Why Previous Estimates of the Cost of Climate Mitigation Might Be Too Low

Jayson Beckman
(USDA/ERS)
JBeckman@ers.usda.gov
Thomas Hertel
(Purdue University)
hertel@purdue.edu

Abstract:

Computable general equilibrium (CGE) models have been heavily utilized in analyses of the costs of Greenhouse Gas mitigation policies. This is in large part due to their ability to simulate potential impacts of prospective economic policies taking into account inter-sectoral and international interactions. Although CGE models have received heavy usage, they are often criticized as being insufficiently validated. Key parameters are often not econometrically estimated, and the performance of the model as a whole is rarely checked against historical outcomes. As a consequence, questions frequently arise as to how much faith one can put in CGE results. Our findings indicate that many earlier CGE-based studies may have understated the cost of meeting Greenhouse Gas mitigation targets by overstating the price elasticity of demand for energy. These results suggest that we must revisit the cost of climate policies in light of newly validated CGE models.

1. Introduction

Computable general equilibrium (CGE) models have garnered much attention recently for analysis of potential climate change and land-use impacts (e.g. Nijkamp et al., 2005; Jaocby et al., 2006; Bosello et al., 2007). This is in large part due to their ability to simulate potential impacts of prospective economic policies taking into account inter-sectoral and international interactions. In particular, a main focus of CGE-based climate change analysis has been determining the cost of Greenhouse Gas (GHG) mitigation policies. Despite this heavy usage; CGE models are often criticized as being insufficiently validated. Key parameters are often not econometrically estimated, and the performance of the model as a whole is rarely checked against historical outcomes.

This article presents a comprehensive examination of key CGE model parameters, and thus the validity, of one of the widely utilized[1] CGE models 'GTAP-E' (Burniaux and Truong, 2002). Although we focus on this single model, the methodology proposed here can readily be applied to other CGE models. The current global focus on climate change/energy policies highlights the importance of providing a sound econometric basis for key energy parameters used in CGE models. The importance of CGE parameters and the subsequent impact on climate change/energy policy analysis was also well recognized by Welsch (2008). In the case of GHG mitigation, many historical estimates of the cost of climate change are likely misleading since the CGE model used has not been properly validated. In order for us to estimate the true cost of GHG mitigation, the economic framework must be correctly specified.

Crude oil is a key component of the energy economy. It is also one of the most volatile commodities, both in terms of production and of prices (Adelman, 1999). Examining prices from 1985-1994, Plourde and Watkins (1998) found that crude oil prices tend to be as volatile, and often more volatile, than other commodities. Examining the coefficient of variation for a five-year average of historical prices (1982-2003) for crude oil, corn, rice, and gold, volatility in crude oil prices (CV of .225) is greater than the others. Indeed it is shown to be greater than that for rice (.191) which is often considered to be one of the most volatile commodity prices (Wailes, 2004).

As usage of CGE models has increased, strengthening their empirical foundations has drawn a lot of attention in the modeling arena. The recent paper by Valenzuela et al.

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[1] See Rosen (2003); Nijkamp et al. (2005); Gan and Smith (2006); Kemfert (2006); Ronneberger (2006); Berrittella et al. (2005, 2006); Banse et al. (2007); Birur et al. (2007); Bosello et al. (2007); Taheripour et al. (2008).

(2007) offers an approach to model validation that seems particularly relevant for energy markets. In their paper, the authors examined the ability of the GTAP model to reproduce historical price volatility in a specific commodity market (wheat), given a set of stochastic shocks based on historical volatility in market fundamentals – in this case production. The probability distribution of supply shocks was obtained from a time-series model of wheat production designed to elicit the randomness inherent in inter-annual output changes.

Extending their approach to petroleum markets, we include both supply- and demand-side shocks to examine crude oil and gasoline price volatility. Time-series models are built to capture the trend in oil production (supply-side) and GDP (demand-side), with the resulting residuals used to create probability distributions for random shocks to the underlying supply and demand schedules for petroleum. Standard deviations estimated by the CGE model are then compared across the two models (old parameters and new) *in order to determine which model best replicates historical year-to-year price changes*. This test of the model's ability to replicate historical price volatility hinges on the specification of key energy parameters as they characterize agents' behavior in the CGE model. If they are incorrectly specified, estimated volatility will not be representative of historical volatility, and thus any estimates from the CGE model will be suspect. These parameters are then re-evaluated in light of recent estimates in the literature; thereby, providing a firmer econometric underpinning for the energy portion of the model.

The results of this work indicate that the existing GTAP-E model does not perform well against the historical test; leading to the conclusion that the energy parameters in the original GTAP-E specification are mis-specified. In particular, the old substitution parameters were much too large, which for GHG analysis, leads to an understatement of the costs of meeting a given emissions reduction target. We find that the model with new parameters, based on historical econometric estimates, is better able to replicate historical price volatility. This improves our confidence in the performance of the model, and results generated using GTAP-E as the framework.

The implications and importance of this work are highlighted with a policy experiment. In particular, we examine the size of the tax required to meet the stylized Kyoto emissions reduction scenario previously analyzed by Burniaux and Truong (2002). Our findings indicate that earlier studies based on the GTAP-E model have greatly understated the cost of meeting these targets. The results lead to the conclusion that we should revisit estimates of the cost of climate policy[2], generated by estimates using CGE models. This work also highlights the importance of providing a firm econometric foundation for CGE models, and calls for further rigorous examination of key parameters in other CGE models.

2. Literature

2.1 Costs of Climate Policies

A wide assortment of instruments has been proposed for mitigating potential climate change. As pointed out by Goulder and Pizer (2006), a carbon tax was the focus

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[2] It should be pointed out that with respect to climate policy there is a big difference between simulating the Kyoto Protocol and simulating stabilization of greenhouse gas concentrations. The former is short-term and the changes in emissions and CO2 prices can be described by elasticities. Stabilization of greenhouse gas concentrations is long-term and requires a complete transition of the energy system. The work here, therefore, is not intended to simulate stabilization of greenhouse gas concentrations; rather it is to provide a platform for current energy analysis.

of early analyses, due to its ease of implementation in economic models wherein the carbon tax is applied to the use of fossil fuels, thereby the amount of CO_2 emitted. Many analyses related to a carbon tax have focused on comparisons between the carbon tax with a provision for countries to trade emission permits, and a carbon tax without such emissions trading.

Bernard and Vielle (2003) point out that the nature of climate change (i.e. the global scope, the long delay between emissions and the effects on climate, and the absence of a device giving direct control on emissions) indicates that general equilibrium models are the instruments which should be used for long-run climate change analysis. Results from their work indicate that emission reductions (2010 targets) with tradable permits lead to a reduction in welfare costs of more than 50%, as compared to emission reductions without such permits.

