% of the world total primary energy consumption in 2004 (BP, 2005). China's share of global energy consumption has almost doubled over the past 20 years, with increasing demand met by energy imports, particularly of oil. For example, China's oil production averaged 25% more than consumption in the 1980s but now nearly half of total oil consumption is imported and attempts to ensure security of supply from overseas have caused political tensions (Stokes, 2005). China's energy demand is also changing due to a rising environmental awareness. Public policy now aims to see the share of coal (which China has large stocks of) consumption gradually decline with oil, gas and electricity increasing.

China's rising energy use and declining reliance on coal will affect both world energy markets and the nature of China's future economic growth. It is therefore important that forecasts for the energy market and for economic growth are based on empirically estimated elasticities of factor and energy substitution, and price elasticities of energy demand (Ozatalay et al, 1979). In an early study, Hogan and Manne (1977) show that if the elasticity of substitution between energy and an aggregate of all other economic factors is in the range of 0.3-0.5, economic growth in the United States to the year 2010 would be predicted to be only slightly impeded by even dramatic constraints on growth in energy supply. Conversely an elasticity of 0.1-0.2 implies a significant depressive effect on the economy if shortage of fuels and electricity occur. Therefore, it is crucial to know the substitution possibilities between energy and non-energy inputs if one is interested in deriving the implications of increasingly scarce and higher priced energy inputs (Berndt and Wood, 1975). Yet when one looks for estimates of inter-factor and inter-fuel substitution possibilities and price elasticities of energy demand for China, one finds that they simply do not exist.

In contrast to the scarcity of micro-level results on the degree of input substitutability, the aggregate relationship between energy consumption and economic growth in China has been extensively studied (Shiu and Lam, 2004; Zou and Chau, 2006; Han et al., 2004; Wang et al., 2005). A related literature studies why the energy-output ratio appears to have fallen through time (Garbaccio et al., 1999; Fisher-Vanden et al., 2004), with several studies claiming that there have been improvements in energy efficiency in the industrial sector (Price et al., 2001; Sinton and Levine, 1998; Sinton and Fridley, 2000; Hu and Wang, 2006). Other studies forecast China's future energy consumption based on time series analysis of energy consumption and economic growth (Intarapravich et al., 1996; Chan and Lee, 1996; Crompton and Wu, 2005).

While these aggregate studies provide a variety of forecasts, more informed estimates of how rising energy prices, coupled with technical change, will affect the Chinese economy require knowledge of: i) the ease with which energy can be substituted for other types of inputs (including substitution between different energy inputs); and ii) the actual and potential effects of technological change on the efficient use of energy (energy intensity).

The focus of this study, therefore, is on two issues. Firstly, technological change, factor demand and interfactor and interfuel substitutability are calculated for China using a new and appropriate dataset and rigorous econometric methods. Secondly we decompose China's changing energy intensity to ascertain the driving forces of the recent increases in energy intensity. Taken together, the new results from this study will provide the inputs necessary to construct informed forecasts of the potential for China to adapt to the rising dependency on energy in a climate of rising fuel prices while, at the same time, attempting to minimize the effects on the environment from its rapid economic growth.

In Section two we introduce the methodologies used in this study followed in Section three by a discussion of the data sources and variable construction. Section four presents the results and Section five concludes.

2. Methodologies

It is typical in the energy economics literature to employ a translog cost function to estimate energy demand elasticities (Cho, et al., 2004; Berndt and Wood, 1979; Debertin, et al., 1990; Christopoulos and Tsionas, 2002; Welsch and Ochsen, 2005). Moreover, the translog cost function is a convenient specification of duality theory and as a second order approximation, it allows one to avoid the need to specify a particular production function (Stratopoulos et al., 2000). Nor is it necessary to assume constant or equal elasticities of substitution (Woodland, 1975).

We model how a change in an individual fuel price affects fuel consumption through the feedback effect between interfuel and interfactor substitution, assuming that the production function is weakly separable in the major components of energy, capital and labor.[1] This assumption allows us to construct an aggregate energy-price index from fuel prices. We can then assume that energy, capital and labor are homothetic in their components so that we can specify a homothetic fuel cost share equation. Thus, a second-order approximation of cost as a function of time, the logged input price and log output is used for the non-homothetic translog total factor cost function:

$$\begin{aligned} \ln TC = {} & \beta_0 + \sum_{i=1}^{m} \beta_i \ln P_{it} + \frac{1}{2} \sum_{i=1}^{m} \sum_{j=1}^{m} \beta_{ij} \ln P_{it} \ln P_{jt} + \beta_t t + \frac{1}{2} \beta_{tt} t^2 \\ & + \beta_y \ln Y_t + \frac{1}{2} \beta_{yy} (\ln Y_t)^2 + \sum_{i=1}^{m} \beta_{iy} \ln P_{it} \ln Y_t + \sum_{i=1}^{m} \beta_{it} t \ln P_{it} + \beta_{yt} t \ln Y_t \end{aligned} \tag{1}$$

where ln indicates the natural logarithm; TC is the equilibrium total cost; P_{jt} (P_{it}) denotes the price of input factor j (i) at time T; Y_t is the level of output in period T; t

[1] The analysis in the paper excludes material inputs due to the general lack of available Chinese data. Material inputs are also excluded in the work of Caloghirou et al. (1997) and Cho et al. (2004) for the same reason.

denotes a time trend to capture technical change (Welsch and Ochsen, 2005).[2] With the proper set of restrictions on its parameters, equation (1) can therefore be used to approximate any of the unknown cost and production functions. The symmetry restrictions are:

$$\beta_{ij} = \beta_{ji} \quad for\, all\ i \neq j \tag{2}$$

which implies equality of the cross-derivatives. Linear homogeneity in prices (when all factor prices double, the total cost has to double) requires the following regularity conditions:

$$\sum_{i=1}^{m}\beta_i = 1, \sum_{j=1}^{m}\beta_{ij} = 0, \sum_{i=1}^{m}\beta_{iy} = 0, \sum_{i=1}^{m}\beta_{it} = 0,\ i,\ j = 1,\cdots,m \tag{3}$$

By Shephard's lemma, a firm's system of cost minimizing demand functions (the conditional factor demands) can be obtained by differentiating equation (1) with respect to input prices to obtain the following system of factor share equations:

$$S_{factor} = \beta_i + \sum_{j=1}^{m}\beta_{ij}\ln P_{jt} + \beta_{iy}\ln Y_t + \beta_{it}t \tag{4}$$

with *i*,*j*=K, L and E (for capital, labor and energy, respectively). The homothetic translog aggregate energy price index function is given by:

$$\ln P_E = \gamma_0 + \sum_{i=1}^{n}\gamma_i \ln P_{it} + \frac{1}{2}\sum_{i=1}^{n}\sum_{j=1}^{n}\gamma_{ij}\ln P_{it}\ln P_{jt} + \sum_{i=1}^{n}\gamma_{it}t\ln P_{it} \tag{5}$$

where ln indicates the natural logarithm; P_E is the aggregated energy price; P_{jt} (P_{it}) denotes the price of fuel *j* (*i*) at time *T;* γ's are the parameters to be estimated. By differentiating equation (5) with respect to individual fuel price, we have the following fuel share equations:

$$S_{fuel} = \gamma_i + \sum_{j=1}^{n}\gamma_j \ln P_{jt} + \gamma_{it}t \tag{6}$$

with *i*,*j*=CO, EL, GA and DI for coal, electricity, gasoline and diesel, respectively.[3]

[2] To test whether the total factor cost equation (1) is the final function form used in this study, we have also estimated various its nested models based on various assumptions (see the Appendix for detailed assumptions made and the nested functions).

[3] Similarly, to test whether equation (6) is the final function form used in this study, we have also estimated various nested models based on a range of assumptions (see Appendix for assumptions and the detailed nested functions).

