Fossil Fuel Producing Economies have Greater Potential for Interfuel Substitution

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Abstract

This study extends the literature on interfuel substitution by investigating the role of transactions costs and technological adjustment, focusing specifically on differences across countries with different potential for fossil fuel production. We find that fossil fuel producing economies have higher elasticities of interfuel substitution. Our simulations show that, compared to the baseline case of uniform elasticities, energy and climate policies result in a greater substitution among different sources of energy for countries with larger potential to produce fossil fuels. These results are important because they imply lower economic cost for policies aimed at climate abatement and more efficient utilization of energy resources in energy-intensive economies.

JEL: E22, H25, Q41

Keywords: climate policies, dynamic linear logit, energy subsidies, fossil fuel production, GTAP-E model, interfuel substitution

1 Introduction

The degree of substitution among different energy services influences the extent of overall energy demand and has serious implications for the ongoing climate change debates across the world. Many economy-wide computable general equilibrium (CGE) models (Burniaux and Truong 2002, Paltsev et al. 2005, Burniaux and Château 2008) and large scale partial equilibrium energy and climate models (Manne and Richels 2005, Bosetti et al. 2006, Kim et al. 2006) depend critically on this aspect. Therefore, various aspects of estimation of interfuel substitution elasticities have been explored in the energy and economic literatures.

Most of the studies on interfuel substitution use time-series data from individual countries and sectors. Econometric analysis of interfuel substitution

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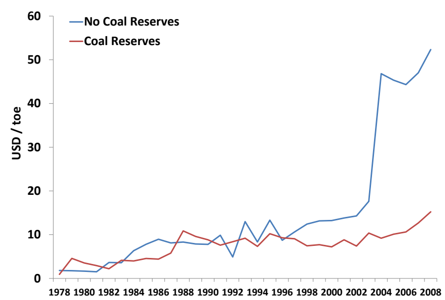
using international cross-country and cross-sector data was until recently restricted to a handful of studies focusing mainly on G7 economies (Pindyck 1979, Jones 1996, Renou-Maissant 1999). Several recent studies estimated interfuel substitution elasticities using aggregate and sector level data for a number of countries (Serletis et al. 2010b, 2011). In these (and earlier) studies, the demand for fuels is modeled as a function of input prices and output following standard derivations based on economic theory.

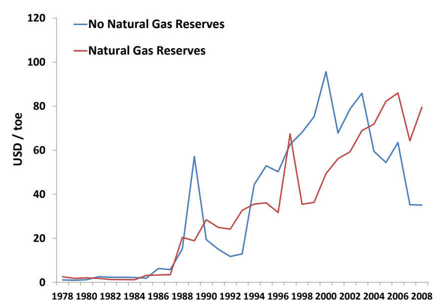
This paper extends the existing literature on interfuel substitution in an international context by investigating the role of non-price factors, focusing specifically on international fuel production. The economic literature makes two arguments as to why the extent of interfuel substitution may differ across the fossil fuel producing and non-producing economies. First, transaction (e.g., transportation, storage, and import clearance) costs and differences in fuel characteristics (e.g., energy and carbon content) render domestically produced fuels to be imperfect substitutes for foreign commodities (Armington 1969). If this is the case, the degree of interfuel substitution will be higher in the fossil fuel producing economies. For example, in the presence of low production (i.e., extraction) and high transactions costs, domestically produced coal will be able to compete against imported oil and natural gas, whereas imported coal won't. Several recent studies attempted to estimate Armington elasticities of substitution for different fuels. The size of estimated elasticities was drastically different across these studies, starting from close to zero (Welsch 2008) to above twenty (Balistreri et al. 2010). These studies use different data and econometric methods, and their results are difficult to reconcile.

Second, many resource-rich countries have historically subsidized the production of their energy resources for the purposes of economic stimulation, enhanced trade performance, inflation control, and energy security (Kosmo 1987). According to International Energy Agency (IEA) estimates, total subsidies to fossil fuel consumption in 37 non-OECD countries amounted in 2008 to USD 557 billions, almost five times the yearly bilateral aid flows to developing countries in the form of Official Development Assistance (Burniaux and Château 2011). Figure 1 demonstrates that only in the recent years fuel consumption taxes in oil and natural gas-rich countries converged to (and even exceeded) the levels of countries with no natural resources.[1] And the taxes on coal consumption are still considerably lower in coal-rich economies. Kosmo (1987) demonstrated that such policies encourage over-investment in energy-intensive industries at the expense of other sectors. Heavy capital investment in a particular fuel-using sector will mean difficulties in shifting to another fuel sector in short and medium run because switching to alternative fuels are not always technologically feasible (Steinbuks 2012) or are too costly to implement (Jacoby and Wing 1999). Combined with organizational barriers to technology adoption, bounded rationality, and information asymmetries, energy subsidies may result in an energy and carbon "lock-in" (Unruh 2000), and negatively affect the degree of

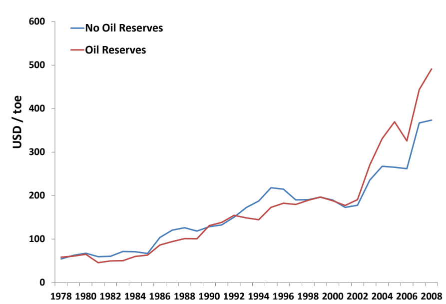
[1] Figure 1 excludes several oil exporting countries where fossil fuel subsidies are still huge, amounting to 10% or more of GDP (Burniaux and Château 2011, annex II)



(a) Coal



(b) Natural Gas



(c) Petroleum Products

Figure 1: Average Industry Real Tax Rates on Fossil Fuels across Countries (Source: IEA Energy Prices and Taxes, EIA International Energy Statistics)

interfuel substitution.

To evaluate these arguments we estimate an econometric model of interfuel substitution using a large unbalanced panel dataset of 63 countries. Based on the model's estimates, we calculate own-price and cross-price elasticities of fuel demand across the entire dataset, and separately across country groups based on their potential to produce fossil fuels.

Our econometric results lend support for both arguments. For evidence of carbon lock-in we find that countries with a potential to produce any of the available fossil fuels (i.e., coal, natural gas, and oil) have a considerably longer adjustment of fuel-using capital stocks. For these, more energy-intensive, countries the share of same year response to fuels' price change was less than fifty percent as opposed to ninety percent in countries with no potential to produce any fossil fuels. As a result, countries with a potential to produce any of available fossil fuels have considerably higher difference between short and long run elasticities of fuel substitution.

As for evidence of transaction costs argument, we find that, for most fuel pairs, the estimated elasticities of fuel substitution are considerably higher for the countries with a potential to produce all fossil fuels or at least one fossil fuel. For example, short run cross-price elasticity of coal with respect to electricity prices (the largest in the sample) is more than four times higher for countries with a potential to produce any fossil fuels than for countries with no potential to produce fossil fuels. Moreover, in many cases *short run* elasticities of fuel substitution for countries with a potential to produce fossil fuels are higher than *long run* elasticities for countries with no potential to produce fossil fuels.

To demonstrate the significance of our findings we use calculated elasticities to evaluate the effects of a carbon tax and reduction in oil subsidies using GTAP-E computable general equilibrium modelling framework. Our simulations show that, compared to the baseline case of uniform elasticities of fuel substitution, carbon tax results in a greater decline in coal consumption in countries with a potential to produce fossil fuels. This happens because these countries have larger elasticities of coal for natural gas and electricity. Our simulations also show that the size of calculated elasticities affects economic response to reduction in oil subsidies. Compared to the baseline case of uniform elasticities of fuel substitution, the production of oil, oil products and natural gas declines, while that of coal and electricity increases by a greater amount in the countries with a potential to produce all fossil fuels. And production of oil and oil products declines, and production of coal, natural gas, and electricity increases by a greater amount in countries with potential to produce one or two fossil fuels.

Our results are important in the light of recent efforts by the international community to reduce carbon emissions (IPCC 2007) and fossil fuel subsidies (IEA et al. 2010). We find greater potential for interfuel substitution in energy intensive, fossil fuel producing economies. This implies lower economic cost for policies aimed at climate abatement and more efficient utilization of energy resources.

2 Model and Empirical Specification

The purpose of this section is to present an econometric model for estimating parameters of fuel demand function. Ideally, such a model should explicitly account for the adjustments of capital stocks of energy-using technologies. Dynamic structural econometric models that account for the adjustment of energy-using capital stocks are well established in the economic literature on energy demand (Berndt et al. 1981, Pindyck and Rotemberg 1983, Popp 2001, Sue Wing 2008, Steinbuks and Neuhoff 2010). However, their implementation in the econometric analysis of interfuel substitution in an international context is not possible due to data limitations on fuel-using capital. This study takes the next available alternative, and, following previous literature, treats capital stocks as dynamic unobserved variables.