Results from Welsch (2007) indicate that Armington trade elasticities are a key driver in the impacts of climate protection policies. Of importance to the parameter work in this paper, the energy substitution parameters used in Bernard and Vielle (2003) are less responsive than those used in the original GTAP-E specification[3] (albeit the production structures are slightly different). The consequence of an energy substitution elasticity which is excessive in size is that the derived demand for petroleum will be too elastic. This is illustrated in figure 1. With an overly elastic demand (D_0), any given adverse supply shock will result in a large decrease in quantity (Q_0 to Q'_0) but a small increase in price (P_0 to P'_0). With a more inelastic demand D_1 (representing less energy

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[3] For example: The GTAP-E electricity/non-electricity nest is 1; their model ‘GEMINI-E3’ is [.2,.4].

substitution); the same backward shift in supply would cause a much larger increase in price (P'_1), accompanied by a much smaller reduction in quantity Q'_1.

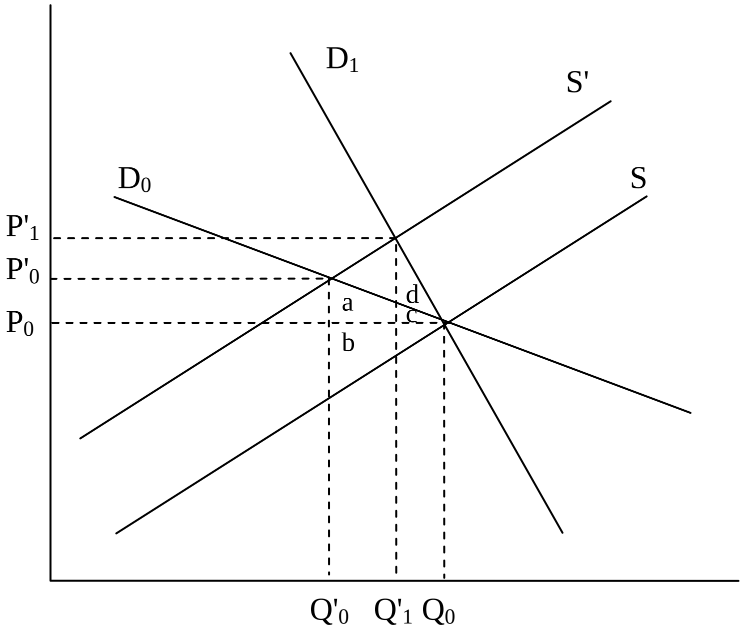

Figure 1. Supply and Demand Graph for a Reduction in Supply, and the Existence of a Reduction in Emissions

Jacoby et al. (2006) conclude that for their model (MIT-EPPA), the substitution elasticity for energy and other value-added is the most important in terms of affecting the cost of a Kyoto emissions policy. These, as well as others (e.g. Abler et al., 1999) have recognized the importance of model parameters. The key contribution in this paper is provide a systematic approach to model validation which can be used to discriminate amongst competing parameter settings.

2.2 Previous Validation Efforts

In order for CGE models to gain prominence in policy analysis, more must be done to ensure the model is an accurate representation of the real economy. Kehoe (2003) notes that to gain credibility CGE models must be rigorously tested *ex post* to ensure that the results match the data. Similarly, Hertel (1999) remarks that to obtain a higher policy profile for CGE models, more must be demanded in the way of model validation, noting that since the typical CGE model has not been econometrically estimated it cannot be subjected to the usual forecasting tests.

Devarajan and Robinson (2002) point out that one way to validate a policy model is to test it against historical data, and examine how well the model explains past events. By doing so, any deficiencies in the model can be better understood, and work can be done to improve them. Arndt et al. (2002) utilize this idea to offer maximum entropy-based estimates of behavioral parameters in a CGE model of Mozambique.

Kehoe (2003) notes that if CGE models are capable of capturing the impact of important policy events, then confidence would be built in applying a model with the same theoretical structure to later experiments. In their work on the Spanish economy, Kehoe et al. (1995) test the predictive ability of their model with respect to changes in relative prices, resource allocation, and alternative closure specifications; and find that with some adjustments, the model replicates historical outcomes well. However, Kehoe (2003) also criticizes CGE models for performing poorly in evaluating the impacts from NAFTA. In this case, he suggests that this is likely due to inadequate treatment of the emergence of new varieties in trade.

3. The GTAP-E Model and Its Use

The CGE model that will be examined here is the GTAP-E model, outlined in Burinaux and Truong (2002). The beauty of using this model is that it is readily accessible on the web, it has been widely used by others, and results based on this model have been published in many journals. The GTAP-E model modifies the production structure of the standard GTAP model in order to more closely mimic the ability of firms to substitute among alternative fuels as well as between labor, capital and energy. It also incorporates CO2 emissions from the combustion of fossil fuels as well as a mechanism to trade these emissions internationally. McDougall and Golub (2007) subsequently streamlined and improved this particular model. The production structure of GTAP-E is shown in Appendix A.

Nijkamp et al. (2005) illustrate how to implement several instruments (international emission trading, joint implementation, and clean development mechanisms) related to climate change within the GTAP-E model. Results indicate that a carbon tax would have to be higher if emission trading was not considered. Kemfert et al. (2006) used the GTAP-E framework to investigate the welfare implications of a European Emissions Trading System. Results from their work highlight the efficiency gains from the use of tradable permits when meeting emission reduction targets.

Other uses of GTAP-E have ranged from biofuels (Banse et al., 2007; Birur et al., 2007; Taheripour et al., 2008) to climate change induced variations on tourism demand (Berrittella et al., 2005). Also, the framework has been used to examine water scarcity (Berrittella et al., 2006) and the economic impacts of a rise in sea levels (Bosello et al., 2007). Additionally, Gan and Smith (2005) utilized the GTAP-E model to investigate the cost competitiveness of woody biomass for electricity production in the U.S. under alternative CO_2 emission targets.

There have been several papers/models which have utilized GTAP-E as the base framework, while developing additional components of the CGE model. Ronneberger et al. (2006) link the model with the global agricultural land-use data base ‘KLUM’ in their assessment of potential climate change impacts. Rosen (2003) developed a version 'GTAP-EX' by augmenting the industrial disaggregation of the GTAP-E model in order to examine the impacts of climate change on health and sea levels. *In short, this model has been widely used and therefore warrants a closer look through the validation lens.*

4. Validation of the CGE Model

Stochastic simulation analysis[4], which provides sensitivity analysis for a CGE framework, can be used to determine how well the GTAP-E model performs when confronted with shocks to fundamental drivers of supply and demand (Valenzuela et al., 2007). To characterize the systematic component in crude oil production, time-series models[5] are fitted to Energy Information Administration (EIA) data on annual crude oil production over the time period of 1980-2005. The structure of the GTAP-E model, and indeed most CGE models, dictates a medium-run[6] (i.e. 3-5 years) time horizon (Borges, 1986). We choose to focus here on a 5 year time horizon. By lengthening the time horizon, we bias our analysis in favor of accepting more elastic petroleum demands (we expect the derived demand elasticity to increase with the time horizon).