Following a two-stage approach suggested by Pindyck (1979), we can first estimate the homothetic translog fuel cost share equation (6) assuming constant returns to scale. The resulting parameter estimates yield the partial own- and cross-price elasticities of the fuel sources. The fitted fuel cost ($\hat{P}_E$) is computed based on equation (5) using the estimated parameters of equation (6) and serves as an instrumental variable for the aggregate price of energy (P_E). We then estimate the non-homothetic translog factor cost function (equation (1)) and factor share equations (4) simultaneously with the relevant restrictions imposed (see equations (2) and (3)).

The Allen partial elasticities of substitution (σ_{ij}) and own-price elasticities (η_{ii}) and cross-price elasticities (η_{ij}) of factor demand for the production process are given by equations (7) and (8) using the estimated parameters from equation (4) (Allen, 1938; Uzawa, 1962):

$$\sigma_{ij} = 1 + \beta_{ij} / S_i S_j \quad \forall\, i \neq j \quad and \quad \sigma_{ii} = (\beta_{ii} + S_i^2 - S_i) / S_i^2 \qquad (7)$$

$$\eta_{ii} = \sigma_{ii} S_i \quad and \quad \eta_{ij} = \sigma_{ij} S_j \quad \forall\, i \neq j \quad for\ i,\ j = K, L, E \qquad (8)$$

where S_i is the cost share of *i*th factor. A positive σ_{ij} between factors *i* and *j* indicates that they are substitutes, while a negative σ_{ij} implies that the factors *i* and *j* are complementary. Likewise, the Allen partial elasticities of substitution (σ_{ij}) between fuels and conditional own-price elasticities (η_{ii}) and conditional cross-price elasticities (η_{ij}) of fuel demand can be estimated by equations (7) and (8) using the estimated parameters from equation (6). Total own- and cross-price elasticities of fuel demand can be estimated as follows (Pindyck, 1979; Cho et al., 2004):

$$\eta_{ii}^* = \eta_{ii} + \eta_{EE} S_i \quad and \quad \eta_{ij}^* = \eta_{ij} + \eta_{EE} S_j \quad for\ i,\ j = CO, EL, GA, DI \qquad (9)$$

where S_i is the cost share of *i*th fuel source in total energy input and η_{EE} is the own-price elasticity of aggregate energy use from equation (8). Total own- and cross-price elasticities of fuel demand actually reflect both the effect of a price change under a given level of aggregate energy consumption (the terms η_{ii} and η_{ij} in equation (9)) without considering the effect of changes in aggregate energy consumption, and the feedback effect between the interfactor and interfuel substitution resulting from an individual fuel price change (the terms $\eta_{EE}S_i$ and $\eta_{EE}S_j$ in equation (9)) between the interfactor and interfuel substitution resulting from an individual fuel price change.[4]

To attribute changes in energy intensity (e) to various driving forces, such as factor substitution and technological change, one can observe that $e = E/Q = (P_Q/P_E)S_E$, where P_Q is the output price, P_E is aggregate energy price, and S_E is aggregate energy factor share in total factor cost function. Following Welsch and Ochsen (2005), we decompose the energy intensity using the estimated parameters of the aggregate energy share equation:

$$
\begin{aligned}
\hat{e} &= E/Q = (P_Q/P_E)S_E \\
&= \frac{P_Q}{P_E}(\hat{\beta}_E + \hat{\beta}_{EE}\ln P_E + \hat{\beta}_{EK}\ln P_K + \hat{\beta}_{EL}\ln P_L + \hat{\beta}_{iy}\ln Y + \hat{\beta}_{Et}t) \qquad (10)\\
&= [\frac{P_Q}{P_E}\hat{\beta}_E] + [\frac{P_Q}{P_E}\hat{\beta}_{EE}\ln P_E] + [\frac{P_Q}{P_E}\hat{\beta}_{EK}\ln P_K] + [\frac{P_Q}{P_E}\hat{\beta}_{EL}\ln P_L] + [\frac{P_Q}{P_E}\hat{\beta}_{iy}\ln Y] + [\frac{P_Q}{P_E}\hat{\beta}_{Et}t]
\end{aligned}
$$

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[4] For example, total own-price elasticity for each fuel source is given by:

$$\eta_{ii}^* = \frac{d\log E_i}{d\log P_i} = \frac{dE_i P_i}{dP_i E_i} = \left[\left.\frac{\partial E_i}{\partial P_i}\right|_{\bar{E}} + \frac{\partial E_i}{\partial E}\frac{\partial E}{\partial P_E}\frac{\partial P_E}{\partial P_i} \right]\frac{P_i}{E_i}, \text{ where } \frac{dE_i}{dP_i} = \left.\frac{\partial E_i}{\partial P_i}\right|_{\bar{E}} + \frac{\partial E_i}{\partial E}\frac{\partial E}{\partial P_E}\frac{\partial P_E}{\partial P_i}$$

The term $(\partial E_i/\partial P_i)(P_i/E_i)$ is the partial fuel-price elasticity, which is derived under a given level of aggregate energy consumption without considering the effect of changes in aggregate energy consumption. The term $(\partial E_i/\partial E)(\partial E/\partial P_E)(\partial P_E/\partial P)$ represents the magnitude of the feedback effect between the interfactor and interfuel substitution resulting from an individual fuel price change (Cho et al., 2004).

where $\hat{\beta}$'s are the estimates of β's. Energy intensity is decomposed into the six terms in square brackets on the right hand side of equation (10), denoted by $\hat{e}_0, \hat{e}_1, \hat{e}_2, \hat{e}_3, \hat{e}_4, \hat{e}_5$, respectively. The terms, $\hat{e}_1, \hat{e}_2, \hat{e}_3$, which include input price and associated substitution parameters, represent the contribution of factor substitution to the variation in energy intensity. The term $\hat{e}_4$ measures the effect of the change in output on energy intensity. Since the coefficient on the time trend, $\hat{\beta}_{Et}$ in equation (4), is meant to capture the effect of technological change on energy share change, the term $\hat{e}_5$ similarly measures the effect of technological change on energy intensity (under the assumption that such change can be represented by time).[5]

Recall the interpretation of $\hat{\beta}_E$ as the autonomous energy cost share (the first term of equation (4)), the variation in $\hat{e}_0 = [\frac{P_Q}{P_E}\hat{\beta}_E]$ hence measures how price changes contribute to changes in energy intensity at a given cost share. In other words, the term $\hat{e}_0$ captures how changes in the energy price affect the amount of energy which can be afforded at a given energy budget share. It may thus be called the budget effect of energy price changes on energy intensity (Welsch and Ochsen, 2005). The straightforward way of allocating changes in energy intensity to these various driving forces mentioned above can be expressed by:

$$\frac{\Delta\hat{e}}{\hat{e}} = \sum_{i=0}^{5} \frac{\Delta\hat{e}_i}{\hat{e}_i}\frac{\hat{e}_i}{\hat{e}} \qquad (11)$$

where $\Delta\hat{e}/\hat{e}$ and $\Delta\hat{e}_i/\hat{e}_i$ denote relative changes over time, and $\hat{e}$ and $\hat{e}_i$ indicate the base year level of energy intensity. The terms on the right hand side can have either positive or negative signs, indicated whether that particular driver has reduced

[5] This time trend could also be capturing shifts in the structure of the economy over time which we cannot distinguish from the effects of technological change (e.g., a growth in less energy intensive industries and fall in more energy intensive industries) over time. We are grateful to a referee for emphasizing this point.

(negative sign) or enhanced (positive sign) energy intensity. The measures calculated from equation (11) provide a richer analysis of changing energy intensity than is possible with the more aggregate calculations used to date for China.