The basic assumption underlying the econometric model is that a fuel-using sector in each country is represented by a neo-classical agent (firm) that solves the cost-minimization problem. The firm's production function requires the use of four energy inputs: coal, natural gas, petroleum products, and electricity. It is assumed that the agent's cost is weakly separable in energy and other (e.g. labor and capital) inputs, and the corresponding cost function is a continuous, nondecreasing, concave, and linear homogenous function of input prices. While these assumptions (especially those of separability and homotheticity) are quite restrictive, they allow us to derive conditional input demand functions for energy inputs without explicit consideration of other inputs.

The empirical model adopted in this study is the dynamic version of the linear logit model suggested by Considine and Mount (1984) and extended by Considine (1990), which is widely employed in the empirical literature on interfuel substitution (Considine 1989, Jones 1995, 1996, Urga and Walters 2003, Brännlund and Lundgren 2004, Steinbuks 2012). The advantage of this functional form is that it is better suited to satisfy the restrictions of economic theory and is consistent with more realistic adjustment of the unobserved capital stocks to input price changes. Jones (1995) and Urga and Walters (2003) compared the predictions of the dynamic specifications of translog and linear logit models. Both studies concluded that a linear logit specification yields more robust results and should, therefore, be preferred in the empirical analysis of interfuel substitution.[2]

As the model is widely employed in the interfuel substitution literature, in this paper we present only main derivations, final estimating forms, and elasticity formulas. Interested reader may refer to Considine and Mount (1984) and Considine (1990) for more details. A dynamic version of the linear logit model can be expressed in terms of a set of non-homothetic cost shares with non-neutral technical change as follows:

[2] Other recent approaches to econometric modelling of inter-fuel substitution (Serletis and Shahmoradi 2008, Serletis et al. 2010a,b, 2011) use globally flexible functional forms (Fourier, AIM), as well as locally flexible (NQ, translog) functional forms. Sorting between the results based on these approaches and the one adopted here is beyond the scope of this paper.

$$\frac{P_{it}}{C_t}\left(\frac{\partial C_t}{\partial P_{it}}\right) = S_{it} = \frac{\exp\left(f_{it}\right)}{\sum\limits_{i,j=c,g,o,e} \exp\left(f_{it}\right)}, \tag{1}$$

in which

$$f_{it} = \mu_i + \sum_{i,j=c,g,o,e} \phi_{ij} \ln P_{jt} + \gamma' W_t + \lambda \ln Q_{i,t-1} + \varepsilon_{it}, \tag{2}$$

and where C_t is the total cost in period t; P_{jt} and Q_{it} are the prices and quantities for coal, c, natural gas, g, petroleum products, o, and electricity, e, respectively; $W = [w_1, w_2, ..., w_m]$ is a vector of control variables; μ_i, ϕ_{ij}, and $\gamma = [\gamma_{i1}, \gamma_{i2}, ..., \gamma_{im}]$ are unknown parameters, λ is a parameter measuring the speed of dynamic adjustment, and ε_{it} are assumed to be normally distributed random disturbances.

Considine (1990) argued that the chosen specification has several advantages. First, the predicted shares are guaranteed to be positive and add up to one given the exponential form of the logistic function. Second, the non-additive error structure of ε_{it} is more appropriate to satisfy normality assumptions. Third, the logit formulation does not place any restrictions on the autoregressive process of the structural error term (Chavas and Segerson 1986).

The linear logit model is well suited to satisfy theoretical restrictions. Zero degree homogeneity can be imposed as

$$\sum_{i=c,g,o,e} \phi_{ij} = d, \tag{3}$$

where d is an arbitrary constant. To impose symmetry conditions, the price coefficients should be redefined as

$$\phi^*_{ij} = \frac{\phi_{ij}}{S^*_{it}}, \tag{4}$$

where S^*_{it} are the equilibrium (time-invariant) fuel cost shares, and

$$\phi^*_{ij} = \phi^*_{ji}. \tag{5}$$

Using the redefined parameters (4), restating homegeneity constraints (3) and imposing symmetry constraint (5) yields the following system of share equations estimated in this study:

$$\ln\left(\frac{S_c}{S_e}\right)_{kt} = \left(\mu_c - \mu_e\right)_k - \left(\phi^*_{cg} S^*_{gt} + \phi^*_{co} S^*_{ot} + \phi^*_{ce}\left(S^*_{ct} + S^*_{et}\right)\right) \ln\left(\frac{P_c}{P_e}\right)_t \tag{6}$$

$$+ \left(\phi^*_{cg} - \phi^*_{ge}\right) S^*_{gt} \ln\left(\frac{P_g}{P_e}\right)_t + \left(\phi^*_{co} - \phi^*_{oe}\right) S^*_{ot} \ln\left(\frac{P_o}{P_e}\right)_t + \lambda \ln\left(\frac{Q_c}{Q_e}\right)_{k,t-1}$$

$$+ \left(\gamma_{cy} - \gamma_{ey}\right) \ln y_{kt} + \left(\gamma_{c\tau} - \gamma_{e\tau}\right) t + \left(\varepsilon_c - \varepsilon_e\right)_{kt},$$

$$\ln\left(\frac{S_g}{S_e}\right)_{kt} = (\mu_g - \mu_e)_k - (\phi^*_{co}S^*_{ct} + \phi^*_{go}S^*_{ot} + \phi^*_{ge}(S^*_{gt} + S^*_{et}))\ln\left(\frac{P_g}{P_e}\right)_t \quad (7)$$
$$+ (\phi^*_{cg} - \phi^*_{ce})S^*_{ct}\ln\left(\frac{P_c}{P_e}\right)_t + (\phi^*_{go} - \phi^*_{oe})S^*_{ot}\ln\left(\frac{P_o}{P_e}\right)_t + \lambda\ln\left(\frac{Q_g}{Q_e}\right)_{k,t-1}$$
$$+ (\gamma_{gy} - \gamma_{ey})\ln y_{kt} + (\gamma_{g\tau} - \gamma_{e\tau})t + (\varepsilon_g - \varepsilon_e)_{kt},$$

$$\ln\left(\frac{S_o}{S_e}\right)_{kt} = (\mu_o - \mu_e)_k - (\phi^*_{co}S^*_{ct} + \phi^*_{go}S^*_{gt} + \phi^*_{oe}(S^*_{ot} + S^*_{et}))\ln\left(\frac{P_o}{P_e}\right)_t \quad (8)$$
$$+ (\phi^*_{co} - \phi^*_{cg})S^*_{ct}\ln\left(\frac{P_c}{P_e}\right)_t + (\phi^*_{go} - \phi^*_{ge})S^*_{gt}\ln\left(\frac{P_g}{P_e}\right)_t + \lambda\ln\left(\frac{Q_o}{Q_e}\right)_{k,t-1}$$
$$+ (\gamma_{oy} - \gamma_{ey})\ln y_{kt} + (\gamma_{o\tau} - \gamma_{e\tau})t + (\varepsilon_o - \varepsilon_e)_{kt}.$$

The equation system (6) − (8) requires some clarification. First of all, it should be noted that it allows for country-specific fixed effects, represented by suffix k in each equation. Hausman's (1978) specification test is employed to verify if the model can be pooled across sectors, and its estimates remain consistent.[3] Second, we specify the control variables entering the vector W in equation (2). These variables are the natural logarithm of industrial output, $\ln y_{kt}$, that accounts for unobserved structural changes in the economy, which affect the countries' fuel intensity, and a time trend, t, that measures the efficiency gains or exogenous technical change in countries' fuel consumption[4].[5] Third, we need identifying ("adding-up") restrictions to obtain model estimates: $\mu_e = \gamma_{ey} = \gamma_{e\tau} = \gamma_{eh} = d = 0$.[6] Fourth, homegeneity and symmetry constraints defined by equations (3) and (5) are based on the economic theory and employed to reduce the degrees of freedom problem. Finally, to consistently estimate the model that satisfies global constraint (5), a two-step iterative procedure suggested by Considine (1990) and described in Jones (1995, p. 460) is employed. In the first step, the actual fuel cost shares observed in each period are used in lieu of the equilibrium cost shares to estimate the parameters and produce an initial set of predicted shares for each observation. These initial predicted shares are then inserted into the model for re-estimation of parameters, yielding a new

[3] In this study Hausman's (1978) test is implemented as likelihood-ratio test as explained in Qian (1999).

[4] As the time trend is a fairly crude proxy for technological change, one should interpret the magnitude of estimated coefficients with caution. An alternative approach not pursued here is to construct more sophisticated measure of technological change, see e.g. Baltagi and Griffin (1988).

