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Validating energy-oriented CGE models ☆

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ABSTRACT

Although CGE models have received heavy usage — particularly in the analysis of broad-based policies relating to energy, climate and trade, 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. In this paper, we employ a novel approach to the validation of a widely utilized global CGE model — GTAP-E. By comparing the variance of model-generated petroleum price distributions – driven by historical demand and supply shocks to the model – with observed five-year moving average price distributions, we conclude that energy demand in GTAP-E is far too price-elastic over this medium run time frame. After incorporating the latest econometric estimates of energy demand and supply elasticities, we revisit the validation question and find the model to perform more satisfactorily. As a further check, we compare a deterministic global general equilibrium simulation, based on historical realizations over the five year period: 2001–2006, during which petroleum prices rose sharply, along with growing global energy demands. As anticipated by the stochastic simulations, the revised model parameters perform much better than the original GTAP-E parameters in this global, general equilibrium context.

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1. Introduction

Computable general equilibrium (CGE) models have garnered much attention recently for use in economic analysis, due in large part to their ability to simulate the impacts of prospective policies taking into account inter-sectoral and international interactions. 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 an examination of the energy-related elasticities, and thus the validity, of a widely utilized[1] CGE model 'GTAP-E' (Burniaux and Truong, 2002). Although we focus on this single model in the present paper, the methodology proposed here can readily be applied to the validation of other CGE models.[2]

The importance of CGE parameters and model validation has been recognized by many authors (e.g., Hertel, 1999; Welsch, 2008; Whalley, 1985). The current focus on global energy and energy price volatility highlights the importance of providing a sound econometric basis for key energy parameters used in CGE models, such as the GTAP-E model. In this context, we focus our efforts specifically on petroleum markets, since oil is the most important component of the energy economy. It is also one of the most volatile commodities, both in terms of production and prices (Adelman, 1999). Examining commodity prices from 1985–1994, Plourde and Watkins (1998) found that crude oil prices tend to be easily as volatile as 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 0.225) is greater than for the other commodities. Indeed it is shown to be greater than that for rice (0.191) which is often considered to be one of the most volatile agricultural commodities (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. (2007) offers an approach to model validation that seems particularly relevant for our work on 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 national wheat production. The probability distribution of supply shocks was

☆ Views expressed here are solely the authors' and do not necessarily represent those of USDA or ERS.

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[1] See Banse et al. (2008); Berrittella et al. (2005, 2006); Bosello et al. (2007); Gan and Smith (2006); Hertel et al. (2010); Kemfert et al. (2006); Nijkamp et al. (2005); Ronneberger et al. (2006); Rosen (2003); Taheripour et al. (2010).

[2] While it could be the case that models which are not as well documented as the GTAP-E model have been put through a rigorous validation procedure, the motivation for this paper is that there is a lack of well-documented validation efforts publicly available.

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obtained from a time-series model designed to elicit the randomness inherent in inter-annual output changes at the national level.

Extending their approach to petroleum markets, where demand-side shocks are also important, we include both supply- and demand-side shocks to examine crude oil and gasoline price volatility. Time-series models are built to capture systematic movements over time in oil production (supply-side shocks) and GDP (demand-side shocks), with the resulting residuals used to create probability distributions for random shocks to the underlying supply and demand schedules for petroleum. Unlike Valenzuela et al. (2007), who consider short run, inter-annual variation in commodity prices, we focus on supply and demand shocks, and price distributions, based on a medium run (five year) time horizon — as this is the relevant length of run for the GTAP-E model. Model-based price distributions are then compared (the GTAP-E model is used in both cases — , first with the old parameters then with the new ones) *in order to determine which parameter set best replicates historical volatility in the five-year moving average petroleum price series*. 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 these medium run stochastic simulations indicate that the existing GTAP-E model does not perform well against the historical record, leading to the conclusion that the energy parameters in the original GTAP-E specification are mis-specified. In particular, the old energy substitution parameters appear to be much too large. We find that the model with new parameters, based on more recent econometric estimates, is better able to replicate historical price volatility. This improves our confidence in the performance of the modified GTAP-E framework.