3. Data

To conduct this study, we use three factor inputs: aggregate energy use (E), capital stock (K) and labor use (L). The total cost series (TC) is constructed as the sum of aggregate energy use, capital stock and labor use. Three factor share series are calculated based on total cost series and three factor inputs. Specifically, the aggregate energy input (E) is the sum of four fuel inputs: coal (CO), electricity (EL), gasoline (GA) and diesel (DI).[6] Each fuel input cost is the product of its consumption and price. Individual fuel consumption and price data are used to construct four fuel cost share series. The labor input cost is based upon the total wage payment.

Three factor price indices are constructed. As stated previously, the aggregate energy price index (P_E) is computed from equation (5) using the estimated parameters of equation (6). The capital stock price index (P_K) is obtained from the China Statistical Yearbook (CSY). The labor price index (P_L) is used as the labor wage rate, which is obtained by dividing total wage payment by total employment. All three factor price indices use 1995 as the base year.

Total output (Y) is represented by real GDP. Since the GDP deflator is not available from the CSY, we use a weighted index of the consumer price index and the fixed assets price index to deflate GDP, based on the fact that GDP in China mainly consists of labor and capital costs.

[6] In this study, only coal, electricity, gasoline and diesel are used because they are the four major energy sources and account for a large share of total energy consumption in China. Moreover, these price data are available for all provinces over the time period used here.

All the above indicators are obtained for each of the 31 provinces (autonomous regions or municipalities) and for each year from 1995-2004, giving us a panel database with a total of 310 observations.

The three main sources of data for this study are CSY, the China Energy Yearbook (CEY) and the State Development Planning Commission of China (SDPC). The CSY provides detailed data for employment (including total employment and wages), capital investment (including replacement and new investment), and gross domestic product (GDP), the consumer price index, and a fixed assets price index. Unfortunately, the CSY does not provide a capital stock statistics. Therefore, to construct a capital stock series, we employ the following equation:

$$K_t = K_{t-1}(1-\delta) + I_t \tag{12}$$

where K_t is current capital stock, K_{t-1} is previous year capital stock, δ is the capital depreciation rate, and I_t is current year capital investment. The total capital stock in 1994 comes from Table 4 of Li (2003). This total stock is disaggregated into agriculture, industry, construction, transportation and commerce, based on the allocation of capital replacement investment in 1994. The total capital depreciation is taken as capital at factor cost, which is consistent with the current cost accounting system in China and the use of GDP as an output indicator.

The CEY provides detailed data on consumption of each energy source and fuel type by province and year. However, the energy consumption data used in this study cover only coal, electricity, gasoline and diesel (see footnote 6 for explanation). This is more disaggregated than previous studies in China such as Cho et al. (2004), which only examine three fuels – coal, electricity and oil.

Individual fuel price data are obtained from SDPC. The SDPC collects fuel price data from 150 city price bureaus nationwide. Their price collection exercise covers coal, electricity, natural gas, crude oil, gasoline, diesel, kerosene, fuel oil and rural diesel and electricity. But this study only uses the price data of coal, electricity, gasoline and diesel (see footnote 6 for explanation). The fuel price data are initially reported and recorded for 10 day periods. For this study, therefore, we aggregate these 10 day data into an annual fuel price series by taking the mean of the 36 periods each year.

4. Results

Since prices are unlikely to be equal across all of China, we calculate a relative energy price index for each of seven regions. We grouped China's 31 provinces into seven regions according to the characteristics of energy production and consumption as well as location and level of aggregate economy.[7] After grouping 31 provinces into seven regions, we also assume that the parameters to be estimated vary across regions in equations (1) and (6) except for the interaction terms of factor prices in equation (1) and the terms of fuel prices in equation (6).[8] To implement these assumptions, we define the parameters as a linear function of regional dummy variables (D_R). They are in equation (1):

$$\beta_0 = \beta_{00} + \sum \beta_{0R} D_R \quad (12)$$

$$\beta_i = \beta_{i0} + \sum \beta_{iR} D_R \quad (13)$$

$$\beta_t = \beta_{t0} + \sum \beta_{tR} D_R \quad (14)$$

$$\beta_{tt} = \beta_{tt0} + \sum \beta_{ttR} D_R \quad (15)$$

$$\beta_y = \beta_{y0} + \sum \beta_{yR} D_R \quad (16)$$

$$\beta_{yy} = \beta_{yy0} + \sum \beta_{yyR} D_R \quad (17)$$

[7] Region 1 includes Hebei, Shanxi, Anhui, Shandong and Henan; region 2 includes Beijing, Tianjin, and Shanghai; region 3 includes Liaoning, Jilin and Heilongjiang; region 4 includes Jiangsu, Zhejiang, Jiangxi and Hubei; region 5 includes Fujian, Hunan, Guangdong, Guangxi and Hainan; region 6 includes Chongqing, Sichuan, Shaanxi, Gansu, Guizhou and Yunnan; region 7 includes Inner Mongolia, Tibet (deleted due to incomplete data), Qinghai, Ningxia and Xinjiang.

[8] It is also expected that the terms of fuel prices in equation (6) vary across regions. However, when we estimated this system of general fuel share equations, the results are not convergent and therefore, empirically we had to drop this assumption.

$$\beta_{iy} = \beta_{iy0} + \sum \beta_{iyR} D_R \tag{18}$$

$$\beta_{it} = \beta_{it0} + \sum \beta_{itR} D_R \tag{19}$$

$$\beta_{yt} = \beta_{yt0} + \sum \beta_{ytR} D_R \tag{20}$$

In Equation (6):

$$\gamma_i = \gamma_{i0} + \sum \gamma_{iR} D_R \tag{21}$$

$$\gamma_{it} = \gamma_{it0} + \sum \gamma_{itR} D_R \tag{22}$$

Based on above assumptions, equations (12)-(20), the final form of equation (1) can be expressed as:

$$\begin{aligned}\ln TC &= (\beta_{00} + \sum \beta_{0R} D_R) + \sum_{i=1}^{m} (\beta_{i0} + \sum \beta_{iR} D_R) \ln P_{it} + \frac{1}{2} \sum_{i=1}^{m} \sum_{j=1}^{m} \beta_{ij} \ln P_{it} \ln P_{jt} \\ &+ (\beta_{t0} + \sum \beta_{tR} D_R) t + \frac{1}{2} (\beta_{tt0} + \sum \beta_{ttR} D_R) t^2 + (\beta_{y0} + \sum \beta_{yR} D_R) \ln Y_t \\ &+ \frac{1}{2} (\beta_{yy0} + \sum \beta_{yyR} D_R)(\ln Y_t)^2 + \sum_{i=1}^{m} (\beta_{iy0} + \sum \beta_{iyR} D_R) \ln P_{it} \ln Y_t \\ &+ \sum_{i=1}^{m} (\beta_{it0} + \sum \beta_{itR} D_R) t \ln P_{it} + (\beta_{yt0} + \sum \beta_{ytR} D_R) t \ln Y_t \end{aligned} \tag{23}$$

Similarly, the final of equation (6) can be expressed as:

$$S_{fuel} = (\gamma_{i0} + \sum \gamma_{iR} D_R) + \sum_{j=1}^{n} \gamma_j \ln P_{jt} + (\gamma_{it0} + \sum \gamma_{itR} D_R) t \tag{24}$$

Equations (23) and (24) are the final functional forms to be estimated and used in this study. Employing the iterative Zellner's seemingly unrelated regression technique, we first estimate the system of translog fuel cost share equation (24). The aggregate energy price index (P_E) is generated using equation (5) and the parameters estimated from equation (6) in this stage. The parameter γ_0 in equation (5) is determined so that $P_E = 1$ in 1995 (Pindyck, 1979). Then, equations (23) and (24) are estimated simultaneously using the same iterative Zellner regression technique. Both symmetry and homogeneity restrictions, (equations (2) and (3)), in price are imposed and we also drop the labor share equation when estimating the system since parameters for this equation can be retrieved using the adding up restrictions.