[5] Other control variables include the Battese-Nerlove dummy variables (Battese 1997), which take values of one when fuel cost share ratios are zero or very close to zero, and zero otherwise, to account for corner solutions. These control variables are not of substantial policy interest, and therefore, are not reported in the empirical specification (6) − (8).

[6] Considine and Mount (1984, p.437) note that these constraints have no effect on any of the computed elasticities.

set of predicted shares. This process continues until the parameter estimates converge. The nonlinear iterative seemingly unrelated estimation procedure is employed to estimate the model.

The parameters central to this study are the elasticities of fuel demand implied by equations $(6)-(8)$. Complete derivation of all elasticities can be found in Jones (1995), and Considine (1989, 1990); for brevity, only final forms (evaluated at sample means) are presented. The short-run own-price fuel demand elasticities, η_{ii}^{SR}, are calculated as

$$\eta_{ii}^{SR} = (\phi_{ii}^{*} + 1)\,\overline{S}_i - 1,\ i = c, g, o, e, \tag{9}$$

where $\overline{S}_i$ are time-invariant sample means of fuel cost shares and ϕ_{ii}^{*} is

$$\phi_{cc}^{*} = -\frac{\phi_{cg}^{*}\overline{S}_g + \phi_{co}^{*}\overline{S}_o + \phi_{ce}^{*}\overline{S}_e}{\overline{S}_c}, \tag{10}$$

$$\phi_{gg}^{*} = -\frac{\phi_{cg}^{*}\overline{S}_c + \phi_{go}^{*}\overline{S}_o + \phi_{ge}^{*}\overline{S}_e}{\overline{S}_g}, \tag{11}$$

$$\phi_{oo}^{*} = -\frac{\phi_{co}^{*}\overline{S}_c + \phi_{go}^{*}\overline{S}_g + \phi_{oe}^{*}\overline{S}_e}{\overline{S}_o}, \tag{12}$$

$$\phi_{ee}^{*} = -\frac{\phi_{ce}^{*}\overline{S}_c + \phi_{ge}^{*}\overline{S}_g + \phi_{oe}^{*}\overline{S}_o}{\overline{S}_e}. \tag{13}$$

The short-run cross-price elasticities of fuel demand, η_{ij}^{SR},are calculated as

$$\eta_{ij}^{SR} = \left(\phi_{ij}^{*} + 1\right)\overline{S}_j,\ i, j = c, g, o, e,\ \ i \neq j. \tag{14}$$

The short-run partial elasticities of fuel demand (i.e., with respect to control variables), η_{iw}^{SR}, can be calculated as

$$\eta_{iw}^{SR} = \gamma_{im} - \sum_{j\neq i}\gamma_{jm}\overline{S}_j + \frac{\partial \ln C_t}{\partial w_m},\ i, j = c, g, o, e;\ m = \ln y, t. \tag{15}$$

Following Considine (1990), the following cost function is estimated to obtain the partial elasticities[7]:

$$\begin{aligned}\ln C_t &= \alpha_k + \sum_{i=c,g,o,e} S_{it}^{*}\ln P_{it} + \gamma_y \ln y_{kt} + \gamma_{yy}\left(\ln y_{kt}\right)^2 \\ &\quad +\gamma_{y\tau}\left(\ln y_{kt}\right)t + \gamma_\tau t + \gamma_{\tau\tau}t^2 + \varepsilon_{kt}.\end{aligned} \tag{16}$$

Finally, the corresponding long-run[8] fuel demand elasticities are:

[7]Note that estimates for cost function are not needed to calculate homothetic price elasticities of fuel demand.

[8]As model specification described by equations $(6)-(8)$ includes fixed effects, the parameter λ captures adjustment only across time, and not across both time and countries. Estimated elasticities therefore capture fuel demand responsiveness in the medium-run to long-run rather than in the very long-run.

$$\eta_{ij}^{LR} = \frac{\eta_{ij}^{SR}}{1-\lambda}, \forall\ i, j, \tag{17}$$

and

$$\eta_{iw}^{LR} = \frac{\eta_{iw}^{SR}}{1-\lambda}, \forall\ i, w. \tag{18}$$

3 Data

The empirical analysis is based on a comprehensive unbalanced panel dataset that comprises 63 countries over the period 1978 - 2008 (for details, see Table A.1, Appendix I). We focus on the industrial consumption of four fuels - coal, natural gas, petroleum products, and electricity. Following Jones (1995), we exclude the consumption of fuels used for non-energy purposes. Specifically, among coal categories we include steam coal, and exclude coking coal. We combine the industrial consumption of natural gas and liquefied petroleum gases (LPG), as those products are close technological substitutes and have similar energy use (Steinbuks 2012). The petroleum products category comprises consumption of light fuel oils, diesel, naphtha, and high-sulphur fuel oils. Finally, we treat electricity as homogenous energy service and do not differentiate across the sources of electricity generation. We obtain country fuel consumption and production data from the *World Energy Statistics and Balances*, published by the International Energy Agency (IEA).

As fossil fuel production is potentially endogenous to unobserved variables affecting fuel demand (e.g., indirect subsidies, government regulations, and capital market imperfections) we use tobit estimates of fuel production instrumented by countries' size of natural resource endowment normalized by its 10 year average resource consumption.[9] Using natural resource endowment is a natural choice for instrumenting fuel production. By Hotelling's (1931) rule the size of natural resource stocks is a critical determinant of fossil fuel extraction decision yet it is uncorrelated with unobserved variables mentioned above. This instrumented variable thus reflects not the actual fuel production but rather the extent to which fuel production is feasible (although these measures are closely correlated). For information on countries' natural resource (respectively, coal, natural gas, and oil) endowments we use the BP Statistical Review of World Energy database.[10]

Table 1 describes the distribution of natural reserves across countries in the dataset in 2008 (for more details, see Table A.2, Appendix I). Most countries in

[9] We do not instrument for electricity production for two reasons. First, as electricity is difficult to store and electricity imports are not always reliable, all countries in the sample produce electricity. Second, as all countries in the sample have access to renewable electricity resources of some sort (biomass, solar, wind, or hydro), instrumenting for electricity will always yield positive production.

[10] Detailed information on the BP Statistical Review of World Energy database can be found on the following website: `http://www.bp.com/en/global/corporate/about-bp/energy-economics/statistical-review-of-world-energy-2013.html`

Table 1: Predicted Energy Production across Countries, 2008

Resources	Obs.	% of Total
Coal Only	6	9.52
Natural Gas Only	5	7.94
Oil Only	1	1.59
Coal and Natural Gas	3	4.76
Coal and Oil	1	1.59
Oil and Natural Gas	11	17.46
All 3 Resources	17	26.98
None	19	30.16
Total	63	100.00

Note: (i) Obs. = number of observations
Source: EIA International Energy Statistics

the dataset either cannot produce any energy resources (19 countries or 30.16% of the sample) or have a potential to produce all energy resources (17 countries or 26.98% of the sample). A smaller share of countries have the potential to produce oil and gas but not coal (11 countries or 17.46% of the sample). Some countries have the potential to produce solely coal (6 countries or 9.5% of the sample), or natural gas (5 countries or 7.94% of the sample). Finally, a small share of countries have the potential to produce coal and natural gas (3 countries or 4.76% of the sample), coal and oil, or solely oil (both 1 country or 1.59% of the sample). Most of these country groups separately account for a relatively small number of observations to yield empirically plausible estimates. To avoid this problem, we aggregate the countries in the dataset into three broad groups. First group of countries has a potential to produce any of the three energy resources. Second group of countries has a potential to produce one or two of three energy resources. Third group of countries does not have a potential to produce energy resources.

A well known problem in the econometric analysis of interfuel substitution in an international context is the limited availability of sound energy price data. While energy consumption data are readily available for almost all countries, the fuel price data exist for a relatively small number of countries (Serletis et al. 2010b). The individual fuel prices, in real terms (2005 U.S. dollars per tonne of oil equivalent), come from two sources: *Energy Prices and Taxes* published by the IEA, and SIEE (Energy Economic Information System) database maintained by Latin American Energy Organization (OLADE).[11] For natural gas and petroleum products aggregates, we define fuel prices as consumption-weighted averages of individual fuel prices. If industrial sector prices are not available,

[11]Detailed information on SIEE database can be found on the following website: `http://www.olade.org.ec/en/product/SIEE`

we use different proxies, such as comparable fuel prices in other sectors.

We obtain the data on country-level industrial output in real terms (expressed as the gross value added in manufacturing sector in 2005 U.S. dollars) from the United Nations Statistics Division (http://data.un.org).