Demand-side shocks also play a role in determining crude oil and gasoline price volatility. Here, we employ the same methodology used for the supply-side. However, given the widespread use of petroleum as both an intermediate input and a final consumer good, we do not perturb firm level demands for petroleum, but rather, we focus on a general indicator of economic activity which is readily measured – Gross Domestic

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[4] See Arndt (1996) and Pearson and Arndt (2000) for a detailed discussion the procedures used. Appendix B1 outlines it use here.

[5] Refer to Appendix B2 for detailed discussion on the estimation of these models.

[6] For GE models the medium-run is typically specified as the time frame when capital and labor are perfectly mobile.

Product (GDP). Again, a time series model is developed in order to isolate the random element in a 5 year moving average of GDP for each region in the model.

The key result of interest from the time-series regressions on both the supply and demand sides is the normalized standard deviation of the estimated residuals, reported in table 1[7]. This result summarizes variability of the non-systematic aspect of production and GDP in each region from 1980 to 2005 (sectors and regions are defined in Appendices C1 and C2). This is calculated as $\sqrt{V}$ (the variance of the estimated residuals) divided by the mean value of production (or GDP), and multiplied by 100%. The normalized standard deviation of residuals indicates that the greatest relative volatility in crude oil production arises in the Oceania region, Japan (which produces little oil), and Rest of Asia (RoAsia), while relative volatility is lowest for the former Soviet Union (EEFSUEX), South Asian Energy Exporters (SASIAEEX), and the U.S. For GDP (column 2), the results indicate that those countries/regions which have the lowest relative GDP volatility are Switzerland, U.K., and Norway. The country/regions with the highest relative volatility are Malaysia, Saudi Arabia, and Thailand.

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[7] Estimates for the time-series models are available upon request.

Table 1. Time-Series Residuals, Used as Inputs for the SSA Analysis.

	Normalized standard deviations of residuals	
Region	Crude Oil Production	GDP
United States	1.23	0.79
Canada	1.35	0.53
United Kingdom (EU)	2.59	0.45
Brazil	3.87	0.86
Japan	4.96	0.51
China	1.24	0.73
India	3.09	0.48
Mexico (LAEEX)	1.45	0.96
Chile (ROLAC)	2.31	1.14
Norway (EEFSUEX)	0.89	0.47
Switzerland (RoE)	1.98	0.34
Saudi Arabia (MEAST)	3.13	2.00
Nigeria (SSAEX)	1.92	0.85
Malaysia (SASIAEEX)	0.90	2.03
Thailand (RoASIA)	4.88	1.65
South Korea (RoHIA)		1.08
South Africa (RoAfr)		0.75
Australia (OCEANIA)	5.95	0.92

Note, the parenthesis indicates the country used as the proxy for variability in GDP. Also, there was insufficient data for RoHIA and RoAFR with respect to production.

Table 2 reports the normalized standard deviation of the percentage changes in observed, crude oil prices[8] (using the 5 year moving average) in the first column. The second column reports the GTAP estimated volatility for crude oil, with respect to random supply and demand shocks for the original parameters. The most striking result is that *the predicted volatility from the GTAP-E model is much lower than historical volatility*. We conclude that the original model does not adequately explain crude oil and gasoline price volatility. This suggests the need for a re-examination of the basic supply and demand parameters underpinning the model.

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[8] Results are similar for petroleum products (gasoline), hence they are not presented.

Table 2. Estimated Crude Oil Historical Price Volatility, and Estimated GTAP Price Volatility across the Original Parameters, the New Household and Supply Parameters (keeping the old energy substitution), and the Complete New Parameterization

		GTAP Results		
Region	Observed Price Changes	Original Parameters	Original Energy Substitution Parameters	New Parameters
United States	8.20	2.44	2.98	7.35
Canada	6.91	2.54	3.05	7.39
United Kingdom (EU)	7.69	2.74	3.28	7.63
China	8.32	2.68	3.25	7.76
Mexico (LAEEX)	7.32	2.61	3.05	7.27
Ecuador (RoLAC)	8.36	2.66	3.12	7.49
Russia (EEFSUEX)	7.48	2.46	2.82	6.74
Saudi Arabia (MEASTNAEX)	9.11	3.61	3.62	6.98
Nigeria (SSAEX)	7.62	2.68	2.91	6.54
Indonesia (SASIAEEX)	8.09	2.93	3.38	7.70
Australia (OCEANIA)	6.54	3.25	3.73	8.00

5. CGE Model Investigation: General Equilibrium Elasticities

As noted in Hertel (1997) “the concept of a general equilibrium (GE) elasticity offers a useful means of combining knowledge of individual agents’ behavior to make inferences about market relationships.” This equilibrium elasticity demonstrates how much total demand or supply changes as a result of a shock to the model, once all firms and households have adjusted to a given perturbation to the system (typically an output tax). In addition, it can be decomposed to identify the individual sources of model-based demand response (from firms, households, government, and investment in each and every region of the world)[9]. Since the goal of this work is to validate the model for energy, and

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[9] Refer to Hertel (1997) for a full decomposition of equations.

as indicated by usage shares, no energy source is more important than petroleum products, this sector will be the focal point of our analysis.[10]

In order to draw out the GE results, a tax on oil products is specified such that the market price rises by 1% for each region individually. The resulting equilibrium change in quantity demanded is then each region's GE demand elasticity. These are reported in table 3, along with the decomposition by source of price response. The total GE demand elasticity (see final column of table 3) is at least -1 for all regions (-.99 for India) and is more than -1.5 for seven of the eighteen regions under the original parameter settings. Notice that the elasticity is quite high for the Middle East and North Africa (MEASTNAEX), which is largely due to the price responsiveness of export demand.[11] The trade elasticities driving these results were econometrically estimated and examined in detail in Hertel et al. (2007) -- hence for this analysis changes to this component are not entertained. Rather the focus is on the producer and household components. Abstracting from the export component, results indicate that the largest contributor to each region's GE elasticity is intermediate use – (i.e. purchases by firms). Indeed, the firms' share of the GE elasticity is the dominant contributor to domestic price response to the oil price shock in virtually every region. Nonetheless, household demand is also an important contributor, so both must be scrutinized. We turn now to a review of agent-level estimates available in the literature.