In order to conduct the tests of whether equations (23) and (24) should be chosen as the final functional forms; whether prices are of separable; whether consumption behaviors vary across regions; and whether there is significant technological change, we estimate various nested functional forms against equations (23) and (24) (the assumptions made and the nested functions can be found in the Appendix 1).

4.1 Interfactor substitution

Table 1 reports the estimated parameters of the translog factor cost function and share equations. Recall that the estimation at this stage includes one total factor cost equation and two factor share equations (aggregate energy and capital shares - the labor share equation is dropped from the system due to the adding-up restriction). The conventional R^2 equals 0.99 for the total factor cost equation, 0.97 for the aggregate energy share equation and 0.96 for the capital share equation. The major parameters have the correct sign and more than 50% of parameters are statistically significant. The estimated total factor cost function is well behaved as the input demand function is strictly positive and concave in the input price (Berndt and Wood, 1975).

Using the estimated parameters reported in Table 1 to apply equations (7) and (8) allows the implied elasticities of substitution (σ_{ij}) and price elasticities (η_{ij}) of factor demand for the interfactor substitution to be calculated. The results of these calculations are shown in Table 2, where several important features are apparent.

First, each of the three factors is responsive to a change in their own price, with the magnitude of the elasticities greatest for energy, then capital and then labour. Specifically, the estimated own-price elasticities are η_{EE} = -0.47, η_{KK} = -0.42 and

η_{LL} = -0.21. Second, energy and capital appear to be substitutable and the estimated σ_{EK} is 0.80 with cross-price elasticities of η_{EK} = 0.11 and η_{KE} =0.22.

An argument could be made that we might expect energy and capital to be complements.[9] However, the empirical literature to date finds evidence of both complementarity and substitutability. Berndt and Wood (1975), Fuss (1977), and Magnus (1975) find energy and capital to be strong complements. Halvorsen and Ford (1978) and Fuss and Waverman (1975) find 'mixed results' on energy-capital substitutability. Griffin and Gregory (1976) find strong evidence of capital-energy substitutability as does Pindyck (1979). Pindyck (1979) provides two ways to reconcile the capital substitutability and complementarity results. Firstly, some studies may be picking-up short run effects (complementarity) versus long run (substitutability). Secondly, the number of factors in the model may (it seems) affect the results. Berndt and Wood (1977) show that complementarity between two factors in a four-dimensional production space can be consistent with substitutability between the same factors in a three-dimensional space. More recent studies, for example, Caloghirou et al. (1997) for Greece and Cho et. al. (2004) for Korea found a similar degree of substitutability to our results for China, see Table 7. Furthermore, in our results, neither the Allen partial elasticity of energy-capital substitution nor the cross-price elasticities η_{EK} and η_{KE} reported here are statistically significant at the 5% level.

The third feature of the results in Table 2 is that the substitution possibilities between energy and labour are almost as large as those for capital and energy, and are more statistically significant, with the Allen partial elasticity of substitution, σ_{EL} of 0.61 and the cross-price elasticities, η_{EL} = 0.36 and η_{LE} =0.17. Fourth, capital and labour are only slightly substitutable, with σ_{KL} =0.34 and cross-price elasticities of

[9] This is a point raised by one of the referees.

η_{KL} = 0.20 and η_{LK} =0.05 (all statistically insignificant). Finally, no complementary is found among energy, capital and labour in this study. As in Cho et al. (2004), all the cross-price elasticities are less than one, suggesting that the scope for substituting capital and labor for energy in China is somewhat limited.

4.2 Interfuel substitution

Table 3 reports the parameters estimates of the fuel share equations. Only three share equations (coal, gasoline and electricity) are estimated, with the fourth share equation (diesel) dropped from the system due to the adding-up restriction. The conventional R^2 figures are 0.89 for the coal share equation, 0.91 for the gasoline share equation, and 0.98 for the electricity share equation. The major parameters also have the correct sign and are statistically significant. The estimated share equations were also checked and found to be well behaved as all the input demand functions are strictly positive and concave in input price.

Based on the estimated parameters reported in Table 3, and again using equations (7) and (8), the implied elasticities of substitution (σ_{ij}) and price elasticities (η_{ij}) of fuel demand for China are calculated and the results are presented in Table 4. Several important features are apparent in Table 4:

(i) coal and electricity have substantial substitution possibilities – the estimated σ_{CO-EL} =1.49 (with a standard error of 0.19);[10]

(ii) in contrast, coal and diesel appear to be complementary – the estimated σ_{CO-DI} = -1.79 (with a standard error of 0.60) while the complementarity

[10] There may be a double counting problem since much of the coal consumed in China is used to generate electricity. However, any double counting problem will become less serious over time because large industrial plants increasingly use more electricity from the outside network with coal used only for their boilers. As for power plants, they mainly use coal to generate electricity and use minimal electricity for their own consumption. We thank the referee for pointing out this issue.

between coal and gasoline is smaller and imprecisely estimated (σ_{CO-GA}= -0.82 with a standard error of 0.53);

(iii) gasoline and electricity are slightly significantly substitutable – the estimated σ_{GA-EL}=0.60;

(iv) likewise, electricity and diesel are slightly significantly substitutable – the estimated σ_{EL-DI}=0.68.

At the policy level, these results have potentially important implications. If coal and electricity are substitutes as suggested above, China would have the potential to switch from the greenhouse-gas emitting coal to electricity, hence retaining the ability to use energy in economic development and reduce the environmental implications.

This finding of substitutability between coal and electricity appears to be consistent with China's changing situation. For example, central heating systems have been constructed in medium and large cities, reducing household reliance on coal. Environmental regulation has also reduced the ability of private companies to directly produce electricity using coal. In fact, annual growth rates of consumption by final users were more than 8% for electricity, but less than 4% for coal according to the 2005 China Statistical Yearbook. Firms are also moving away from self-generation of electricity and instead purchasing electricity from the grid (which is produced more efficiently). We would therefore expect to see some reduction in carbon emissions due to these improvements in the efficiency of generation. There are also possibilities of substitution from gasoline and diesel to electricity, although on a somewhat smaller scale. However, all of these implications could, to some extent, be undermined by the use of coal (and less problematically oil) in the production of electricity, something we cannot measure using the data that we have.

Looking forward, the estimated substitution parameters and the fact that electricity consumption is growing at twice the rate of coal imply likely changes in the future structure of the Chinese economy. First, since coal is abundant domestically, movement away from this energy source suggests that there will either be even more reliance on imported sources of energy to fuel power stations (noting the limited role of trans-border trade in electricity for China) or a reliance on new sources of generation. Second, because electricity benefits much more from efficient transmission and inter-regional trade than coal, due to the ease of coal storage, growing reliance on electricity can be expected to further advance the integration of the domestic Chinese energy market (See Ma, Oxley and Gibson, 2007).

The computed values of the fuel-price elasticities are displayed in Table 4. It can be seen that all the own-price elasticities of fuel demand are negative. It is also obvious that coal and electricity display the highest own-price elasticities (0.535 and 0.405, respectively) and are statistically significant. However, gasoline and diesel show much smaller own-price elasticites (0.214 and 0.108, respectively) and are statistically insignificant.

