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Energy Substitution in U.S. Electricity Generation

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Abstract: Rising electricity cost and increasing electricity consumption threatens the ability of businesses to continue in operation by complicating industrial production and operational requirement, thus the need for firms to substitute away from electricity to minimize cost. This paper uses panel seemingly unrelated regression (SUR) model to estimate the substitution between electricity and other forms of energy in U.S electricity generation. The factor share equations for different forms of energy are derived from translog cost function for 48 states from 1970 to 2010. The results from the empirical application suggest limited substitution potential for all the energy inputs. Further, natural gas was found to be the main substitute while wood and waste was a net compliment.

Key words: input substitution; energy; elasticity of substitution; factor shares
JEL codes: C33, Q4

1. Introduction

One of the critical issues in current energy policy debates in both the U.S. and other energy consuming countries is the feasibility of substantially reducing the use of electricity. Issues on electricity have recently dominated the economic decisions of several states across the U.S. economy. In the year 2012, the total amount of electricity produced and the total amount of electricity consumed varied by US regions (National Energy Board of Canada and DOE, 2012). Electricity consumption among states has increased more rapidly on a percentage basis in recent years. Though natural gas and oil are known to occur in certain states, they are not currently produced. Offshore drilling still remains controversial since some of these states often face severe hurricanes and storms. Policymakers, environmentalists, and conservationists in some states admit that drilling for oil or natural gas off shores poses incredible environmental and economic risks to valuable regional resources, including aquatic

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ecosystems and tourism. Besides prospects for drilling, the different states produce several dry tons of forest, agricultural, urban and mill residues which can potentially generate substantial amounts of electricity each year to adequately supply the annual needs of the residential electricity use of the states in the U.S.A. Majority of the states in U.S. have not engaged in a detailed evaluation of energy in recent years.

Currently, apart from few states, most states import virtually all of their fuel resources from other states in the U.S. These imports represent an annual financial diversion of several billions of dollars some of which could be used to develop domestic, alternative energy resources. Growth in electricity consumption for the residences, commercial sectors, transportation sectors and industrial sectors still remain a key focus when it comes to electricity efficiency among the states. Moreover, "clean" electricity for residents has certainly become a critical issue recently. Several states face serious concerns regarding their natural environment. There have been dramatic increases in emissions of air pollutants from electricity use, including nitrogen oxides (NO_x), sulfur dioxide (SO_2), particulates, mercury, and green house gases, such as carbon dioxide (CO_2) and methane. The cost of air pollution in terms of human health alone has been unusual among states in the southeast. The rising electricity cost to certain states further complicates industrial production and operation requirements, often threatening the ability of businesses to continue in operation. In essence, it is high time states and the U.S as a whole considered other types of energy inputs that are environmentally friendly and can adequately substitute for the conventional energy sources at lower costs.

The main objective of this paper is to determine the substitution between electricity and other energy input forms in the U.S electricity generation. The specific objectives are to: derive the shares of coal, natural gas, petroleum oil, wood and waste, and electricity as inputs in the energy sector; use a panel econometric model to estimate the system of factor share equations; and construct the elasticity of factor substitution matrix using the estimated parameters to determine the substitutability of energy inputs. Findings of this study will be relevant in the development of a comprehensive energy policy for the region. It will also contribute significantly to the energy policy of the entire U.S. and the regions.

The paper is organized into five sections. Section 2 is a brief review of empirical studies on input substitution. Section 3 presents the methodology employed in the analysis. Results of the analysis and its discussions are presented in Section 4 while Section 5 presents the conclusions.

2. Review of Empirical Studies

Studies conducted on energy substitution include works by Giffin (1977), Caloghiro et al. (1997), Barnett et al. (1998), Kemfert (1998), Mahmud (2000), Kuper and Soest (2003), Thompson (2005), Roy et al. (2006), Koetse et al. (2007); and Thompson (2011). Most of these studies assessed factor substitution between non-energy inputs specifically labor and capital and energy inputs in different non-energy industries (Caloghiro et al., 1997; Barnett et al., 1998; Kemfert, 1998; Mahmud, 2000; Kuper & Soest, 2003; Thompson, 2005; and Thompson, 2011) while Roy et al. (2006) estimated the substitution and price elasticities of energy and compared across different industries and countries. Most of these studies employed panel data and used log linear and transcendental logarithm production functions to estimate the own price and cross price elasticities of both the energy and non-energy inputs under consideration with the main industries of focus being the non-energy production and manufacturing industries.