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[10] In a recent example of using GE elasticities to compare the performance of a CGE model, Keeney and Hertel (2005) calculate and compare these elasticities for agricultural commodities for the U.S. and Canada in their GTAP-AGR framework.

[11] The export demand elasticity facing any region in the model can be approximated by the (Armington) elasticity of substitution amongst sources of goods by importers. Indeed, this is the upper bound on the demand elasticity. It reduces in size as the exporter's market share rises.

Table 3. Total Demand (GE) Elasticity for Oil Products by Components, GTAP-E Original and New Parameters (in parentheses)

Region	Firms	Hhlds.	Exports	Total
US	-0.68 (-.27)	-0.17 (-.11)	-0.18 (-.18)	-1.03 (-.56)
Canada	-0.72 (-.37)	-0.13 (-.12)	-0.57 (-.57)	-1.42 (-1.05)
EU	-0.69 (-.38)	-0.17 (-.14)	-0.46 (-.40)	-1.32 (-.92)
Brazil	-0.77 (-.38)	-0.07 (-.07)	-0.30 (-.30)	-1.13 (-.74)
Japan	-0.82 (-.33)	-0.14 (-.04)	-0.06 (-.06)	-1.03 (-.43)
ChiHkg	-0.79 (-.36)	-0.11 (-.14)	-0.18 (-.18)	-1.09 (-.68)
India	-0.65 (-.26)	-0.10 (-.14)	-0.24 (-.24)	-0.99 (-.64)
LAEEX	-0.57 (-.30)	-0.12 (-.07)	-0.85 (-.84)	-1.54 (-1.20)
RoLAC	-0.65 (-.42)	-0.14 (-.11)	-0.80 (-.78)	-1.59 (-1.31)
EEFSUEX	-0.72 (-.24)	-0.07 (-.06)	-0.76 (-.75)	-1.55 (-1.05)
RoE	-0.88 (-.53)	-0.33 (-.36)	-0.12 (-.12)	-1.33 (-1.01)
MEASTNAEX	-0.45 (-.14)	-0.08 (-.01)	-1.15 (-1.12)	-1.67 (-1.28)
SSAEX	-0.88 (-.67)	-0.33 (-.38)	-0.44 (-.44)	-1.65 (-1.49)
RoAFR	-0.55 (-.18)	-0.08 (-.04)	-0.57 (-.56)	-1.20 (-.78)
SASIAEEX	-0.69 (-.40)	-0.23 (-.28)	-0.46 (-.46)	-1.37 (-1.14)
RoHIA	-0.99 (-.61)	-0.10 (-.04)	-0.47 (-.47)	-1.56 (-1.12)
RoASIA	-0.64 (-.36)	-0.14 (-.15)	-0.84 (-.82)	-1.62 (-1.33)
Oceania	-0.72 (-.28)	-0.14 (-.05)	-0.24 (-.22)	-1.09 (-.56)

6. Literature Estimates of Elasticities

6.1 Household Demand Response

Table 4 presents a summary of econometric estimates of household price and income elasticities of demand for gasoline. There have been many studies of price elasticities undertaken in the U.S., which have produced a wide range of results[12]. The recent work by Bernard (2008) is utilized here. Estimates for other countries are drawn from Sterner et al. (1992): EU [-1.62,-.37], Turkey (-.61), Japan (-.76); McRae (1994) for developing Asian countries, and Wohlgemuth (1997) for additional developing countries. Nicol (2003) uses household data to estimate the range of long run income elasticities of

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[12] A meta-analysis of these elasticities was conducted by Brons et al. (2008). However, most of the studies used (29/43) were pre-1990; hence, we adopt a more recent estimate.

demand for gasoline and finds they vary by household type, with the range spanning [.29,.94] for the U.S. and [.44,1.23] for Canada. Wohlgemuth (1997) reviewed the estimates of income elasticities of demand for OECD and non-OECD countries and points out that the literature on is thin for the latter group of countries. When multiple sources of household response elasticities are given in the literature, the lower bound of the literature estimates is used here, as supported by the work of Hughes et al. (2006) who has shown that recently the price elasticity of demand for gasoline has become more inelastic.

Table 4. Literature Price Elasticities of Demand Considered for the New Parameters. Note countries in parentheses represent the country specific study chosen for that region.

Region	Long-Run Household Demand		Long-Run Household Income	
USA	-0.20	Bernard (2008)	[.29,1]	Nicol (2003)
Canada	[-.83,-.47]	Nicol (2003)	[.44,1.30]	Nicol (2003)
EU	[-1.62,-.37]	Sterner et. al (1992)	[.71,2.03]	Sterner et. al (1992)
Brazil	-0.26	Wohlgemuth (1999)	[.88,1.10]	Wohlgemuth (1999)
Japan	-0.76	Sterner et. al (1992)	0.77	Sterner et. al (1992)
China			[.91,.95]	Sterner et. al (1992)
India	-0.42	Ramanathan (1999)	[1.39,2.68]	Ramanathan (1999)
LAEEX (Mexico)	-0.21	Wohlgemuth (1999)	[.99,1.72]	Wohlgemuth (1999)
RoLAC				
EEFSUEX				
RoE (Norway, Turkey)	[-0.90,-.61]	Sterner et. al (1992)	[1.29,1.32]	Sterner et. al (1992)
MEASTNAEX (Kuwait)	-0.46	Eltony and Al-Mutairi (1995)	[.32,.99]	Wohlgemuth (1999)
SSAEX (Nigeria)	-0.53	Wohlgemuth (1999)	[1,1.28]	Wohlgemuth (1999)
RoAFR				
SASIAEEX (Indonesia)		McRae (1994)	1.69	McRae (1994)
RoHIA (Korea)		McRae (1994)	0.72	McRae (1994)
RoASIA (Philippines)		McRae (1994)		
Oceania (Australia)	-0.18	Sterner et. al (1992)	0.71	Sterner et. al (1992)

6.2 Supply Response

Supply response is also important to our study. Here we draw on Krichene (2002) who estimates the long-run supply elasticity to be 0.25 for oil and 0.60 for gas for the

U.S. These estimates are adopted for our model, across all regions, and a supply elasticity of 1.0 for coal is taken from Toman et al. (2008).

6.3 Energy Substitution

Given that we have tied down household demand and supply response, the final piece is intermediate energy substitution. Inter-fuel substitution is key to the price responsiveness of firms' demand for oil and other energy sectors. Stern (2009) has recently conducted a meta-analysis of studies on this topic. His work is the starting point for our inter-fuel substitution discussion. His main conclusion (with respect to this work) is that estimated elasticities tend to be smaller at higher levels of economic aggregation. He notes that, with the exception of the gas-electricity elasticity it seems that the true values of the elasticities of substitution are greater than unity at the industrial sector level; however, at the macro level, all but one of the elasticities (coal-gas) are not significantly less than unity, and some are not significantly different than zero. It is clear from his analysis that we must be careful in determining which elasticities to incorporate into the GTAP-E model. In examining the results from Stern (1999) we need to keep in mind that the level of aggregation in our work is relatively high (i.e. there are 3 dominant fuel using sectors: electricity, energy intensive industry (En_Int_Ind), and other industry and services (Oth_Ind_Se). Also, the time-frame considered (i.e. short-run or long-run) is important. For our analysis we are focusing on the medium-term; hence we lean towards the longer length of run.