Total own- and cross-price elasticities of fuel demand are presented in Table 5, which provides several notable conclusions:

(i) The estimated results suggest that some fuel sources are substitutable while others are complementary. For example, coal-gasoline, gasoline-diesel and coal-diesel are all complementary, while electricity-diesel and gasoline-electricity are substitutable;

(ii) The fuel demands of coal and electricity are more sensitive to their own price change than of gasoline and diesel. In other words, the former are elastic while the later are inelastic;

(iii) Electricity demand is more sensitive to coal-price change than to gasoline- and diesel-price change, η^*_{EI-CO} =0.597 and η^*_{EI-GA} =0.072 and η^*_{EL-DI} =0.123. This finding implies that in the long run, a coal-price change has greater effect on electricity demand rather than a gasoline-price change;

(iv) Diesel demand is more sensitive to coal-price change than to gasoline-price change, η^*_{DI-CO} = -0.314 and η^*_{DI-GA} = - 0.067;

4.3 The roles of substitution, technologies and production

Using equations (10) and (11), we allocate the change in energy intensity into budget, substitution, technology and output effects. The results are displayed in Table 6. From Table 6, it can be seen that the estimated energy intensity of China at the national level increased by about 7.3% during the study period (1995-2004),[11] which is mainly due to two driving forces (rising energy price and adopting energy intensive technology) because the effects of substitution and production are small and they also are offset. In detail, the 'budget-effect' is –19.3%, which means that due to 'budget constraints', the increasing energy price forces enterprises to reduce energy use, which reduce energy intensity by approximately 20%. In fact, the aggregate energy price increased by 25% during the study period (1995-2004), which theoretically hinders energy use. The larger effect, however, comes from technological change, which increases energy intensity by 23.7% over the period. This finding suggests that China is adopting energy intensive technology, which is embodied in capital investment. The total substitution effect of energy intensity is negligible - the price of labor suggests it falls by about 5.6%, which is almost offset by the effect of the energy price (6.2%). The capital price effect is close to zero.

The same types of scenario can be found across the regions except region 3 where the energy intensity decomposition looks quite different due to a substantial budget effect (-35.9%). This region is the old industrial heartland in China's northeast (China's equivalent of the "rustbelt") and unsurprisingly this region has the smallest

[11] To make the estimate more stable and reliable, we take three-year averages of 1995-1997 and 2002-2004 for the base year and reporting year to calculate the growth rate of energy intensity.

effect of technological change; region 3 decreased its energy intensity by about 4.3%. In addition, the aggregate energy price in region 3 increased by more than 45%, which is almost twice of national average (only 25%). Until recently, this region lacked investment so that its energy intensity reflects the minimum effect of technological change and the continuing importance of heavy industry and military industry bases. Price changes will contribute more to changes in energy intensity in regions such as this where the energy intensity (at given cost shares) is high.

Although there is a similar pattern of decomposition in energy intensity change across regions, the driving forces behind energy intensity vary regionally. For example, energy intensity declined by 35.9% in region 3, but it only decreased by about 11% in regions 4 and 6 due to the budget effect at the aggregate economy level (Table 6). Energy intensity increased by 9.2% in region 3, but it only increased by 4.1% in region 4 due to the substitution of energy. Likewise, the effect of the substitution of labour also varies across regions. For instance, energy intensity decreased by about 12.1% in region 2 but it only declined by less than 4% in regions 1 and 5 due to the substitution of labour (Table 6). These findings suggest that the effects of energy price (budget effect) and substitution are extremely different across regions.

The findings presented here are generally consistent with estimates from *The Report on the Work of the Central Government of China 2006.* Here Premier Jiaobao Wen quotes official statistics which show that energy consumption per unit GDP *increased* by 4.9%, 5.5% and 0.2% in 2003, 2004 and 2005, respectively. Our results are in line with these statistics and suggest positive increases of 2.0% and 1.7% in 2003 and 2004. It should be noted that *The Report* indicates a greater increase in energy intensity than estimated by this paper, perhaps suggesting either their underreporting of energy consumption or over-reporting of GDP.

As there is no similar study on China with which to compare our estimated results Table 7 lists similar estimates for South Korea, West Germany, Greek, Portugal and Spain. However, these are for periods ten years older that those of this study. It can be seen from that Table that some estimates are quite similar, while some are quite different, not only the magnitudes, but also the signs.

5. Conclusions

In this paper, we calculate the missing technological change, factor demand and interfactor and interfuel substitutability measures for China using a new and appropriate dataset and rigorous econometric methods. In particular, we use individual fuel price data, obtained from 150 city price bureaus covering a variety of energy sources and a two-stage approach, total factor cost functions and fuel share equations were estimated and the parameters used to calculate implied elasticities of substitution (σ_{ij}) and price elasticities (η_{ij}) for interfactor substitution and interfuel substitution.

A central issue in energy policy planning and analysis is the extent to which other factors can substitute for energy in the economy and the effects of such substitution on future economic growth. Until now, these data on Chinese inter-factor and inter-fuel substitution possibilities between energy and non-energy inputs were unavailable and results presented above fill this important gap.

We decomposed China’s changing energy intensity to ascertain the driving forces of the recent increases in energy intensity. Taken together, the new results presented here provide the inputs necessary to construct informed forecasts of the potential for China to adapt to the rising dependency on energy in a climate of rising fuel prices while, at the same time, attempting to minimize the effects on the environment, economic growth.

Energy is Allen substitutable for all capital and labor. Some fuel sources are substitutable, while our results suggest that others are complementary. Energy intensity in China has increased slightly during the past five years where the major driver seems to be the growth of energy-intensive technologies. In other words, China is employing more and more energy intensive capital. Whether this trend in increasing energy intensity continues or declines will be significant and important for China and the rest of the World.

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Table 1
Estimates of the total factor cost function for aggregate energy demand

Variable	Coeff.	t-stat.	Variable	Coeff.	t-stat.	Variable	Coeff.	t-stat.
P_E	0.287	3.62	P_LD_4	-0.991	-5.42	P_EtD_3	-0.003	-0.79
P_K	0.287	4.54	P_LD_5	0.024	0.09	P_EtD_4	-0.001	-0.42
P_L	0.426	4.38	P_LD_6	-0.004	-0.03	P_EtD_5	0.004	1.28
P_EP_E	0.070	3.62	YD_1	5.359	1.23	P_EtD_6	0.008	2.64
P_EP_K	-0.007	-0.42	YD_2	-8.549	-2.93	P_KtD_1	-0.015	-4.84
P_EP_L	-0.062	-3.70	YD_3	-3.149	-2.39	P_KtD_2	-0.023	-7.59
P_KP_K	0.061	2.48	YD_4	0.434	0.64	P_KtD_3	-0.006	-2.20
P_KP_L	-0.054	-3.31	YD_5	-4.762	-5.46	P_KtD_4	0.003	1.24
P_LP_L	0.116	5.20	YD_6	1.853	1.44	P_KtD_5	-0.002	-0.94
Y	0.628	0.96	tD_1	-0.541	-1.41	P_KtD_6	-0.003	-1.28
YY	0.025	0.29	tD_2	0.651	2.31	P_LtD_1	0.014	2.92
P_EY	-0.009	-0.87	tD_3	0.190	1.18	P_LtD_2	0.018	3.88
P_KY	-0.021	-2.60	tD_4	0.002	0.02	P_LtD_3	0.008	2.08
P_LY	0.030	2.40	tD_5	0.370	3.61	P_LtD_4	-0.002	-0.46
T	0.050	0.60	tD_6	-0.136	-0.99	P_LtD_5	-0.002	-0.44
Tt	0.003	0.81	P_EYD_1	0.040	1.90	P_LtD_6	-0.005	-1.33
P_Et	0.010	4.59	P_EYD_2	-0.035	-1.60	YYD_1	-0.769	-1.25
P_Kt	-0.001	-0.38	P_EYD_3	0.091	5.89	YYD_2	1.201	2.99
P_Lt	-0.009	-3.54	P_EYD_4	0.049	4.06	YYD_3	0.411	2.35
Yt	-0.013	-1.18	P_EYD_5	-0.052	-3.61	YYD_4	-0.038	-0.42
P_ED_1	-0.233	-1.56	P_EYD_6	-0.032	-2.52	YYD_5	0.667	5.52
P_ED_2	0.269	1.63	P_KYD_1	0.049	2.96	YYD_6	-0.324	-1.51
P_ED_3	-0.704	-5.88	P_KYD_2	0.195	11.0	ttD_1	-0.004	-0.48
P_ED_4	-0.360	-3.93	P_KYD_3	0.052	4.21	ttD_2	0.008	1.14
P_ED_5	0.358	3.43	P_KYD_4	-0.022	-2.29	ttD_3	0.012	1.95
P_ED_6	0.189	2.09	P_KYD_5	0.029	2.49	ttD_4	-0.002	-0.46
P_KD_1	-0.168	-1.41	P_KYD_6	0.017	1.72	ttD_5	0.007	1.46
P_KD_2	-1.327	-10.1	P_LYD_1	-0.089	-3.48	ttD_6	-0.007	-1.22
P_KD_3	-0.377	-3.96	P_LYD_2	-0.159	-5.88	YTD_1	0.079	1.48
P_KD_4	0.150	2.07	P_LYD_3	-0.143	-7.56	YtD_2	-0.096	-2.47
P_KD_5	-0.212	-2.54	P_LYD_4	-0.027	-1.83	YtD_3	-0.036	-1.62
P_KD_6	-0.075	-1.04	P_LYD_5	0.023	1.32	YtD_4	0.005	0.38
P_LD_1	-0.117	-0.34	P_LYD_6	0.015	0.94	YtD_5	-0.055	-3.81
P_LD_2	1.229	5.37	P_EtD_1	0.001	0.33	YtD_6	0.027	1.22
P_LD_3	2.350	7.15	P_EtD_2	0.005	1.31			