Caloghiro et al. (1997) and Barnett et al. (1998) found electricity to be a weak substitute for capital and labor, implying electricity subsidies lowered the demand for capital and labor. In Pakistani manufacturing, Mahmud

(2000) employed the partial equilibrium method of analysis and found weak substitution between electricity and gas although there was a slight substitution between aggregate energy and other inputs. Also, Kemfert (1998) employed three different nested CES production function to estimate substitution effects between energy, labor and capital inputs and reported that aggregate energy, capital, and labor are substitutes in West German manufacturing industries in the long run. Roy et al. (2006) also found energy substitution elastcities to vary widely across different industries and countries although they did not consider the factors that accounted for the observed variations. Although these studies have established that energy and capital are substitutes, Hunt (1984), in studying the UK industry sector, found capital and energy to be complements with capital and labor as well as energy and labor being substitutes. To solve this dilemma of conflicting findings, Chichilnisky (1993) employed the general equilibrium model to study energy capital substitution and concluded that whether energy and capital are complements or substitutes depended on the parameters of the model and the price of energy.

Alternatively, a study that considered the substitution of energy inputs in the energy industry is the study by Griffin (1997). Employing pooled international sample data, Griffin (1977) used the transcendental logarithm production function model to estimate the inter-fuel substitution relationships between fossil fuels (coal, gas, and residual fuel oil) in the generation of electricity. His findings suggested a greater possibility of substitution among the three energy inputs in the generation of electricity.

These reviews reveal that much research has not been conducted on the substitutability of energy inputs within the energy industries as compared to substitution between energy inputs and non-energy inputs in non-energy industries. In terms of energy generation, most studies focus on the environmental impact of switching energy inputs (Goldemberg, 2007; Ogden & Williams, 1989; Chynoweth et al., 2001; and Olah, 2005) with few studies (Giffin, 1977) focusing on the possibility of substitutability between energy inputs in the energy industry. This study therefore addresses this issue by determining the potential substitution between electricity and other energy input forms in the U.S.A electricity generation.

3. Methodology

The theory underpinning the study is the theory of production which shows how inputs are combined to produce a given level of output. Energy substitution in the U.S. electricity generation starts with the electricity production function which is given as:

$$X = X(Z, K, T) \tag{1}$$

Where:

X = Quantity of electricity produced

Z = Energy inputs employed in the electricity production

K = Non-energy inputs employed in the electricity production

T = Technology

The firm is assumed to produce the profit maximizing output X* using the optimal levels of the inputs that minimizes cost of production. The model assumes that the firm is a price taker in both input and output markets. However, the focus of this study will be on the optimal energy input levels that are chosen in other to minimize cost of production. This thus reduces the production function to:

$$X = X(Z, T) \tag{2}$$

Thus, the basic results concern the comparative static substitution between the various energy inputs employed in the production of U.S. electricity. The energy inputs (Z_i) being considered are coal, natural gas, electricity, wood and waste and petroleum with W_C, W_N, W_E, W_W and W_P as the prices of each of the energy input, respectively.

3.1 Derivation of the Factor Shares of Coal, Natural Gas, Petroleum Oil, Wood and Waste, and Electricity

The translog cost function as developed by Fuss and McFadden (1978) and exemplified by Saicheua (1987) is adopted and is generally given as:

$$In\,TC = C_0 + a\,In\,X + \sum b_i In\,(W_i) + 0.5(\sum b_{ii}\,(InW_{ii}\,)^2) + \sum bij\,(In\,W_i)(InW_j) \quad (3)$$

Specifically, this is written as:

$$In\,TC = C_0 + a\,In\,X + b_c\,In\,W_c + b_N\,In\,W_N + b_E\,In\,W_E + b_W\,In\,W_W + b_P\,In\,W_P + 0.5(b_{CC}(In\,W_C)^2 + b_{NN}(In\,W_N)^2 + b_{EE}(In\,W_E)^2 + b_{WW}(In\,W_W)^2 + b_{PP}(In\,W_P)^2) + b_{CN}(InW_C)(InW_N) + b_{CE}(InW_C)(InW_E) + b_{CW}(InW_C)(InW_W) + b_{CP}(InW_C)(InW_P) + b_{NE}(InW_N)(InW_E) + b_{NW}(InW_N)(InW_W) + b_{NP}(InW_N)(InW_P) + b_{EW}(InW_E)(InW_W) + b_{EP}(InW_E)(InW_P) + b_{WP}(InW_W)(InW_P) + a_t\,In\,T + 0.5\,a_{tt}(In\,T)^2 + a_{ct}\,T\,In\,W_C + a_{Nt}\,T\,In\,W_N + a_{Et}\,T\,In\,W_E + a_{Wt}\,T\,In\,W_W + a_{Pt}\,T\,In\,W_P \quad (4)$$