Table 2 shows the descriptive statistics for energy prices, taxes, and consumption (relative to output) of fossil fuels and electricity in 2005 across countries grouped by their potential to produce fossil fuels. Countries that have a potential to produce any of the three fossil fuels have considerably lower end-use prices of coal, natural gas, petroleum products, and electricity compared to the rest of the sample. Countries that cannot produce any fossil fuels have the highest end-use prices for all energy sources. Energy prices in countries that can produce one or two fossil fuels are in between two previous groups. The end-use prices of coal, petroleum products, and electricity are about 1.3 to 1.5 times higher in countries that cannot produce any fossil fuels. The end-use prices of natural gas in these countries are about 2 times higher compared to countries that have a potential to produce any of the three fossil fuels, and about 1.3 times higher compared to countries that have a potential to produce one or two fossil fuels. The end-use prices of coal, petroleum products, and electricity are of a similar magnitude for countries that have a potential to produce one or two fossil fuels and countries that cannot produce any fossil fuels.

There is a significant heterogeneity in energy taxes across different country groups. Taxes on coal and natural gas are considerably (2 to 4 times) lower in countries with the potential to produce all three fossil fuels or at least one fossil fuel, compared to countries that cannot produce fossil fuels. This finding is consistent with the historical evidence of subsidizing energy production in coal and natural gas rich economies. Taxes on petroleum products across country groups exhibit a similar pattern but the difference magnitude (1.2 to 1.65 times) is more subtle. Countries with the potential to produce all three fossil fuels also have the lowest tax on electricity, which is 2 times smaller compared to countries that have a potential to produce one or two fossil fuels, and 1.4 times smaller compared to countries that cannot produce any fossil fuels.

Table 2 also shows that countries with the potential to produce all three fossil fuels or at least one fossil fuel are more intensive in use of coal, natural gas, and electricity compared to countries that cannot produce fossil fuels. Countries that have a potential to produce any of the three fossil fuels are 4 times more intensive in their use of coal and natural gas, and 1.5 times more intensive in use of electricity compared to countries that cannot produce any fossil fuels. Similarly, countries that have a potential to produce one or two of three fossil fuels are 2 times more intensive in their use of coal and natural gas, and 1.2 times more intensive in use of electricity compared to countries that cannot produce any fossil fuels. However, there are no substantial differences in the intensive use of petroleum products across country groups.

[htbp]

Table 2: Descriptive Statistics across Country Groups, 2005

Variables	Full Sample			Production: All Fuels			Production: 1 or 2 Fuels			Production: No Fuels		
	Obs.	Mean	S.D.	Obs.	Mean	S.D.	Obs.	Mean	S.D.	Obs.	Mean	S.D.
Fuel Prices, USD/toe												
Coal	63	137	(61)	17	99	(47)	27	143	(62)	19	159	(55)
Natural Gas	63	340	(206)	17	208	(126)	27	342	(207)	19	445	(196)
Petroleum Products	63	490	(319)	17	381	(279)	27	519	(325)	19	539	(321)
Electricity	63	966	(403)	17	764	(296)	27	968	(412)	19	1131	(392)
Fuel Taxes, USD/toe												
Coal	32	9	(18)	8	8	(10)	18	5	(10)	10	20	(31)
Natural Gas	48	41	(85)	10	22	(32)	24	36	(76)	19	65	(112)
Petroleum Products	59	179	(192)	15	129	(183)	27	179	(187)	19	213	(198)
Electricity	55	65	(106)	13	41	(81)	27	81	(109)	19	57	(112)
Fuel Use Intensities, toe/million USD												
Coal	63	37	(98)	17	73	(166)	27	31	(66)	19	15	(24)
Natural Gas	63	67	(110)	17	111	(137)	27	67	(112)	19	29	(50)
Petroleum Products	63	85	(126)	17	85	(110)	27	78	(150)	19	95	(97)
Electricity	63	81	(74)	17	99	(84)	27	80	(73)	19	68	(62)

Notes: (i) Obs. = number of observations; S.D. = Standard Deviation; (ii) toe = tonnes of oil equivalent

[htbp]

Table 3: Results for Models of Fuel Consumption, 1978-2008

Parameter	Full Sample		Production: All Fuels		Production: 1 or 2 Fuels		Production: No Fuels	
	coeff.	s.e.	coeff.	s.e.	coeff.	s.e.	coeff.	s.e.
ϕ^*_{cg}	-0.62	(0.53)	-0.47	(1.92)	-0.25	(0.17)	-0.69***	(0.25)
ϕ^*_{co}	-0.61	(0.66)	-0.55	(0.47)	-0.36***	(0.04)	-0.80	(0.61)
ϕ^*_{ce}	-0.63***	(0.06)	-0.44	(0.31)	-0.25***	(0.02)	-0.83	(34.78)
ϕ^*_{go}	-0.61***	(0.06)	-0.70***	(0.06)	-0.35***	(0.11)	-0.55***	(0.05)
ϕ^*_{ge}	-0.61***	(0.06)	-0.47***	(0.04)	-0.71***	(0.07)	-0.79***	(0.07)
ϕ^*_{oe}	-0.94***	(0.10)	-0.94***	(0.09)	-0.99***	(0.10)	-0.79***	(0.07)
λ	0.35***	(0.04)	0.57***	(0.05)	0.29***	(0.03)	0.11***	(0.01)
γ_{cy}	-0.12**	(0.04)	-0.29***	(0.03)	-0.07	(0.13)	0.30	(0.47)
γ_{gy}	-0.12***	(0.04)	-0.03	(0.66)	-0.19***	(0.06)	0.02***	(0.002)
γ_{oy}	-0.08**	(0.04)	-0.13**	(0.05)	-0.14**	(0.06)	0.17***	(0.02)
$\gamma_{c\tau}$	0.004***	(0.0004)	0.01	(0.07)	-0.01***	(0.001)	0.0003***	(0.0001)
$\gamma_{g\tau}$	0.01***	(0.002)	-0.006	(0.003)	0.01***	(0.001)	0.02***	(0.001)
$\gamma_{o\tau}$	-0.02***	(0.003)	-0.01***	(0.001)	-0.03***	(0.003)	-0.04***	(0.004)
				Summary Statistics				
Obs.	1562		399		684		479	
pseudo-R^2_1	93.70		89.82		95.55		97.91	
pseudo-R^2_2	88.90		82.57		91.50		93.02	
pseudo-R^2_3	92.03		94.72		93.10		86.88	
Hausman test ($\chi^2(N)$, $p > \chi^2$)	3021.23	(0.00)	844.30	(0.00)	1627.64	(0.00)	703.21	(0.00)

Notes: (i) Obs. = number of observations; d.f. = degrees of freedom.
(ii) Estimates for Battese-Nerlove, fixed-effect, and structural shift dummy variables are not reported, and available upon request.

4 Results

Table 3 presents the parameter estimates and summary statistics for dynamic linear logit model (equations 6-8) applied to fuel consumption across the entire dataset, and separately to the country groups defined in the previous section. All model specifications have a reasonably good fit, characterized by high pseudo-R squares. The results from Hausman's (1978) specification test indicate that the hypothesis that a pooled model's estimates are consistent is rejected at a 1 percent level of significance for all model specifications. Estimates of structural parameters ϕ^*_{ij} vary across country groups, indicating heterogeneity in estimated elasticities.

Econometric estimates of the adjustment parameter λ reveal that fuel demand is responsive in the short-run, with about two-thirds of the long-run response taking place in the same year as the price change. The size of the estimated adjustment parameter is the highest for countries that have a potential to produce any of the three fossil fuels. For these countries less than a half of the long-run response takes place in the same year as the fuels' price change. The size of the estimated adjustment parameter is considerably smaller for countries that have a potential to produce one or two fossil fuels. For these countries about 70 percent of the long-run response takes place in the same year as the fuels' price change. The size of the estimated adjustment parameter is the smallest for countries that have no potential to produce any of the three fossil fuels. For these countries about 90 percent of the long-run response takes place in the same year as the fuels' price change. These results indicate that more fossil fuel-intensive industries of energy producers have higher capital adjustment costs, and are consistent with the carbon lock-in hypothesis.

As regards other explanatory variables, the coefficients of the logarithm of real gross value added are negative (and, in most cases, statistically significant) across all country groups, except for countries that have no potential to produce any of the three fossil fuels. These results imply that, as output increases, the shares of coal, natural gas, and petroleum products in the industrial fuel mix decline, and the share of electricity increases. For countries that have no potential to produce any of the three fossil fuels, the coefficients of the logarithm of real gross value added are positive (and statistically significant for natural gas-to-electricity and petroleum products-to-electricity ratios). These results imply that, as output increases, the share of electricity in the industrial fuel mix decreases, and the shares of natural gas and petroleum products increase.