Note: All variables are measured in natural logarithms, P and Y represent price and output, and D represents regional dummy variables. Regional dummy variables and constant term are not shown in the table.

Table 2
Implied elasticities of substitution (σ_{ij}) and price elasticities (η_{ij}) of factor demand for the interfactor substitution for the aggregate economy from equations (7) and (8)

	Elasticities	Standard Error
σ_{EE}	-1.7229**	0.2574
σ_{EK}	0.8034	0.5102
σ_{EL}	0.6130**	0.1198
σ_{KK}	-3.0342**	0.9237
σ_{KL}	0.3384	0.2168
σ_{LL}	-0.3646**	0.0645
η_{EE}	-0.4715**	0.0704
η_{EK}	0.1109	0.0643
η_{EL}	0.3606**	0.0615
η_{KE}	0.2199	0.1275
η_{KK}	-0.4189**	0.1784
η_{KL}	0.1991	0.1177
η_{LE}	0.1678**	0.0286
η_{LK}	0.0467	0.0276
η_{LL}	-0.2145**	0.0380

Note: E denotes aggregate energy, K denotes capital and L denotes labour. Elasticities are calculated at the mean of each share. S_E=0.2727, S_K=0.1381 and S_L=0.5882.
** Denotes significant at the 5% level.

Table 3
Estimates of the fuel share equations for aggregate energy demand

Coal			Gasoline			Electricity			Diesel		
Variable	Coeff.	t-stat.	Variable	Coeff.	t-stat.	Variable	Coeff.	t-stat.	Variable	Coeff.	t-stat.
Cons	0.278	26.70	Cons	0.080	12.59	Cons	0.574	44.41	Cons	0.068	7.71
D_1	-0.081	-3.85	D_1	0.026	2.04	D_1	0.022	0.84	D_1	0.033	1.83
D_2	0.004	0.18	D_2	0.048	3.73	D_2	-0.101	-3.83	D_2	0.050	2.77
D_3	-0.056	-2.93	D_3	0.008	0.71	D_3	0.004	0.18	D_3	0.043	2.68
D_4	-0.086	-4.87	D_4	0.028	2.66	D_4	-0.009	-0.42	D_4	0.066	4.46
D_5	0.004	0.21	D_5	0.019	1.89	D_5	-0.029	-1.39	D_5	0.006	0.45
D_6	-0.090	-4.75	D_6	0.071	6.11	D_6	-0.010	-0.43	D_6	0.030	1.83
P_1	0.051	2.74	P_1	-0.035	-3.41	P_1	0.046	2.65	P_1	-0.062	-4.62
P_2	-0.035	-3.41	P_2	0.079	3.42	P_2	-0.028	-1.97	P_2	-0.017	-0.80
P_3	0.046	2.65	P_3	-0.028	-1.97	P_3	0.007	0.24	P_3	-0.026	-1.35
P_4	-0.062	-4.62	P_4	-0.017	-0.80	P_4	-0.026	-1.35	P_4	0.104	4.40
T	-0.011	-6.17	t	-0.001	-0.87	t	0.010	5.07	t	0.002	1.06
tD_1	0.000	0.03	tD_1	0.002	1.11	tD_1	-0.001	-0.22	tD_1	-0.001	-0.50
tD_2	-0.009	-2.49	tD_2	0.001	0.55	tD_2	0.009	1.93	tD_2	-0.001	-0.34
tD_3	0.000	0.11	tD_3	0.000	0.13	tD_3	-0.001	-0.22	tD_3	0.000	0.09
tD_4	0.001	0.39	tD_4	0.001	0.63	tD_4	-0.002	-0.50	tD_4	0.000	-0.17
tD_5	-0.003	-0.99	tD_5	0.001	0.93	tD_5	-0.001	-0.42	tD_5	0.003	1.12
tD_6	0.010	3.22	tD_6	-0.006	-3.37	tD_6	-0.004	-0.97	tD_6	0.000	0.06

Note: Coefficients for the diesel share are calculated based on the adding-up restriction. Prices are measured in terms of logarithms.

Table 4

Implied elasticities of substitution (σ_{ij}) and the price elasticities (η_{ij}) of fuel demand for the interfuel substitution of the aggregate economy from equations (7) and (8)

	Elasticities	Standard Error		Elasticities	Standard Error
σ_{CO-CO}	-3.2666**	0.7140	η_{CO-CO}	-0.5249**	0.1147
σ_{CO-GA}	-0.8175	0.5338	η_{CO-GA}	-0.1314**	0.0632
σ_{CO-EL}	1.4948**	0.1869	η_{CO-EL}	0.2402**	0.1088
σ_{CO-DI}	-1.7908**	0.6043	η_{CO-DI}	-0.2878**	0.0838
σ_{GA-GA}	-1.8035	1.6485	η_{GA-CO}	-0.0968	0.0858
σ_{GA-EL}	0.5951**	0.2052	η_{GA-GA}	-0.2137	0.1953
σ_{GA-DI}	-0.0099	1.2603	η_{GA-EL}	0.0705	0.1195
σ_{EL-EL}	-0.6964**	0.0896	η_{GA-DI}	-0.0012	0.1748
σ_{EL-DI}	0.6826**	0.2346	η_{EL-CO}	0.8702**	0.0300
σ_{DI-DI}	-0.7814	1.2348	η_{EL-GA}	0.3464**	0.0243
			η_{EL-EL}	-0.4054**	0.0522
			η_{EL-DI}	0.3973**	0.0326
			η_{DI-CO}	-0.2484**	0.0971
			η_{DI-GA}	-0.0014	0.1493
			η_{DI-EL}	0.0947	0.1366
			η_{DI-DI}	-0.1084	0.1713

Note: CO, GA, EL and DI denote coal, gasoline, electricity and diesel, respectively; elasticities are calculated at the mean of each share (namely, S_C=0.1607, S_G=0.1185, S_E=0.5821 and S_D=0.1387).
** denotes significant at the 5% level.