Most of the original GTAP-E model specified parameters which were closely aligned with Stern's argument, i.e. they were specified at unity. We investigate his argument by running the SSA experiment, using the new household demand and supply response parameters; however, we keep the original energy substitution parameters. The results of this experiment (table 2, column 3) indicate that the model still does a poor job explaining historical crude oil volatility. Even with the new household demand and supply response, we are still only able to predict less than half the price volatility in all regions (except for Oceania). We conclude that energy substitution is highly important in representing price volatility, and that we need a different approach to selecting the parameters.

In that vein, a comprehensive examination of the literature considered by Stern (2009) is undertaken. We draw on several of those articles (Jones, 1995; Urga, 1999; Renou-Maissant, 1999; Urga and Walters, 2003; Cho et al., 2004; and Ma et al., 2008) which exhibited the desired characteristics (e.g. relatively recent studies at a high level of aggregation). These estimates are used to determine the targets for inter-fuel substitution. The resulting parameters used here are: 0.25 for substitution between oil and natural gas (non-coal energy sources); 0.07 for coal/non-coal substitution; and 0.16 for electricity/non-electricity.

Literature examining capital/energy substitution is more widespread, here we draw on the average of four estimates[13]. First, Thompson and Taylor (1995) examined 8 major studies, which produced 92 elasticity estimates for capital/energy substitution. Those authors determined that the mean Allen Partial elasticity of substitution between capital and energy was 0.17. With respect to Canada, Jaccard and Bataille (2000) estimated this elasticity to be 0.24. Christopoulos (2000) estimated it to be 0.25 for

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[13] Koetse et al. (2008) also provide a meta-analysis for these estimates. Results from their work indicate that an elasticity of .25 would be reasonable, albeit at the lower end of their [.18,.52] cross-price elasticity range.

Greece. Finally, in a more recent study, Okagawa and Ban (2008) estimated this elasticity across 14 countries, and 19 industries, using panel data from 1995 to 2004. The average elasticity across the industries was 0.33. With respect to the GTAP regions, we average the four studies, and apply them across all regions, yielding a value of 0.25[14].

With the GTAP-E model recalibrated to these elasticities we can re-compute the GE demand elasticities. These new estimates are reported in parentheses in Table 3. Note that the total oil demand elasticity is now inelastic in US, EU, Brazil, Japan, China, India, RoAFR and Oceania. In the other regions, the GE price elasticity of demand is considerably smaller, although still larger than one in absolute value. The composition of demand response has also changed, with relatively more of the (albeit smaller) total coming from household consumption.

7. Reevaluation

The next step is to examine if the re-parameterized model is better able to replicate historical volatility in crude oil and gasoline markets. Accordingly, the stochastic simulation is undertaken as before and results are reported in the final column of table 2. The results with the new parameters indicate that the standard deviation of crude oil price volatility has increased for every region, and is much closer to historic volatility (five year moving average). It would be interesting to undertake this comparison for oil products as well. However, a time series for this variable was only obtained for the U.S. The re-parameterized model produces volatility in U.S. oil products price similar to historical estimates (5.84 in the model versus 6.13 historical, whereas 1.47 was the value

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[14] The original capital/energy substitution parameter was also used in the ‘energy-substitution’ unity test; which suggested that the original parameter (1) was too responsive.

using original GTAP-E parameters). Therefore, we conclude that the new specification is far better at reproducing historical volatility in crude oil and gasoline than the original specification and we retain the new parameters for our subsequent policy analysis.

8. Policy Application

In order to further examine the implications of this work, an application common in energy-oriented CGE models (including the GTAP-E model) is now undertaken. The application, a stylized Kyoto emissions trading scenario, is specified for the GTAP-E model, using two sets of parameters (original and revised). The scenario is now briefly outlined, followed by a discussion of the results with special attention to the differences which arise due to the change in parameters.

8.1 Kyoto Emissions Trading Scenario

Along with the construction of the GTAP-E model, Burniaux and Truong (2002) also implemented potential Kyoto non-trading/trading scenarios to illustrate the use of their model. We pick one of those to highlight the importance of the work improving the energy parameters for the model. The application is the implementation of the Kyoto Protocol, while allowing worldwide emissions trading. We follow the shocks implemented by Burniaux and Truong (2002), which corresponded to the expected reductions required of Annex 1 countries in 2012, as drawn from the OECD GREEN model (OECD, 1999, p. 29). As noted by Burniaux and Truong (2002) this Kyoto scenario is highly stylized, since: (i) it only considers fossil fuel-based CO_2 emissions, (ii) it includes abatement targets in the US, and (iii) it assumes global equalization of marginal abatement costs. However, insofar as the purpose of this application is to draw out the implications of mis-specified parameters for climate change policy analysis, this highly simplified scenario is quite attractive[15].

8.2 Results

We first replicated the results of this Kyoto scenario for the old parameters as reported in Burniaux and Truoung (2002); we compare these to the results of the same scenario with the new parameters. The most striking difference is the size of the carbon tax needed for emission reduction. The marginal abatement costs are $9.38 (2001 USD) with the old parameters, but $14.72 with the new set. This suggests that analysis of GHG mitigation policies using the GTAP-E model underestimates marginal abatement costs by 36.3%. Not surprisingly, the higher tax rate also leads to large differences in worldwide[16] welfare costs, which rise from $30,741million to $34,214million[17]. Examining the sources of these efficiency losses (table 5), we see that for countries required to cut emissions (i.e. U.S., Can, EU27, Japan, and Oceania) there is very little change across the two models (e.g. U.S.: $-5,698million with old, $-5,707million with new). In contrast, the non-emission reducing countries show a substantially higher welfare cost resulting from the Kyoto scenario.

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[15] Note that the scenario specifies a decline in emissions for the U.S.; although, the U.S. withdrew from the treaty. However, for a more complete analysis of any climate change analysis, the reductions by the largest emitter (U.S.) should be considered.

[16] We abstain from single region analysis, since those results are sensitive to other issues. Therefore, the discussion is focused on allocative efficiency impacts, not trading or terms of trade (which have small overall world results). Note that allocative efficiency is the reallocation of resources based on the shock.

[17] Welfare as calculated in the GTAP model follows the equivalent variation measure (McDougal, 2001).