Finally, the estimated coefficients for the time trend are negative and statistically significant for the petroleum products-electricity ratio across all groups of countries. The estimated coefficients for natural gas-electricity ratio are positive and statistically significant across all groups of countries, except for the countries that have a potential to produce any of the three fossil fuels. The estimated coefficients for coal-electricity ratio are positive and statistically significant for the full sample, and for countries that have no potential to produce fossil fuels. The estimated coefficients for coal-electricity ratio are positive and not statistically significant for countries that have a potential to produce any of the three fossil fuels. The estimated coefficients for coal-electricity ratio are negative and statistically significant for countries that have a potential to produce one or two fossil fuels. These results indicate that the direction of the technological change in fuel choice is from petroleum products to electricity and natural gas.

4.1 Elasticities

Tables 4 and 5 show the estimated short-run and long-run elasticities of fuel demand evaluated at the sample means for fuel consumption across the entire dataset, and separately to country groups based on their potential to produce energy fuels. All of the estimated own-price elasticities are statistically significant at the 1% level. Estimated elasticities have expected signs and are broadly comparable to the results from recent studies on international interfuel substitution (Serletis et al. 2010b, 2011).[12]

4.1.1 Own Price Elasticities

The top section of tables 4 and 5 shows the estimated short run and long run own-price elasticities of demand for coal, natural gas, petroleum products, and electricity. The demand for all fuels is inelastic in both the short-run and the long-run. Petroleum products and electricity are the most inelastic energy services, with the estimated short-run own-price elasticities of -0.1 and -0.08, using the full dataset. Demand for other fossil fuels is more elastic. Estimated short-run own-price elasticities using full dataset are -0.34 for natural gas and -0.36 for coal. In the long run demand for petroleum products and electricity is still very unresponsive to fuel prices, with estimated own-price elasticities of -0.15 and -0.12, using the full dataset. Demand for coal and natural gas becomes more responsive to fuel prices, with estimated long-run own-price elasticities of -0.56 and -0.52.

Estimated own-price elasticities of demand for coal vary significantly across different country groups. In the short run, own-price elasticities of coal, natural gas, and electricity demand are all smaller for countries that have no potential to produce fossil fuels. Own-price elasticities of coal demand in those countries are about 2.5 times smaller compared to countries that have a potential to produce all fossil fuels, and about 3.5 times smaller compared to countries that have a potential to produce one or two fossil fuels. Own-price elasticities of natural gas demand in those countries are about 1.5 times smaller compared to countries that have a potential to produce all fossil fuels. Own-price elasticities of electricity demand in those countries are about 1.3 times smaller compared to countries that have a potential to produce all fossil fuels, but 1.5 times larger compared to countries that have a potential to produce one or two fossil fuels. However, the short run own-price elasticities of petroleum products demand are

[12]Serletis et al. (2010b) and Serletis et al. (2011) both report Morishima elasticities of substitution, σ_{ij}. We obtain the estimates of their cross-price elasticities of substitution, η_{ij}, using $\eta_{ij} = \sigma_{ij} + \eta_{jj}$, where η_{jj} are the own-price elasticities of substitution.

[htbp]

Table 4: Short-Run Elasticities for Models of Fuel Consumption, 1978-2008

Elasticities	Full Sample		Production: All Fuels		Production: 1 or 2 Fuels		Production: No Fuels	
Own-price								
Coal	-0.36***	(0.0004)	-0.51***	(0.002)	-0.70***	(0.001)	-0.19***	(0.001)
Natural Gas	-0.34***	(0.001)	-0.39***	(0.003)	-0.35***	(0.003)	-0.26***	(0.002)
Petroleum products (PP)	-0.10***	(0.001)	-0.10***	(0.002)	-0.12***	(0.003)	-0.16***	(0.003)
Electricity	-0.08***	(0.001)	-0.12***	(0.003)	-0.06***	(0.002)	-0.09***	(0.002)
Cross-price								
Coal - Natural Gas	0.05***	(0.001)	0.09***	(0.003)	0.11***	(0.004)	0.03***	(0.001)
Coal - PP	0.10***	(0.002)	0.10***	(0.003)	0.16***	(0.004)	0.06***	(0.002)
Coal - Electricity	0.21***	(0.001)	0.33***	(0.004)	0.44***	(0.004)	0.10***	(0.001)
Natural Gas - Coal	0.01***	(0.0004)	0.02***	(0.001)	0.02***	(0.001)	0.01***	(0.0003)
Natural Gas - PP	0.10***	(0.002)	0.06***	(0.002)	0.16***	(0.004)	0.15***	(0.004)
Natural Gas - Electricity	0.23***	(0.001)	0.31***	(0.004)	0.17***	(0.001)	0.12***	(0.002)
PP - Coal	0.01***	(0.0004)	0.02***	(0.001)	0.02***	(0.001)	0.003***	(0.0002)
PP - Natural Gas	0.05***	(0.001)	0.05***	(0.002)	0.09***	(0.003)	0.04***	(0.002)
PP - Electricity	0.04***	(0.0002)	0.03***	(0.0004)	0.01***	(0.0001)	0.12***	(0.002)
Electricity - Coal	0.01***	(0.0004)	0.02***	(0.002)	0.02***	(0.001)	0.003***	(0.0002)
Electricity - Natural Gas	0.05***	(0.001)	0.09***	(0.003)	0.04***	(0.001)	0.02***	(0.001)
Electricity - PP	0.02***	(0.0003)	0.01***	(0.0004)	0.002***	(0.0001)	0.07***	(0.002)
Partial								
Coal - Output	0.72***	(0.005)	0.68***	(0.002)	0.83***	(0.003)	1.08***	(0.005)
Natural Gas - Output	0.71***	(0.005)	0.94***	(0.002)	0.67***	(0.003)	0.80***	(0.005)
PP - Output	0.74***	(0.005)	0.81***	(0.002)	0.72***	(0.003)	1.01***	(0.004)
Electricity - Output	0.85***	(0.005)	0.98***	(0.002)	0.90***	(0.003)	0.78***	(0.005)
Coal - Time Trend	0.01***	(0.0003)	0.004***	(0.001)	-0.01***	(0.001)	0.01***	(0.001)
Natural Gas - Time Trend	0.01***	(0.0003)	-0.01***	(0.001)	0.01***	(0.001)	0.03***	(0.001)
PP - Time Trend	-0.03***	(0.0003)	-0.02***	(0.001)	-0.04***	(0.001)	-0.05***	(0.001)
Electricity - Time Trend	0.002***	(0.0003)	-0.004***	(0.001)	-0.01***	(0.001)	0.01***	(0.001)

Note. All elasticities are evaluated at sample means. Standard errors (in parentheses) are computed based on stochastic simulations of elasticity formulas (9), (14), and (17); *** $p<0.01$, ** $p<0.05$, * $p<0.1$.

[htbp]

Table 5: Long-Run Elasticities for Models of Fuel Consumption, 1978-2008

Elasticities	Full Sample		Production: All Fuels		Production: 1 or 2 Fuels		Production: No Fuels	
Own-price								
Coal	-0.56***	(0.001)	-1.18***	(0.004)	-0.98***	(0.002)	-0.21***	(0.001)
Natural Gas	-0.52***	(0.002)	-0.91***	(0.007)	-0.49***	(0.004)	-0.29***	(0.003)
Petroleum Products (PP)	-0.15***	(0.002)	-0.23***	(0.004)	-0.16***	(0.004)	-0.18***	(0.003)
Electricity	-0.12***	(0.002)	-0.27***	(0.007)	-0.09***	(0.002)	-0.10***	(0.002)
Cross-price								
Coal - Natural Gas	0.08***	(0.002)	0.20***	(0.007)	0.15***	(0.005)	0.03***	(0.002)
Coal - PP	0.16***	(0.003)	0.22***	(0.007)	0.22***	(0.005)	0.07***	(0.002)
Coal - Electricity	0.33***	(0.002)	0.76***	(0.01)	0.61***	(0.005)	0.11***	(0.001)
Natural Gas - Coal	0.02***	(0.001)	0.04***	(0.003)	0.03***	(0.002)	0.01***	(0.0004)
Natural Gas - PP	0.16***	(0.003)	0.14***	(0.005)	0.22***	(0.005)	0.17***	(0.005)
Natural Gas - Electricity	0.35***	(0.002)	0.73***	(0.009)	0.24***	(0.002)	0.13***	(0.002)
PP - Coal	0.02***	(0.001)	0.04***	(0.003)	0.02***	(0.001)	0.004***	(0.0002)
PP - Natural Gas	0.08***	(0.002)	0.11***	(0.004)	0.13***	(0.004)	0.04***	(0.002)
PP - Electricity	0.06***	(0.0004)	0.08***	(0.001)	0.01***	(0.0001)	0.14***	(0.002)
Electricity - Coal	0.01***	(0.001)	0.04***	(0.004)	0.03***	(0.002)	0.003***	(0.0002)
Electricity - Natural Gas	0.08***	(0.002)	0.20***	(0.007)	0.06***	(0.002)	0.02***	(0.001)
Electricity - PP	0.03***	(0.0004)	0.03***	(0.001)	0.003***	(0.0001)	0.08***	(0.002)
Partial								
Coal - Output	1.11***	(0.008)	1.57***	(0.004)	1.16***	(0.004)	1.22***	(0.005)
Natural Gas - Output	1.10***	(0.008)	2.18***	(0.005)	0.95***	(0.004)	0.91***	(0.005)
PP - output	1.15***	(0.007)	1.88***	(0.004)	1.01***	(0.004)	1.14***	(0.004)
Electricity - Output	1.31***	(0.007)	2.26***	(0.005)	1.26***	(0.004)	0.88***	(0.005)
Coal - Time Trend	0.01***	(0.001)	0.01***	(0.001)	-0.02***	(0.001)	0.01***	(0.001)
Natural Gas - Time Trend	0.01***	(0.001)	-0.03***	(0.001)	0.01***	(0.001)	0.03***	(0.001)
PP - Time Trend	-0.04***	(0.0005)	-0.04***	(0.001)	-0.06***	(0.001)	-0.05***	(0.001)
Electricity - Time Trend	0.004***	(0.001)	-0.01***	(0.001)	-0.01***	(0.001)	0.01***	(0.001)