Table 5

Total own- and cross-price elasticities (η_{ij}^{*}) of fuel demand for the interfuel substitution of the aggregate economy from equation (9)

	Elasticities		Elasticities
η_{CO-CO}^{*}	-0.6007	η_{EL-CO}^{*}	0.5956
η_{CO-GA}^{*}	-0.2072	η_{EL-GA}^{*}	0.0718
η_{CO-EL}^{*}	0.1644	η_{EL-EL}^{*}	-0.6800
η_{CO-DI}^{*}	-0.3635	η_{EL-DI}^{*}	0.1228
η_{GA-CO}^{*}	-0.1527	η_{DI-CO}^{*}	-0.3139
η_{GA-GA}^{*}	-0.2695	η_{DI-GA}^{*}	-0.0668
η_{GA-EL}^{*}	0.0146	η_{DI-EL}^{*}	0.0293
η_{GA-DI}^{*}	-0.0571	η_{DI-DI}^{*}	-0.1738

Note: CO, GA, EL and DI denote coal, gasoline, electricity and diesel, respectively; elasticities are calculated at the mean of each share (namely, S_C=0.1607, S_G=0.1185, S_E=0.5821 and S_D=0.1387).

Table 6

Decomposition of the change in energy intensity for the aggregate economy [a]

Region [b]	$\Delta\hat{e}/\hat{e}$	Budget	Substitution				GDP	Tech.
			Sum	Energy	Capital	Labor		
National	0.0727	-0.1934	0.0043	0.0619	-0.0017	-0.0559	0.0251	0.2368
Region 1	0.0702	-0.2387	0.0363	0.0701	-0.0014	-0.0324	0.0387	0.2340
Region 2	0.0550	-0.1540	-0.0581	0.0641	-0.0010	-0.1212	0.0153	0.2517
Region 3	-0.0429	-0.3589	0.0214	0.0916	-0.0019	-0.0683	0.0647	0.2299
Region 4	0.1336	-0.1123	-0.0099	0.0409	-0.0014	-0.0494	0.0071	0.2487
Region 5	0.0638	-0.2242	0.0195	0.0594	-0.0008	-0.0391	0.0341	0.2343
Region 6	0.1345	-0.1161	0.0069	0.0523	-0.0026	-0.0428	0.0095	0.2342
Region 7	0.0602	-0.1686	-0.0143	0.0656	-0.0027	-0.0771	0.0113	0.2318

[a] To make the estimate more stable and reliable, we take three year averages of 1995-1997 and 2002-2004 for the base year and reporting year to calculate the growth rate of energy intensity.

[b] Region 1 includes Hebei, Shanxi, Anhui, Shandong and Henan; region 2 includes Beijing, Tianjin, and Shanghai; region 3 includes Liaoning, Jilin and Heilongjiang; region 4 includes Jiangsu, Zhejiang, Jiangxi and Hubei; region 5 includes Fujian, Hunan, Guangdong, Guangxi and Hainan; region 6 includes Chongqing, Sichuan, Shaanxi, Gansu, Guizhou and Yunnan; region 7 includes Mongolia, Tibet (data unavailable), Qinghai, Ningxia and Xinjiang.

Table 7
International comparison of implied elasticities of substitution (σ_{ij}) and price elasticities (η_{ij}) of factor demand for the aggregate economy

	China (1995-04)	South Korea (1981-97)	West Germany (1976-94)	Greece (1970-90)	Portugal (1980-96)	Spain (1980-96)
σ_{EE}	-1.723	4.850	-	-	-3.73	-0.729
σ_{EK}	0.803	0.783	-0.399	0.972	0.893	-0.012
σ_{EL}	0.613	-1.418	-0.075	0.976	0.812	0.300
σ_{KK}	-3.034	-1.111	-	-	-0.299	-0.275
σ_{KL}	0.338	0.867	-	1.061	-0.134	0.952
σ_{LL}	-0.365	-0.556	-		-0.219	-1.043
η_{EE}	-0.472	0.356	-	-0.845	-0.689	-0.122
η_{EK}	0.111	0.341	-0.320	0.361	0.301	-0.005
η_{EL}	0.361	-0.697	0.867	0.236	0.388	0.127
η_{KE}	0.220	0.058	-0.133	0.060	0.165	-0.002
η_{KK}	-0.419	-0.484	-	-0.436	-0.101	-0.400
η_{KL}	0.199	0.426	-	0.386	-0.064	0.402
η_{LE}	0.168	-0.104	0.191	0.058	0.150	0.050
η_{LK}	0.047	0.377	-	0.565	-0.045	0.391
η_{LL}	-0.215	-0.277	-	-0.604	-0.105	-0.441

Note: E denotes aggregate energy, K denotes capital and L denotes labor; the figures in parentheses are the standard errors; the elasticities for South Korea are from Cho, Nam and Pagan (2004), for West Germany from Welsch and Ochsen (2005); for Greece are from Christopoulos and Tsionas (2002), for Portugal and Spain are from Vega-Cervera and Medina (2000).

Appendix 1

Maximum likelihood ratio tests for the separability of prices and incorporation of regional dummy variables for nested functions against equations (23) and (24)

The assumptions for the nested function forms to be tested	Critical values		# Restrictions	χ^2 Statistics
	5%	1%		
Against equation (23):				
1. $\sum D_R \ln P_i = 0$	27.6	33.4	17	344.4***
2. $\sum \ln P_i t = 0$ and $\sum D_R \ln P_i t = 0$	23.7	29.1	14	231.4***
3. $\sum D_R \ln P_i t = 0$	21.0	26.2	12	104.7***
4. $\sum \ln P_i \ln P_j = 0$	7.8	11.3	3	35.0***
5. $\sum D_R \ln Y = 0$ and $\sum D_R (\ln Y)^2 = 0$	21.0	26.2	12	122.3***
6. $\sum D_R t = 0$ and $\sum D_R tt = 0$	21.0	26.2	12	49.7***
7. $\sum D_R t\ln Y = 0$	12.6	16.8	6	48.2***
8. $\sum D_R = 0$	12.6	16.8	6	86.7***
Against equation (24):				
9. $\sum D_R = 0$	28.9	34.8	18	116.1***
10. $t = 0$ and $\sum D_R t = 0$	28.9	34.8	18	84.1***
11. $\sum D_R t = 0$	25.0	30.6	15	32.4***
12. $\sum \ln P_j = 0$	12.6	16.8	6	38.4***

Note: The null hypotheses relate to any two of price, output and time variables are separable; the null hypotheses for regional dummy variables are "there are no significant differences in production behaviour across regions." The estimated nested functional forms based on the above assumptions 1-12 are shown in Appendix 2.
*** denotes significant at the 1% level.

Appendix 2

The estimated nested functional forms based on the above assumptions 1-12 in Appendix 1 are shown below in order:

$$\ln TC = (\beta_{00} + \sum \beta_{0R} D_R) + \sum_{i=1}^{m} \beta_{i0} \ln P_{it} + \frac{1}{2} \sum_{i=1}^{m} \sum_{j=1}^{m} \beta_{ij} \ln P_{it} \ln P_{jt}$$
$$+ (\beta_{t0} + \sum \beta_{tR} D_R) t + \frac{1}{2} (\beta_{tt0} + \sum \beta_{ttR} D_R) t^2 + (\beta_{y0} + \sum \beta_{yR} D_R) \ln Y_t$$
$$+ \frac{1}{2} (\beta_{yy0} + \sum \beta_{yyR} D_R)(\ln Y_t)^2 + \sum_{i=1}^{m} (\beta_{iy0} + \sum \beta_{iyR} D_R) \ln P_{it} \ln Y_t$$
$$+ \sum_{i=1}^{m} (\beta_{it0} + \sum \beta_{itR} D_R) t \ln P_{it} + (\beta_{yt0} + \sum \beta_{ytR} D_R) t \ln Y_t$$