From Shephard's lemma, the partial derivative of total cost function with respect to an input price is that input level thus, the demand for coal (C*) is given as; $C^* = \frac{dTC}{dW_C}$

$$\text{But} \quad \frac{d\,In\,TC}{d\,In\,W_C} = \frac{dTC}{dW_C} * \frac{W_C}{TC} \qquad \text{hence} \quad \frac{d\,In\,TC}{d\,In\,W_C} = C^*\left(\frac{W_C}{TC}\right) \quad (5)$$

For a perfect competitive firm, total cost (TC) equals total revenue (PX), i.e., $TC = PX = X$. It follows that

$$\frac{dIn\,TC}{d\,In\,W_C} = C^*\left(\frac{W_C}{X}\right) \quad (6)$$

Where $C^*\left(\frac{W_C}{X}\right)$ is the factor share of coal.

Similarly, the factor share for all the other energy inputs are derived using the same formula which is stated generally as:

$$Q * (\frac{W_Q}{X})$$

Where

Q = Quantity of energy input used

W_Q = Unit price of the energy input

3.2 Estimating the System of Factor Share Equations for All the Energy Inputs

From the factor share Equation in (5) above;

$$\frac{dIn\,TC}{d\,In\,W_C} = C^*\left(\frac{W_C}{X}\right)$$

This implies $\frac{d\,In\,TC}{d\,In\,W_C}$ is the factor share equation for coal.

Similarly, differentiating the TC function in Equation (4) with respect to each of the energy input prices yields the following factor share (θ_i) systems

$$\theta_C = b_C + b_{CC}\,In\,W_C + b_{CN}\,In\,W_N + b_{CE}\,In\,W_E + b_{CW}\,In\,W_W + b_{CP}\,In\,W_P + a_{Ct}\,T$$
$$\theta_N = b_N + b_{NN}\,In\,W_N + b_{NC}\,In\,W_C + b_{NE}\,In\,W_E + b_{NW}\,In\,W_W + b_{NP}\,In\,W_P + a_{Nt}\,T$$
$$\theta_E = b_E + b_{EE}\,In\,W_E + b_{EC}\,In\,W_C + b_{EN}\,In\,W_N + b_{EW}\,In\,W_W + b_{EP}\,In\,W_P + a_{Et}\,T$$
$$\theta_W = b_W + b_{WW}\,In\,W_W + b_{WC}\,In\,W_C + b_{WN}\,In\,W_N + b_{WE}\,In\,W_E + b_{WP}\,In\,W_P + a_{Wt}\,T$$
$$\theta_P = b_P + b_{PP}\,In\,W_P + b_{PC}\,In\,W_C + b_{PN}\,In\,W_N + b_{PE}\,In\,W_E + b_{PW}\,In\,W_W + a_{Pt}\,T \quad (7)$$

Where each equation is the factor share equation for energy input, respectively. For the assumption of linear homogeneity of the cost function in input prices to hold, $\sum bi$ = 1 and $\sum bij$ = 0 for each factor share equation. The returns to scale of the electricity industry can also be calculated from the factor share equations. Returns to scale refers to how much output changes as all inputs are changed by the same proportion. If the sum of the cross coefficients in each factor equation is more than one, then the inputs exhibit increasing returns to scale (IRS), if their sum equals zero, they exhibit constant returns to scale (CRS) and if their sum is less than one, they exhibit decreasing returns to scale (DRS).

The estimation of the system of equations is based on the stepwise algorithm using generalized least squares and Maximum Likelihood procedures developed by Bjorn (2004) and implemented in STATA by Nguyen and Nguyen (2010).