Note. All elasticities are evaluated at sample means. Standard errors (in parentheses) are computed based on stochastic simulations of elasticity formulas (9), (14), and (17); *** p<0.01, ** p<0.05, * p<0.1.

1.3 to 1.6 times larger for countries that have no potential to produce fossil fuels relative to energy-producing countries.

In the long-run, own-price elasticities of demand for all energy sources are larger for countries that have potential to produce any of fossil fuels. Own-price elasticities of coal demand in those countries are about 6 times larger compared to countries that have no potential to produce any of energy fuels, and about 1.2 times larger compared to countries that have a potential to produce one or two fossil fuels. Own-price elasticities of natural gas demand in those countries are about 3 times larger compared to countries that have no potential to produce all fossil fuels, and about 1.8 times larger compared to countries that have a potential to produce one or two fossil fuels. Own-price elasticities of petroleum products demand in those countries are about 1.3 to 1.4 times larger compared to countries that have a potential to produce one or two of fossil fuels or cannot produce any fossil fuels. Own-price elasticities of electricity demand in those countries are about 3 times larger compared to countries that have a potential to produce one or two of fossil fuels or cannot produce any energy fuels.

4.1.2 Cross Price Elasticities

The middle section of tables 4 and 5 shows the estimated short run and long run cross-price elasticities of fuel demand with respect coal, natural gas, petroleum, and electricity prices. Estimated cross-price elasticities are all positive in both short- and the long run, indicating that all four fuels are substitutes. Those elasticities are, however, small in their absolute magnitude (less or equal to 0.23 in the short-run, using full dataset), indicating limited possibilities for inter-fuel substitution. The largest scope for interfuel substitution is for coal and natural gas with respect to electricity prices (0.21 and 0.23 in the short-run using full dataset) and petroleum products prices (0.1 in the short-run using full dataset). Both petroleum products and electricity appear to be very poor substitutes to other fuels with estimated short-run elasticities less than 0.05 using full dataset.

As regards variation across country groups based on natural resources, estimates of both short and long run cross-price elasticities do vary significantly across different country groups. Specifically, estimated cross-price elasticities of coal with respect to other fuels' prices, and cross-price elasticities of other fuels with respect to coal's prices are all considerably higher for countries with the potential to produce all fossil fuels or at least one fossil fuel. The largest estimated short run cross-price elasticity is of coal with respect to electricity prices for countries with the potential to produce at least one fossil fuel (0.44), which is more than 4 times higher than for countries with no potential to produce any fossil fuels. Similarly, estimated short run cross-price elasticities of natural gas with respect to electricity prices, and of electricity and petroleum products with respect to natural gas prices are higher for countries with the potential to produce all fossil fuels or at least one fossil fuel. These differences become even more pronounced in the long run. This is because (as shown in the section above) the countries with the potential to produce fossil fuels account for smaller share of the long-run response in the year of the fuels' price change.

On the contrary, estimated cross-price elasticities of petroleum products with respect to electricity prices, and of electricity with respect to petroleum prices are higher for countries with the potential to produce all fossil fuels or at least one fossil fuel. Finally, estimated short run cross-price elasticity of natural gas with respect to petroleum prices, is smaller for countries with the potential to produce all fossil fuels than in other countries. This difference becomes smaller in the long run.

4.1.3 Partial Elasticities

The bottom section of tables 4 and 5 shows the estimated partial elasticities of fuel demand with respect to changes in manufacturing output and time trend. Estimated average elasticities of fuel demand with respect to output are all positive and less than one, indicating that "as output increases there will be substitution away from energy" (Pindyck 1979, p. 176). In the long-run, output elasticities of fuel demand are all above one, which implies that an increase in output results in more than proportional increase in energy consumption. Estimated short run elasticities of coal and petroleum products demand with respect to output are largest for countries with no potential to produce fossil fuels. Estimated short run elasticities of natural gas and electricity demand with respect to output are largest for countries with the potential to produce all fossil fuels. Estimated long run elasticities of all four fuels with respect to output are largest for countries with the potential to produce all fossil fuels.

Estimated average elasticities of fuel demand with respect to time trend are positive for coal, natural gas and electricity, and negative for petroleum products. This result implies that the technological change results in greater consumption of coal, natural gas and electricity, and smaller consumption of petroleum products. However, the estimated elasticities of fuel demand with respect to time trend are negative for natural gas, petroleum products, and electricity for countries with the potential to produce all fossil fuels. Similarly, the estimated elasticities of fuel demand with respect to time trend are negative for coal, petroleum products, and electricity for countries with the potential to produce at least one fossil fuel. These results indicate that technological change results in smaller fuel consumption in energy producing economies.

5 Counterfactual Analysis using GTAP-E Model

This section applies econometric estimates from dynamic linear logit model to evaluate the effects of energy and climate policies in energy producing and non-producing countries. Because dynamic linear logit model is a partial equilibrium model, and cannot account for all market mediated responses, for our analysis we employ computable general equilibrium (CGE) model GTAP-E (Burniaux and Truong 2002). GTAP-E is a special extension of a widely used multi-sector multi-country GTAP model (Hertel 1997). In GTAP model, consumers are represented by a utility-maximizing private household, whose preferences are determined by a constant difference elasticity (CDE) demand system. Producers maximize profits using intermediate inputs and primary factors. Governments can distort prices paid by purchasers and prices received by producers by imposing ad valorem taxes and subsidies on commodities and primary factors. Regional income is exhausted through constant share to private household consumption, government expenditures and national savings. Investment in each region is financed from a global pool of savings, to which each region contributes a fixed proportion of its income.

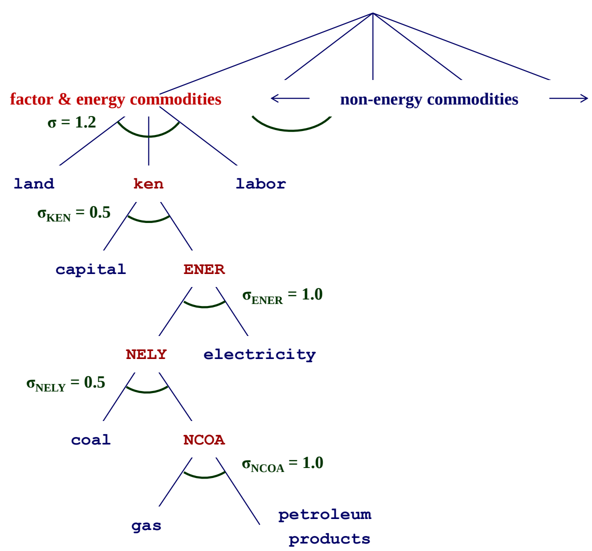


Figure 2: Production Structure of GTAP-E Model

GTAP-E is a special extension of the GTAP model, aimed at studying implications of energy and environmental policies. The standard GTAP model assumes nested production: Leontief nest between intermediate inputs and primary-factor; Constant Elasticity of Substitution (CES) nest between primary-factors (labor, capital, and land); Armington CES nest between: imported inputs from different regions; imported and domestic inputs. GTAP-E introduces additional substitution between capital and energy (Figure 2). There are different levels of CES nests in GTAP-E model: capital and energy; electric and non-electric (ENER); coal and non-coal (NELY) and finally, oil, gas and petroleum products (NCOA). Armington structure of inputs is preserved. Consumers substitute between energy and non-energy products and also within them. Emission changes arising from the simulations are calculated as being proportional to usage, based on initial emission intensity values. Trading blocs can trade emissions by imposing carbon taxes at the bloc level.