Table 5. Decomposition of Global Efficiency Changes under the Kyoto Scenario by Region and Parameter Specification

Region	Original Parameters	Demand Only	Demand & Energy Substitution	New Parameters
USA	-5698	-4126 (0.6)	-5240	-5707
CAN	-961	-1004 (1.0)	-1160	-1132
EU27	-4752	-4552 (0.8)	-8049	-4184
BRAZIL	-225	-244 (1.2)	-300	-234
JAPAN	-1819	-1558 (0.6)	-1282	-834
CHIHKG	-5915	-6274 (1.4)	-6848	-7160
INDIA	-1043	-1223 (1.4)	-1335	-1317
LAEEX	-889	-818 (0.6)	-890	-976
RoLAC	-312	-287 (0.6)	-159	-83
EEFSUEX	-3267	-3393 (1.6)	-3457	-4033
RoE	-379	-548 (1.6)	-731	-436
MEASTNAEX	-2648	-2512 (0.6)	-4243	-5012
SSAEX	-229	-254 (2.0)	-233	-311
RoAFR	-425	-424 (1.6)	-429	-454
SASIAEEX	-276	-307 (1.8)	-313	-369
RoHIA	-543	-531 (0.7)	-478	-393
RoASIA	-565	-614 (1.4)	-664	-652
Oceania	-720	-606 (0.4)	-657	-717
Total	-30666	-29274	-36468	-34002

Note: () indicates the ratio of the new demand elasticity to the original

Table 5 also decomposes global efficiency changes associated with the Kyoto scenario by region, for four different parameter specifications. These changes may be viewed as the “economic effort” associated with attainment of a given Kyoto target. These efficiency changes are distributed around the world, due to the presence of a global trading mechanism wherein Annex I countries can pay non-Annex I countries to abate emissions on their behalf. These efficiency changes correspond to the “dead-weight loss triangles” shown in figure 1. Assume, for example, that D_0 is the original household demand specification for petroleum in the US, and S is supply. The emissions reduction experiment requires the U.S. to reduce quantity, or buy permits, thereby shifting the “effort” to other regions. (Table 6 reports the emissions trading outcomes under different model specifications.) The relatively elastic household demand specification in GTAP-E leads to a large reduction in US petroleum quantity (to Q'_0), as consumers respond to the increase in petroleum prices. The efficiency loss attributable to the tax is the sum of the two triangles, labeled ‘a’ and ‘b’ in Figure 1. The first column of table 5 reports the efficiency changes for all regions under the original parameter settings. Here, we see that the largest changes come about in USA, followed by China, a region which sells $9,693 million in abatement to the Annex I regions (table 6, column China).

When we specify a more inelastic demand (column 2 in tables 5 and 6), it takes a larger increase in price to change quantity. Thus the U.S. responds by purchasing 9% more permits (as indicated in table 6, column 2), and reducing its own volume used by less (as indicated in table 5). Returning to figure 1, this situation can be portrayed by the steeper sloped demand schedule, Q'_1 in figure 1. The efficiency loss is equal to the sum of triangles ‘d’ and ‘e’ in figure 1 and the end result is that the diminished quantity outweighs the effect of the higher price of petroleum, and the USA efficiency loss is less under the more inelastic demand specification. On the other hand, emissions abatement sold by China rises by 8% in this case (table 6, column 2), as does China’s contribution to overall efficiency changes (table 5, column 2).

Adjacent to the entries in the second column of table 5 are a series of parenthetic figures which report the ratio of the new household demand elasticity to the old one. We expect that with a reduction in the household demand elasticity, welfare losses would be reduced, since there would be less of a decrease in volume used and the efficiency changes are driven by volume changes interacting with distortions. Conversely for those regions where the demand elasticity becomes larger in absolute value, i.e. the ratio is greater than 1.0 (e.g., China). This is indeed the case for nearly all countries[18]. For non-emission reducing regions, there is a much smaller impact from the new demand parameters, since these were not reduced as much as for the emission-reducing regions, and in some cases, there were increased.

As a result of the new parameter specifications, the pattern of emissions trading changes, which influences the pattern of global abatement and efficiency changes. Table 6 presents the net emissions trading revenue, and the subsequent ratio (new/old) of the results by parameter specification. Examining first the results of the Kyoto scenario with the original parameters, regions which are specified to reduce emissions, experience a decline in net emissions trading revenue, indicating that they purchase permits. The U.S. and the EU are the largest emitters in the base data; and they are the ones who spend the most on permits. When we introduce the new household demand parameters, all regions experience a further movement in the direction of their original revenue (i.e. the U.S. spends more, hence the ratio is greater than 1), except for the Middle East (MEASTNAEX). Here the reduction in the household demand response essentially has a similar impact to the U.S. Volume used does not decrease by as much as with the original parameters, and the relatively high household expenditures on oil_pdts (MEASTNAEX is the region with the 4th highest expenditure, following the U.S., EU, and Japan) dictates that the region sells less of their emissions permits.

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[18] Canada is the only deviant, which is due to a small change in its elasticity and a large loss in intermediate input use of oil products.

Table 6. Net Emissions Trade Revenue and Subsequent Ratios (new/old), by Region and Parameter Specification

Region	Original Parameters	Demand Only	Demand & Energy Substitution	New Parameters
USA	-12,853	1.09	1.62	1.73
CAN	-1,338	1.03	1.42	1.54
EU27	-5,211	1.03	1.38	1.56
BRAZIL	212	1.10	1.05	1.05
JAPAN	-2,616	1.05	1.50	1.63
CHIHKG	9,693	1.08	1.34	1.43
INDIA	2,660	1.08	1.56	1.67
LAEEX	710	1.03	1.98	2.08
RoLAC	586	1.05	1.41	1.50
EEFSUEX	4,959	1.06	1.63	1.78
RoE	243	1.14	1.49	1.47
MEASTNAEX	1,724	0.97	2.57	2.99
SSAEX	108	1.28	1.57	1.67
RoAFR	540	1.06	1.24	1.36
SASIAEEX	388	1.27	1.58	1.68
RoHIA	496	1.03	1.09	1.12
RoASIA	591	1.10	1.35	1.43
Oceania	-892	1.07	1.61	1.72

We then add the revised energy substitution parameter specification, to the household demand response (column 3: while leaving supply elasticities unchanged) and run the Kyoto experiment again. Energy substitution parameters were reduced by the same factor across all regions and the result is a relatively uniform rise in efficiency costs worldwide, as the size of the requisite global carbon tax rises. The results of the two cases combined indicate that the change in efficiency cost attributable to lesser energy substitution typically outweighs that due to demand response. However, for the U.S., and other countries which had a large reduction in the demand parameters, the changes due to demand response are more significant, such that the overall effect of the two parameter specifications is a smaller efficiency change. Overall, the global efficiency loss due to the

Kyoto scenario in the presence of the new demand specification rises by about $6 billion to $36,468 billion.