3.3 Construction of Elasticity of Factor Substitution Matrix

The cross price elasticities of substitution are obtained by taking the second derivative of the TC function in Equation (4) with respective to each input. Let's consider the cross price elasticity of coal for natural gas.

$$\frac{d^2 In\,TC}{d\,In\,W_C W_N} = \frac{d\theta_C}{d\,In\,W_N} = b_{CN} \tag{8}$$

Substituting $\frac{d\,In\,TC}{d\,In\,W_C} = \theta_c = C^*\left(\frac{W_C}{TC}\right)$ into Equation (8) gives $\frac{d\theta_C}{d\,In\,W_N} = \frac{d\left(C^* W_C/_{TC}\right)}{d\,In\,W_N} = b_{CN}$

$b_{CN} = \frac{d\left(C^* W_C/_{TC}\right)}{d^{W_N}/_{W_N}} = W_C W_N \left[\frac{d[C^*/TC]}{dW_N}\right]$ Since $\frac{dW_C}{dW_N} = 0$

$$b_{CN} = W_C W_N \left[\frac{TCC_L^* - C^* dTC}{TC^2}\right] \tag{9}$$

Where $C_L^* = \frac{dC^*}{dW_N}$

However by Shepherd Lemma, $\frac{dTC}{dW_N}$ = N, thus, expanding and simplifying Equation (9)

$$b_{CN} = W_C W_N \left(\frac{C_L^*}{TC} - \frac{C^* N}{TC^2}\right) = \frac{W_C \varepsilon_{CN} C^*}{TC} - \frac{W_C C^* W_N}{TC^2} = \left(\frac{W_N C^*}{TC}\right)\varepsilon_N - \theta_C \theta_N$$

$$b_{CN} = \theta_C \varepsilon_{CN} - \theta_C \theta_N$$

Where ε_{CN} is the cross price elasticity of coal with respect to the price of natural gas input, thus:

$$\varepsilon_{CN} = (b_{CN} + \theta_C \theta_N)/\theta_C$$

Derivation of the other cross price elasticities is similar, and the own price elasticity is also given as

$$\varepsilon_{ii} = \left(b_{ii} - \theta_i + \theta_i^2\right)/\theta_i$$

Historical data covering 1970 to 2012 from the U.S. Energy Information Administration (http://www.eia.gov) on total energy expenditure (million dollars), natural gas expenditure (million dollars), petroleum oil expenditure (million dollars), coal expenditure (million dollars), wood and waste expenditure (million dollars) and electricity expenditure (million dollars) were obtained for all the 48 states. Also, historical data covering the same period on prices (dollars/million Btu) of natural gas, petroleum oil, coal, wood and waste and electricity were obtained for the above mentioned states (http://www.eia.gov).

4. Results

Petroleum has the highest average factor share value of 0.509 followed by electricity with an average factor share value of 0.303 while wood and waste had the least; 0.005. The average factor share value for coal was 0.056 with the average factor share value for natural gas being 0.126. This implies that petroleum accounts for the most of the energy input cost for production. The factor shares of the five inputs are plotted in Figure 1. The petroleum share has slightly decreased over the period while the other factor shares have slightly shown an increase.

Figure 2 shows the history of factor prices. Electricity prices (W_E) rose substantially over the period while the price of coal (W_C) remained stationary. Also, the prices of petroleum, natural gas and wood and waste increased slightly over the period.

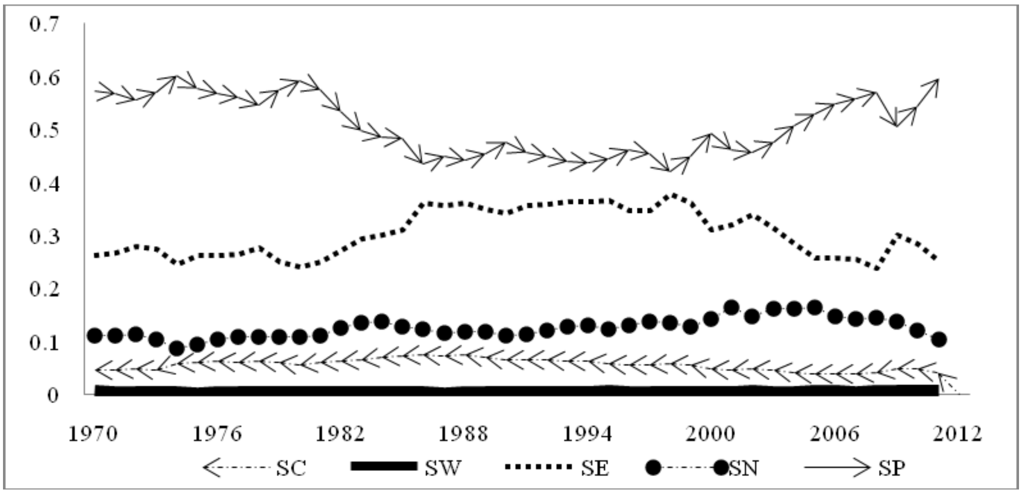

Figure 1 Trend of Factor Shares (1970-2012)