The default version of GTAP-E model imposes *ad hoc* assumptions on magnitudes of CES elasticities for different fuels and assumes they are same for all countries. We replace the default energy substitution elasticities with the elasticities derived from our econometric results. To use the results from dynamic linear logit model in CGE framework we have to convert calculated cross-price elasticities to CES elasticities of substitution. The relationship between short-run cross-price elasticities, η_{ij}^{SR}, and CES elasticities of substitution, σ_{ij}, are given by

$$\sigma_{ij} = \frac{\eta_{ij}^{SR}}{\bar{S}_i}. \tag{19}$$

Table 6 shows calculated CES elasticities across different country groups. By averaging across the σ's, we calculate the CES elasticities needed for the GTAP-E model: all the elasticities between coal and non-coal fuels for the NELY nest; those between electricity and non-electric fuels for the ENER nest. For the NCOA nest, the only elasticity needed is that between oil and gas.

Table 6: CES Elasticities for revised GTAP-E model

Elasticities	Full Sample	Production: All Fuels	Production: 1 or 2 Fuels	Production: No Fuels
σ_{ce}	0.37	0.56	0.75	0.17
σ_{ge}	0.39	0.53	0.29	0.21
σ_{oe}	0.06	0.06	0.01	0.21
σ_{ENER}	0.28	0.38	0.35	0.20
σ_{cg}	0.38	0.53	0.75	0.31
σ_{co}	0.37	0.45	0.64	0.20
σ_{NELY}	0.38	0.49	0.69	0.25
σ_{NCOA}	0.39	0.30	0.65	0.45

Notes: (i) $\sigma_{NCOA} = \sigma_{go}$; (ii) $\sigma_{NELY} = \frac{1}{2}(\sigma_{co} + \sigma_{cg})$; (iii) $\sigma_{ENER} = \frac{1}{3}(\sigma_{ce} + \sigma_{ge} + \sigma_{oe})$.

Using these calculations, we conduct counterfactual simulations to test the implications of differences in elasticities of fuel substitution across different country groups. We employ revised GTAP-E version (McDougall and Golub 2007), which is based on GTAP 7.1 Data Base (Narayanan and Walmsley 2008) with a base year of 2004. We aggregate the 112 regions in the data base into three groups: those with no potential to produce fossil fuels, those with potential to produce all fossil fuels and those with the potential to produce one or two fossil fuels, based on our estimation results.[13] We follow Burniaux and Truong (2002) in the sectoral aggregation from 57 GTAP sectors to 8 sectors: agriculture, coal,

[13] For countries where estimation results were not available we used actual instead of predicted energy production.

oil, natural gas, oil products, electricity, energy intensive industries (en_int_ind) and other industries and services (oth_ind_ser).

We use two different sets of fuel substitution elasticities: one that employs the elasticities estimated using full sample (as baseline); another that employs region-specific elasticities as shown in table 6. With each of these sets of elasticities we conduct two independent policy experiments. In first experiment impose a uniform carbon tax of US$ 30 per ton of CO_2 across all countries. In the second experiment, we increase production and consumption taxes on the usage of oil (and oil products) to the extent that all existing oil subsidies are eliminated. Our estimate of fossil fuel subsidies are based on the report by the IEA et al. (2010), which quotes the total subsidy bill as being US$ 557 billion for 37 non-OECD economies in 2008. Given that many other countries including the OECD economies are left out of that report, this estimate represents the lower bound of fossil fuel subsidies. Even this turns out to be over 25% of total expenditure on oil and oil products by firms and private households in GTAP Data Base. Thus we assume an increase of tax rates on firm and household consumption of all these products by 25 percentage points, as the equivalent for the removal of fossil fuel subsidies for policy experiment 2.

The mechanisms with which carbon tax and elimination of fuel subsidies act in GTAP-E model are different, though they both act as wedge between different prices. Carbon taxes are imposed in specific terms (e.g., US$ per unit of carbon) on all commodities and agents, weighted by the corresponding emission intensity. For example, a carbon tax of 10 US$ per ton of carbon will result in 10 percent increase in commodity prices if the emission intensity associated with the private household consumption of that commodity is 0.01 ton of carbon per US$. All other taxes and subsidies in the GTAP-E model are represented as *ad valorem* percent changes. In our example, the power of subsidies[14] should be reduced by 10% of its initial value to achieve a similar effect of 10 percent increase agents' prices. Thus, for changes in subsidies to affect the agents' prices, emissions intensities are irrelevant.

Table 7 shows the differences between the results of changes in sectoral output from the counterfactual and baseline simulations, for each of the 2 experiments, in millions of US$ (for details of these simulations, see Table A.3, Appendix I). These results demonstrate that the effect of energy and climate policies depends critically on the extent to which countries can substitute between different fuels.

First, let us consider the implications of fuel substitution on the carbon tax policy. As explained above the effect of carbon tax on energy prices depends critically on emission intensities of fossil fuels. These intensities are the highest for coal ($\sim$ 3.7 tCO_2 / toe), followed by oil and oil products ($\sim$ 2.9 - 3.1 tCO_2 / toe), and natural gas ($\sim$ 2.2 tCO_2 / toe).[15] We would thus expect that a carbon tax will result in a substitution from coal to less carbon intensive

[14]Power of tax or subsidy is defined as one plus rate of tax or subsidy. For example, if the rate of tax is 0.1 or 10%, power of tax is 1.1.

[15]The emission intensity of electricity is difficult to determine as it is idiosyncratic to generation fuel mix in each country.

Table 7: Output change differences between the counterfactual and baseline simulations using GTAP-E model (in USD million)

Industry	Carbon Tax			Oil Subsidies Removal		
	Production: All Fuels	Production: 1 or 2 Fuels	Production: No Fuels	Production: All Fuels	Production: 1 or 2 Fuels	Production: No Fuels
Agriculture	14	-37	14	-15	16	1
Coal	-2120	-263	20	413	41	5
Oil	470	403	37	-406	-286	-21
Gas	1020	83	23	-596	-5	-10
Oil Products	464	1171	-58	-485	-557	23
Electricity	464	86	-61	2059	537	20
En_int_ind	414	-564	11	-350	341	22
Oth_ind_ser	132	-594	-194	-464	258	83
Total	857	285	-208	156	346	122

Note: Baseline simulations employ fuel substitution elasticities estimated using full sample and reported in column 2 of Table 6. Counterfactual simulations employ fuel substition elasticities estimated using region-specific subsamples reported in columns 3, 4, and 5 of Table 6.

fuels. As shown in table 6 countries with potential to produce all fossil fuels and countries with potential to produce one or two fossil fuels have higher than average elasticities of substitution of coal for oil, natural gas, and electricity. Table 7 shows that production of coal declines and production of natural gas and electricity increases by a greater amount in these countries. Compared to baseline scenario the consumption of coal declines by additional 2120 $US million in countries with potential to produce all fossil fuels, and by additional 263 $US million in countries with potential to produce one or two fossil fuels. The production of natural gas and electricity increase by additional 1020 and 464 $US million in countries with potential to produce all fossil fuels, and by additional 83 and 86 $US million in countries with potential to produce one or two fossil fuels.

Next, let us consider the implications of fuel substitution on the policy of phasing out oil subsidies. Reduction in oil subsidies increases the relative price of oil and oil products. We would thus expect that the policy of phasing out oil subsidies will result in a substitution from oil to coal, electricity, and natural gas. As shown in table 6 countries with potential to produce all fossil fuels have higher than average elasticities of substitution of oil for coal and electricity, and lower than average elasticities of substitution of oil for natural gas. Table 7 shows that production of oil, oil products and natural gas declines and production of coal and electricity increases by a greater amount in these countries. Compared to baseline scenario consumption of oil, oil products, and natural gas declines by additional 406, 485, and 596 $US million in countries with potential to produce all fossil fuels. Production of coal and electricity increase by additional 413 and 2059 $US million in countries with potential to produce all fossil fuels. Table 6 demonstrates that countries with potential to produce one or two energy fuels have higher than average elasticities of substitution of oil for coal, natural gas and electricity. Table 7 shows that production of oil and oil products declines and production of coal and electricity increases by a greater amount in these countries. Compared to baseline scenario consumption of oil and oil products declines by additional 286, and 557 $US million in countries with potential to produce one or two fossil fuels. Production of coal and electricity increase by additional 41 and and 537 $US million in countries with potential to produce one or two fossil fuels.