$$\ln TC = (\beta_{00} + \sum \beta_{0R} D_R) + \sum_{i=1}^{m} (\beta_{i0} + \sum \beta_{iR} D_R) \ln P_{it} + \frac{1}{2} \sum_{i=1}^{m} \sum_{j=1}^{m} \beta_{ij} \ln P_{it} \ln P_{jt}$$
$$+ (\beta_{t0} + \sum \beta_{tR} D_R) t + \frac{1}{2} (\beta_{tt0} + \sum \beta_{ttR} D_R) t^2 + (\beta_{y0} + \sum \beta_{yR} D_R) \ln Y_t$$
$$+ \frac{1}{2} (\beta_{yy0} + \sum \beta_{yyR} D_R)(\ln Y_t)^2 + \sum_{i=1}^{m} (\beta_{iy0} + \sum \beta_{iyR} D_R) \ln P_{it} \ln Y_t$$
$$+ (\beta_{yt0} + \sum \beta_{ytR} D_R) t \ln Y_t$$

$$\ln TC = (\beta_{00} + \sum \beta_{0R} D_R) + \sum_{i=1}^{m} (\beta_{i0} + \sum \beta_{iR} D_R) \ln P_{it} + \frac{1}{2} \sum_{i=1}^{m} \sum_{j=1}^{m} \beta_{ij} \ln P_{it} \ln P_{jt}$$
$$+ (\beta_{t0} + \sum \beta_{tR} D_R) t + \frac{1}{2} (\beta_{tt0} + \sum \beta_{ttR} D_R) t^2 + (\beta_{y0} + \sum \beta_{yR} D_R) \ln Y_t$$
$$+ \frac{1}{2} (\beta_{yy0} + \sum \beta_{yyR} D_R)(\ln Y_t)^2 + \sum_{i=1}^{m} (\beta_{iy0} + \sum \beta_{iyR} D_R) \ln P_{it} \ln Y_t$$
$$+ \sum_{i=1}^{m} \beta_{it0} t \ln P_{it} + (\beta_{yt0} + \sum \beta_{ytR} D_R) t \ln Y_t$$

$$\ln TC = (\beta_{00} + \sum \beta_{0R} D_R) + \sum_{i=1}^{m} (\beta_{i0} + \sum \beta_{iR} D_R) \ln P_{it}$$
$$+ (\beta_{t0} + \sum \beta_{tR} D_R) t + \frac{1}{2} (\beta_{tt0} + \sum \beta_{ttR} D_R) t^2 + (\beta_{y0} + \sum \beta_{yR} D_R) \ln Y_t$$
$$+ \frac{1}{2} (\beta_{yy0} + \sum \beta_{yyR} D_R)(\ln Y_t)^2 + \sum_{i=1}^{m} (\beta_{iy0} + \sum \beta_{iyR} D_R) \ln P_{it} \ln Y_t$$
$$+ \sum_{i=1}^{m} (\beta_{it0} + \sum \beta_{itR} D_R) t \ln P_{it} + (\beta_{yt0} + \sum \beta_{ytR} D_R) t \ln Y_t$$

$$\ln TC = (\beta_{00} + \sum \beta_{0R} D_R) + \sum_{i=1}^{m} (\beta_{i0} + \sum \beta_{iR} D_R) \ln P_{it} + \frac{1}{2} \sum_{i=1}^{m} \sum_{j=1}^{m} \beta_{ij} \ln P_{it} \ln P_{jt}$$
$$+ (\beta_{t0} + \sum \beta_{tR} D_R) t + \frac{1}{2} (\beta_{tt0} + \sum \beta_{ttR} D_R) t^2 + \beta_{y0} \ln Y_t$$
$$+ \frac{1}{2} \beta_{yy0} (\ln Y_t)^2 + \sum_{i=1}^{m} (\beta_{iy0} + \sum \beta_{iyR} D_R) \ln P_{it} \ln Y_t$$
$$+ \sum_{i=1}^{m} (\beta_{it0} + \sum \beta_{itR} D_R) t \ln P_{it} + (\beta_{yt0} + \sum \beta_{ytR} D_R) t \ln Y_t$$

$$\ln TC = (\beta_{00} + \sum \beta_{0R} D_R) + \sum_{i=1}^{m} (\beta_{i0} + \sum \beta_{iR} D_R) \ln P_{it} + \frac{1}{2} \sum_{i=1}^{m} \sum_{j=1}^{m} \beta_{ij} \ln P_{it} \ln P_{jt}$$

$$+ \beta_{t0} t + \frac{1}{2} \beta_{tt0} t^2 + (\beta_{y0} + \sum \beta_{yR} D_R) \ln Y_t$$

$$+ \frac{1}{2} (\beta_{yy0} + \sum \beta_{yyR} D_R)(\ln Y_t)^2 + \sum_{i=1}^{m} (\beta_{iy0} + \sum \beta_{iyR} D_R) \ln P_{it} \ln Y_t$$

$$+ \sum_{i=1}^{m} (\beta_{it0} + \sum \beta_{itR} D_R) t \ln P_{it} + (\beta_{yt0} + \sum \beta_{ytR} D_R) t \ln Y_t$$

$$\ln TC = (\beta_{00} + \sum \beta_{0R} D_R) + \sum_{i=1}^{m} (\beta_{i0} + \sum \beta_{iR} D_R) \ln P_{it} + \frac{1}{2} \sum_{i=1}^{m} \sum_{j=1}^{m} \beta_{ij} \ln P_{it} \ln P_{jt}$$

$$+ (\beta_{t0} + \sum \beta_{tR} D_R) t + \frac{1}{2} (\beta_{tt0} + \sum \beta_{ttR} D_R) t^2 + (\beta_{y0} + \sum \beta_{yR} D_R) \ln Y_t$$

$$+ \frac{1}{2} (\beta_{yy0} + \sum \beta_{yyR} D_R)(\ln Y_t)^2 + \sum_{i=1}^{m} (\beta_{iy0} + \sum \beta_{iyR} D_R) \ln P_{it} \ln Y_t$$

$$+ \sum_{i=1}^{m} (\beta_{it0} + \sum \beta_{itR} D_R) t \ln P_{it} + \beta_{yt0} t \ln Y_t$$

$$\ln TC = \beta_{00} + \sum_{i=1}^{m} (\beta_{i0} + \sum \beta_{iR} D_R) \ln P_{it} + \frac{1}{2} \sum_{i=1}^{m} \sum_{j=1}^{m} \beta_{ij} \ln P_{it} \ln P_{jt}$$

$$+ (\beta_{t0} + \sum \beta_{tR} D_R) t + \frac{1}{2} (\beta_{tt0} + \sum \beta_{ttR} D_R) t^2 + (\beta_{y0} + \sum \beta_{yR} D_R) \ln Y_t$$

$$+ \frac{1}{2} (\beta_{yy0} + \sum \beta_{yyR} D_R)(\ln Y_t)^2 + \sum_{i=1}^{m} (\beta_{iy0} + \sum \beta_{iyR} D_R) \ln P_{it} \ln Y_t$$

$$+ \sum_{i=1}^{m} (\beta_{it0} + \sum \beta_{itR} D_R) t \ln P_{it} + (\beta_{yt0} + \sum \beta_{ytR} D_R) t \ln Y_t$$

$$S_{fuel} = \gamma_{i0} + \sum_{j=1}^{n} \gamma_j \ln P_{jt} + (\gamma_{it0} + \sum \gamma_{itR} D_R) t$$

$$S_{fuel} = (\gamma_{i0} + \sum \gamma_{iR} D_R) + \sum_{j=1}^{n} \gamma_j \ln P_{jt}$$

$$S_{fuel} = (\gamma_{i0} + \sum \gamma_{iR} D_R) + \sum_{j=1}^{n} \gamma_j \ln P_{jt} + \gamma_{it0} t$$

$$S_{fuel} = (\gamma_{i0} + \sum \gamma_{iR} D_R) + (\gamma_{it0} + \sum \gamma_{itR} D_R) t$$