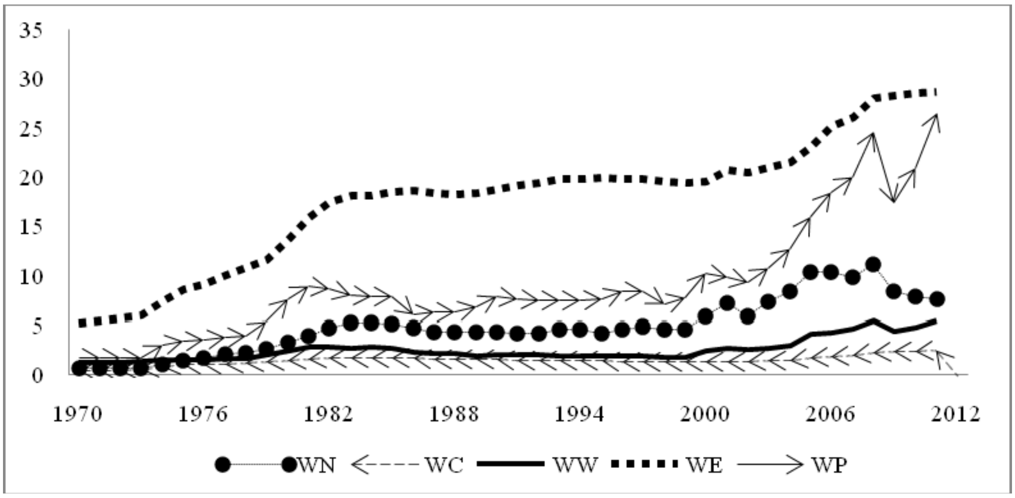

Figure 2 Trend of Factor Prices (1970-2012)

4.1 Estimated System of Factor Share Equations for All the Energy Inputs

The estimated factor share equations are:

$$\theta_C = 0.0783^{***} + 0.0068^{*}\, InW_C - 0.0067^{***}\, InW_N - 0.0053^{*}\, InW_E + 0.0052^{***}\, InW_W + 0.0002 InW_P - 0.0002\, T$$

(10.41) (1.89) (-2.65) (-1.67) (15.08) () (-1.4)

$$\theta_N = 0.0813^{***} - 0.0037\, InW_N - 0.0067^{***}\, InW_C - 0.0098^{***}\, InW_E + 0.0006\, InW_W + 0.0011 InW_P - 0.0011^{***}\, T$$

(13.54) (-1.18) (-2.65) (3.49) (1.62) () (9.81)

$$\theta_E = 0.2846^{***} + 0.0001 InW_E - 0.0053^{*}\, InW_C - 0.0098^{***}\, InW_N - 0.0044^{***}\, InW_W + 0.0005 InW_P + 0.0005^{***}\, T$$

(31.3) (-0.02) (-1.67) (3.49) (-11.54) () (3.57)

$$\theta_W = 0.0143^{***} - 0.0014^{***} InW_W + 0.0052^{***}\, InW_C + 0.0006\, InW_N - 0.0044^{***}\, InW_E - 0.0001 InW_P + 0.0001^{***}\, T$$

(17.57) (-7.15) (15.08) (1.62) (-11.54) () (5.09)

$\theta_P = 0.5415 + 0.0015\, InW_P + 0.0002\, InW_C - 0.0011\, InW_N - 0.0005^{***}\, InW_E - 0.0001 InW_W$

With the exception of the estimated factor share equation for coal, the null hypothesis of continuously improving technology cannot be rejected in any of the other factor share estimates. The estimated coefficients are used for the estimation of the substitution elasticities. The sum of the constant terms in all the factor share equations is 1.00. In addition, the sums of the factor price coefficients for each factor share equation are Σ_c = 0.0002, Σ_N = -0.0185, Σ_E = -0.0189, Σ_W = -0.0001 and Σ_P = 0.00. Since the sum of the constant terms add up to 1.00 and the sum of the cross coefficients in each factor share equation are approximately 0.00, the conditions for CRS are met thus the U.S electricity industry exhibits constant returns to scale (CRS). CRS implies if the prices of all energy inputs decrease, total cost and output will both fall by the same percentage.