6 Conclusions

This study extends the literature on interfuel substitution by investigating the role of transactions costs and technological adjustment, focusing specifically on differences across countries with different potential for fossil fuel production. We estimate an econometric model of interfuel substitution using a large unbalanced panel dataset of 63 countries, and calculate elasticities of energy demand for fossil fuel producing and non-producing economies.

We find that countries with the potential to produce coal, natural gas, or oil have higher elasticities of fuel substitution. In many cases short run elasticities of fuel substitution for countries with a potential to produce fossil fuels are higher than long run elasticities for countries with no potential to produce fossil fuels. We also find that countries with a potential to produce all fossil fuels or at least one fossil fuel have a considerably longer adjustment of fuel-using capital stocks. For these, more energy-intensive, countries, the share of same year response to fuels' price change was less than fifty percent as opposed to ninety percent in countries with no potential to produce any fossil fuels. As a result, countries with a potential to produce any of the available fossil fuels have considerably higher difference between short and long run elasticities of fuel substitution.

We then use calculated elasticities to evaluate the effects of a carbon tax and reduction in oil subsidies using GTAP-E computable general equilibrium modelling framework. Our simulations show that, compared to the baseline case of uniform elasticities of fuel substitution, carbon tax results in a greater decline in coal consumption in countries with a potential to produce fossil fuels, as these countries have larger elasticities of substitution of coal for natural gas and electricity. Compared to the baseline case, reduction in oil subsidies lowers production of oil, oil products and natural gas and raises production of coal and electricity by a greater amount in countries with a potential produce all fossil fuels. And production of oil and oil products declines and production of coal, natural gas, and electricity increases by a greater amount in countries with potential produce one or two fossil fuels.

These results are important because they imply lower economic cost for policies aimed at climate abatement and more efficient utilization of energy resources.

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Appendix I

Table A.1: Data Availability across Countries and Time

Country	Obs.	Period	Country	Obs.	Period
Argentina	20	1988 - 2008	Japan	31	1978 - 2008
Australia	27	1978 - 2004	Kazakhstan	14	1995 - 2008
Austria	31	1978 - 2008	Korea	31	1978 - 2008
Belgium	31	1978 - 2008	Luxembourg	31	1978 - 2008
Bolivia	20	1988 - 2008	Mexico	31	1978 - 2008
Brazil	21	1988 - 2008	Netherlands	31	1978 - 2008
Canada	31	1978 - 2008	New Zealand	31	1978 - 2008
Chile	20	1988 - 2008	Nicaragua	20	1988 - 2008
China	19	1990 - 2008	Norway	31	1978 - 2008
Colombia	20	1988 - 2008	Panama	20	1988 - 2008
Costa Rica	20	1988 - 2008	Paraguay	20	1988 - 2008
Croatia	9	2000 - 2008	Peru	20	1988 - 2008
Cuba	19	1988 - 2006	Poland	30	1979 - 2008
Cyprus	31	1978 - 2008	Portugal	31	1978 - 2008
Czech Republic	19	1990 - 2008	Romania	12	1995 - 2008
Denmark	31	1978 - 2008	Russian Federation	11	1993 - 2008
Dominican Republic	19	1988 - 2006	Singapore	7	2002 - 2008
Ecuador	20	1988 - 2008	Slovak Republic	19	1990 - 2008
Finland	31	1978 - 2008	Slovenia	20	1988 - 2008
France	31	1978 - 2008	South Africa	31	1978 - 2008
Germany	31	1978 - 2008	Spain	31	1978 - 2008
Greece	31	1978 - 2008	Sweden	31	1978 - 2008
Guatemala	19	1988 - 2006	Switzerland	31	1978 - 2008
Haiti	20	1988 - 2008	Taiwan	28	1981 - 2008
Honduras	20	1988 - 2008	Thailand	31	1978 - 2008
Hungary	29	1980 - 2008	Trinidad and Tobago	20	1988 - 2008
India	31	1978 - 2008	Turkey	31	1978 - 2008
Indonesia	31	1978 - 2008	United Kingdom	31	1978 - 2008
Ireland	31	1978 - 2008	United States	31	1978 - 2008
Israel	15	1994 - 2008	Uruguay	20	1988 - 2008
Italy	31	1978 - 2008	Venezuela	27	1981 - 2008
Jamaica	19	1988 - 2006			

Table A.2: Predicted Energy Production across Countries in 2008

Country	Coal	Gas	Oil	Country	Coal	Gas	Oil
Argentina	No	Yes	Yes	Japan	Yes	No	No
Australia	Yes	Yes	Yes	Kazakhstan	Yes	Yes	Yes
Austria	No	Yes	No	Korea	Yes	No	No
Belgium	No	No	No	Luxembourg	No	No	No
Bolivia	No	Yes	Yes	Mexico	Yes	Yes	Yes
Brazil	Yes	Yes	Yes	Netherlands	No	Yes	Yes
Canada	Yes	Yes	Yes	New Zealand	Yes	Yes	Yes
Chile	No	Yes	No	Nicaragua	No	No	No
China	Yes	Yes	Yes	Norway	No	Yes	Yes
Colombia	Yes	Yes	Yes	Panama	No	No	No
Costa Rica	No	No	No	Paraguay	No	No	No
Croatia	No	Yes	Yes	Peru	No	Yes	Yes
Cuba	No	Yes	Yes	Poland	Yes	Yes	No
Cyprus	No	No	No	Portugal	No	No	No
Czech Republic	Yes	No	No	Romania	Yes	Yes	Yes
Denmark	No	Yes	Yes	Russian Federation	Yes	Yes	Yes
Dominican Republic	No	No	No	Singapore	No	No	No
Ecuador	No	Yes	Yes	Slovak Republic	No	No	No
Finland	No	No	No	Slovenia	No	No	No
France	Yes	No	No	South Africa	Yes	Yes	No
Germany	Yes	Yes	Yes	Spain	Yes	No	No
Greece	Yes	No	No	Sweden	No	No	No
Guatemala	No	No	Yes	Switzerland	No	No	No
Haiti	No	No	No	Taiwan	No	Yes	No
Honduras	No	No	No	Thailand	Yes	Yes	Yes
Hungary	Yes	Yes	No	Trinidad and Tobago	No	Yes	Yes
India	Yes	Yes	Yes	Turkey	Yes	No	Yes
Indonesia	Yes	Yes	Yes	United Kingdom	Yes	Yes	Yes
Ireland	No	Yes	No	United States	Yes	Yes	Yes
Israel	No	Yes	No	Uruguay	No	No	No
Italy	No	Yes	Yes	Venezuela	Yes	Yes	Yes
Jamaica	No	No	No				

Table A.3: Output Change in the Counterfactual and Baseline Simulations using GTAP-E Model (in USD million)

Industry	Counterfactual Simulations			Baseline Simulations		
	Production: All Fuels	Production: 1 or 2 Fuels	Production: No Fuels	Production: All Fuels	Production: 1 or 2 Fuels	Production: No Fuels
Policy 1: Carbon Tax, $US 30 per ton of CO_2						
Agriculture	-1581	-665	-1833	-1595	-627	-1847
Coal	-19052	-2141	-401	-16932	-1878	-421
Oil	-6219	-5422	-710	-6689	-5825	-747
Gas	-14274	-2671	-1087	-15294	-2754	-1110
Oil products	-16825	-4146	-355	-17289	-5317	-297
Electricity	-28432	-6360	-1240	-28896	-6446	-1180
En_int_ind	-5749	10519	-16318	-6162	11083	-16329
Oth_ind_ser	-28624	-15396	12769	-28756	-14802	12964
Total	-120756	-26282	-9175	-121613	-26566	-8967
Policy 2: Removal of Oil Subsidies						
Agriculture	-1998	-798	-67	-1982	-814	-68
Coal	-760	-55	-3	-1174	-97	-8
Oil	-12375	427	384	-11969	713	406
Gas	-2440	-591	-215	-1844	-586	-205
Oil products	-45966	-5955	9703	-45481	-5398	9680
Electricity	-5795	-2883	254	-7854	-3420	234
En_int_ind	-9240	-3327	3819	-8889	-3668	3798
Oth_ind_ser	-24352	-17022	-4233	-23888	-17280	-4316
Total	-102925	-30204	9642	-103082	-30550	9521

Note: Baseline simulations employ fuel substitution elasticities estimated using full sample and reported in column 2 of Table 6. Counterfactual simulations employ fuel substition elasticities estimated using region-specific subsamples reported in columns 3, 4, and 5 of Table 6.