Finally, we add the change in supply elasticities to the model. These results are reported in the final columns of tables 5 and 6. More inelastic supplies of energy products mean that the global emissions tax has a stronger impact on market prices. This translates into generally more modest abatement effort in the Annex I countries and more significant effort on the part of the non-Annex I countries. Overall, the efficiency cost of reaching the Kyoto target is somewhat diminished with the smaller supply response in energy sectors. When combined, the changes in demand and supply specifications raise the global efficiency cost of this stylized scenario by $4 billion, or about 13% of the initial estimate.

9. Discussion

CGE models have garnered much use recently, particularly in applications related to energy, climate change, and biofuels. However, with few exceptions, these models have not been validated against historical data. This paper performs such a validation exercise using the widely used/adapted GTAP-E model of energy and climate policy. A careful investigation into the ability of this model to replicate historical price volatility, given medium run stochastic shocks to supply and demand in the world petroleum market, reveals that both demand and supply specifications in this model are too price-elastic. Further investigation suggests that the elasticities of substitution between petroleum and other fuels are too high, as is the consumer demand elasticity for petroleum products in many countries. In addition, supply response in the petroleum sector appears to be too large. After revising the model parameters to bring them in line with estimates from the literature, we obtain a model which is capable of more closely replicating the second moments of the regional petroleum price distributions. We recommend using these revised parameter specifications in future analyses of energy and climate policy

To illustrate the implications of the improved parameter specification for greenhouse gas mitigation costs, we implemented a Kyoto style scenario. Comparison of the results across the two parameter sets yielded some important findings. In particular, the revised model requires a substantially higher carbon tax in order to achieve the desired reduction in emissions and the global welfare cost of the stylized Kyoto scenario rises. We conclude that previous analyses of climate policy using the GTAP-E model – and perhaps other global CGE models -- have likely underestimated the costs of greenhouse gas reduction.

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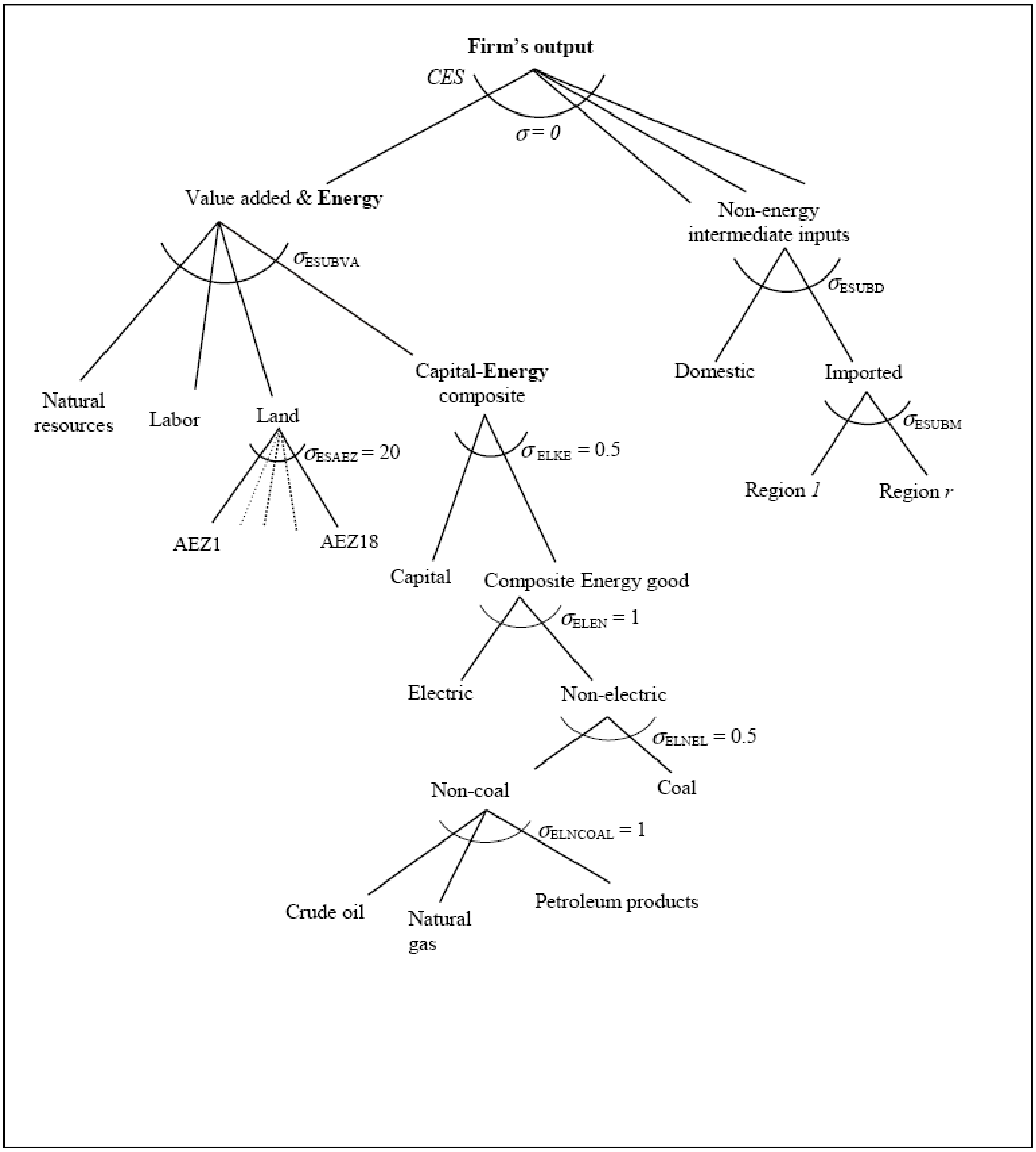
Appendix A

GTAP-Energy Production Structure



Appendix B1
Time Series Models

An Autoregressive Moving Average (ARIMA) model is used and different specifications of the autoregressive and the moving average portions of the ARIMA model are specified; however, the data must also be stationary for this to be a valid modeling approach. With time-series data, a stationary time-series model indicates that the mean, variance, and autocorrelations can usually be well approximated by sufficiently long time averages (Enders, 2003). The following ARIMA model is hypothesized:

$$\hat{P}_t - P_{t-1} = c + \sum_{i=1}^{n} \theta_i (P_{i-1}) + \varepsilon_t + \sum_{i=1}^{n} \phi_i (\varepsilon_{i-1}) \quad (1)$$

where P is observed production ($\hat{P}$ is predicted production), c is the constant, θ is the autoregressive process, ε is the error term, and ϕ is the moving average process.