4.2 The Elasticity of Factor Substitution Matrix

The derived elasticity matrix is presented in Figure 3 below.

$$\begin{pmatrix} \varepsilon_{CC} & \varepsilon_{CE} & \varepsilon_{CN} & \varepsilon_{CW} & \varepsilon_{CP} \\ \varepsilon_{EC} & \varepsilon_{EE} & \varepsilon_{EN} & \varepsilon_{EW} & \varepsilon_{EP} \\ \varepsilon_{NC} & \varepsilon_{NE} & \varepsilon_{NN} & \varepsilon_{NW} & \varepsilon_{NP} \\ \varepsilon_{WC} & \varepsilon_{WE} & \varepsilon_{WN} & \varepsilon_{WW} & \varepsilon_{WP} \\ \varepsilon_{PC} & \varepsilon_{PE} & \varepsilon_{PN} & \varepsilon_{PW} & \varepsilon_{PP} \end{pmatrix} = \begin{pmatrix} -0.822 & 0.209 & 0.007 & 0.097 & 0.513 \\ 0.039 & -0.697 & 0.159 & -0.009 & 0.508 \\ 0.003 & 0.381 & -0.903 & 0.009 & 0.500 \\ 1.104 & -0.582 & 0.239 & -0.271 & 0.496 \\ 0.057 & 0.302 & 0.124 & 0.005 & -0.488 \end{pmatrix}$$

Figure 3 Elasticity of Substitution Matrix

Where:

ε_{CC} = Own price elasticity of coal

ε_{CE} = Elasticity of substitution of coal for electricity

ε_{CN} = Elasticity of substitution of coal for natural gas

ε_{CW} = Elasticity of substitution of coal for wood and waste

ε_{CP} = Elasticity of substitution of coal for petroleum

ε_{EE} = Own price elasticity of electricity

ε_{EC} = Elasticity of substitution of electricity for coal

ε_{EN} = Elasticity of substitution of electricity for natural gas

ε_{EW} = Elasticity of substitution of electricity for wood and waste

ε_{EP} = Elasticity of substitution of electricity for petroleum

ε_{NN} = Own price elasticity of natural gas

ε_{NC} = Elasticity of substitution of natural gas for coal

ε_{NE} = Elasticity of substitution of natural gas for electricity

ε_{NW} = Elasticity of substitution of natural gas for wood and waste

ε_{NP} = Elasticity of substitution of natural gas for petroleum

ε_{WW} = Own price elasticity of wood and waste

ε_{WC} = Elasticity of substitution of wood and waste for coal

ε_{WE} = Elasticity of substitution of wood and waste for electricity

ε_{WN} = Elasticity of substitution of wood and waste for natural gas

ε_{WP} = Elasticity of substitution of wood and waste for petroleum

ε_{PP} = Own price elasticity of petroleum

ε_{PC} = Elasticity of substitution of petroleum for coal
ε_{PE} = Elasticity of substitution of petroleum for electricity
ε_{PN} = Elasticity of substitution of petroleum for natural gas
ε_{PW} = Elasticity of substitution of petroleum for wood and waste

There is limited substitution potential when energy prices rise in electricity production. The own electricity substitution elasticity of -0.697 implies that a 10% increase in the price of electric power will reduce input only 7% and expenditure will rise 3%. There would be weak substitution toward electricity input with coal input rising 2.1 Wood and waste and electricity are compliments. Thus wood and waste and electricity inputs fall with higher wood and waste prices. Wood and waste have the least substitution potential. The own elasticity of substitution of -0.271 implies a 10% increase in the price of wood and waste will reduce input only 2.7% and expenditure will rise 7.3%. However, the energy industry can substitute coal for wood and waste to a higher degree. The substitution elasticity of 1.104 implies a 10% increase in the price of coal will increase the use of wood and waste input by 11.04%; and coal spending will fall by 1.04%. Energy producers respond more to rising natural gas prices. If the current export of natural gas products continues and raises prices by 10% there would be a 9.3% reduction in natural gas input use and expenditures will only go up by 0.7%.

5. Concluding Remarks

This paper determines the potential substitution between electricity and other energy input forms in the U.S electricity generation. The present estimates predict electricity producers will spend more on energy as energy prices rise. An increasing price of natural gas only inelastically lowers electricity input while raising wood and waste input. Also, electricity producers are sensitive to wood and waste prices, however, substituting natural gas for wood and waste as their prices rise. The combination of the current U.S. natural gas exports and the rising natural gas prices leaves little room for substitution. The estimated constant returns to scale suggest there is neither under nor over production of electricity. If subsidies on fossil fuels are cut as fuel prices rise over the coming decades, the present model of substitution predicts a proportional decrease in US electricity production.

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