Autocorrelation functions (both partial and inverse) indicate that the crude oil production data exhibits a trend, i.e. it is non-stationary. The next step is to determine if the trend is deterministic or stochastic. A deterministic trend indicates that there are systematic changes over time, and the proper way to handle this is by modeling the trend within the estimation. One such is:

$$\hat{P}_t = c + \psi_i * t_i + \sum_{i=1}^{n} \theta_i (P_{i-1}) + \varepsilon_t + \sum_{i=1}^{n} \phi_i (\varepsilon_{i-1}) \qquad (2)$$

where P, c, θ, ε and ϕ are the same as in equation (1); and t is the time trend. Stochastic trends give rise to a unit-root, which may be specified as a random walk model, a random walk plus drift model, or a random walk plus noise model.

For the demand-side we use GDP as the driver. . The specifications for the demand models is:

$$\hat{Y}_t - Y_{t-1} = c + \sum_{i=1}^{n} \theta_i (Y_{i-1}) + \varepsilon_t + \sum_{i=1}^{n} \phi_i (\varepsilon_{i-1}) \qquad (3)$$

where Y is the growth of gross domestic product at time t, and the other variables are similar to the discussion of (1).

Appendix B2
Systematic Sensitivity Analysis

Historically, sensitivity analysis was undertaken primarily by Monte Carlo methods; however, systematic sensitivity analysis (SSA) has been shown to provide robust results with substantially fewer draws (Arndt, 1996). Using the Stroud quadratures method, this approach gives approximations to means and standard deviations, with the model only needing to be solved 2*N times (where N is the number of exogenous inputs).

SSA works by using a symmetric triangular distribution to approximate the distribution of residuals from the supply and demand time-series equations. To implement SSA in GTAP, the model is solved for a zero shock to output (for supply) and income[19] (for demand). The next step is to calculate observed crude oil and gasoline price variability, by using external data, in order to compare with the results from the SSA. The desire is to test the model in the context of a policy-neutral experiment. In addition, since the GTAP benchmark data refer to 2001 (version 6.1: Dimaranan, 2006), a period similar to that benchmark should be utilized. Unfortunately, as pointed out earlier, crude oil prices are extremely volatile; therefore, caution must be used in selecting the time period. With these considerations in mind, the 1982-2003 period was chosen to calculate the observed price volatility by region. A five-year moving average was specified to allow for any sudden movements to dissipate, allowing the capture of the true trend of the objective.

The observed measure of crude oil and gasoline price volatility are calculated using data from EIA (2007). The GTAP-E model makes predictions of prices in real

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[19] Income is used as the demand shock, with GDP growth the proxy for the input shocks.

terms, using the global factor prices as the numeraire. However, the EIA price series are nominal and have therefore been deflated by the gross domestic product (GDP) index from International Financial Statistics. Accordingly, the GTAP price predictions were adjusted by a GDP deflator before undertaking the validation comparison. The model also makes predictions in terms of percentage changes from base levels. This is taken into account when calculating the validation criterion, since the measure of price volatility is the standard deviation of percentage price changes.

Appendix C1
Industries, Commodities, and their Corresponding GTAP Notation

Industry Name	Commodity Name	Description	GTAP Notation
CrGrains	CrGrains	Cereal Grains	gro
OthGrains	OthGrains	Other Grains	pdr, wht
Oilseeds	Oilseeds	Oilseeds	osd
Sugarcane	Sugarcane	Sugarcane and sugarbeet	c_b
Cattle	Cattle	Bovine Cattle, sheep and goats	ctl, wol
Nonrum	Nonrum	Non-ruminants	oap
Milk	Milk	Raw Milk	rmk
Forestry	Forestry	Forestry	frs
Ethanol2	Ethanol2	Ethanol produced from sugarcane	eth2
OthFoodPdts	OthFoodPdts	Other food products	b_t, ofdn
VegOil	VegOil	Vegetable oils	voln
ProcLivestoc	ProcLivestoc	Meat and dairy products	cmt, mil, omt
OthAgri	OthAgri	Other agriculture goods	ocr, pcr, pfb, sgr, v_f
OthPrimSect	OthPrimSect	Other primary products	fsh, omn
Coal	Coal	Coal	coa
Oil	Oil	Crude oil	oil
Gas	Gas	Natural gas	gas, gdt
Oil_Pcts	Oil_Pcts	Petroleum and coal products	p_c
Electricity	Electricity	Electricity	ely
En_Int_Ind	En_Int_Ind	Energy intensive industries	crpn, i_s, nfm
Oth_Ind_Se	Oth_Ind_Se	Other industry and services	atp, cmn, cns, dwe, ele, fmp, isr, lea, lum, mvh, nmm, obs, ofi, ome, omf, osg, otn, otp, ppp, ros, tex, trd, wap, wtp, wtr
EthanolC	Ethanol1	Ethanol produced from grains	eth1
	DDGS	DDGS	ddgs
Biodiesel	Biodiesel	Biodiesel	biod
	BDBP	BDBP	bdbp

Appendix C2

Regions and their Members

Region	Corresponding Countries in GTAP
USA	United States
CAN	Canada
EU27	Austria; Belgium; Bulgaria; United Kingdom; Cyprus; Czech Republic; Germany; Denmark; Spain; Estonia; Finland; France; Greece; Hungary; Ireland; Italy; Lithuania; Luxembourg; Latvia; Malta; Netherlands; Poland; Portugual; Romania; Slovakia; Slovenia; Sweden
BRAZIL	Brazil
JAPAN	Japan
CHIHKG	China and Hong Kong
INDIA	India
LAEEX	Argentinal; Columbia; Mexico; Venezuela
RoLAC	Chile; Peru; Uruguay; Rest of Andean Pact; Central America; Rest of the Caribbean; Rest of Free Trade Area of the Americas; Rest of North America; Rest of South America
EEFSUEX	Russia; Rest of EFTA; Rest of Former Soviet Union
RoE	Albania; Switzerland; Croatia; Turkey; Rest of Europe
MEASTNAEX	Botswana; Tunisia; Rest of Middle East; Rest of North Africa
SSAEX	Madagascar; Mozambique; Malawi; Tanzania; Uganda; Rest of South African Customs Union; Rest of Southern African Development Community; Rest of Sub-Saharan Africa; Zimbabwe
RoAFR	Morocco; South Africa; Zambia
SASIAEEX	Indonesia; Malaysia; Vietnam; Rest of Southeast Asia
RoHIA	Korea; Taiwan
RoASIA	Bangladesh; Sri Lanka; Philippines; Singapore; Thailand; Rest of East Asia; Rest of South Asia
Oceania	Australia; New Zealand; Rest of Oceania