We further explore the implications of the revised model by performing a stylized, deterministic, medium run historical global general equilibrium simulation in which we shock population, labor, capital, investment, oil prices, and economy-wide, total factor productivity in each region by "observed" changes over the 2001–2006 period.[3] While this simulation does not have enough richness to capture differential sectoral changes in each region (largely due to the common regional TFP factor), it is sufficient to give a broad sense of shifts in regional and global energy demands. This was a period of rapidly rising demands, accompanied by rising oil prices (crude petroleum prices rose by 154% over the 2001–2006 period). The global economy grew by about 54% and global purchases of petroleum rose by about 10% despite the sharp price increase in this product, suggesting a rather price-inelastic demand.

We find that the existing GTAP-E model is unable to capture these broad changes in energy markets. Medium run demand in this model is too price-elastic, such that the outward shift in demand is insufficient to prevent a sharp decline in global petroleum consumption over this period. In contrast, the revised model which we propose does predict the rise in global consumption over this period. This work thus highlights the importance of providing a firm econometric foundation for CGE models.

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) criticizes CGE models for performing poorly in evaluating the impacts of the North America Free Trade Agreement. In this case, he suggests that this is likely due to inadequate treatment of the emergence of new varieties in trade.

With the exception of the Valenzuela et al. (2007) paper mentioned previously, all of these previous studies have focused on deterministic simulation of an historical period. This is fundamentally limited by our inability to observe all of the exogenous variables in the model. In particular, technical change is a key driver of general equilibrium outcomes, but it is poorly measured and is often treated as a residual in such historical simulations. Therefore, in this paper, we take a stochastic simulation approach which focuses on the higher moments of the model predictions.

3. The GTAP-E model and its use

The CGE model that will be examined here is the GTAP-E model, outlined in Burniaux 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 several 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 CO_2 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 nested CES production structure of GTAP-E is shown in Appendix A.

Uses of GTAP-E have ranged from biofuels (Banse et al., 2008; Hertel et al., 2010; Taheripour et al., 2010) to climate-change-induced changes in tourism demand (Berrittella et al., 2005), to the costs of climate mitigation policies[4] (Nijkamp et al., 2005; Kemfert et al., 2006). 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 (2006) 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 that have utilized GTAP-E as a starting point, 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

[3] Total factor productivity is unobserved, so this must be inferred from growth in real GDP.

[4] We note that the GTAP-E model is not ideal for long-term (i.e. 50 year) climate policy analysis. Rather for this sort of analysis the GTAP data base is often used, along with more detailed climate modeling systems.

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,[5] 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[6] 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 dictates a medium-run[7] (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, since we expect the derived demand elasticity for energy 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 crude oil as both intermediate inputs and final consumer goods, we do not perturb firm level demands for crude oil; rather, we focus on a general indicator of economic activity which is readily measured — Gross Domestic 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 variable 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.[8] This variable is calculated as $100 * \sqrt{V}/\mu$(i.e., the square root of the variance of the estimated residuals divided by the mean value of production or GDP multiplied by 100%). This effectively summarizes variability in the non-systematic aspect of production or GDP in each region from 1980 to 2005 (sectors and regions are defined in Appendices C1 and C2). As can be seen from the entries in Table 1, 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. In the case of GDP (column 2 of Table 1), 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.

Table 2 reports the normalized standard deviation of the medium run percentage changes in observed, crude oil prices[9] (5 year moving averages) in the first column. The second column reports the GTAP estimated price 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 is invalid, in the sense that it does not adequately explain crude oil and gasoline price volatility. This suggests the need to re-examine the basic supply and demand parameters underpinning the model.

Table 1
Time-series residuals, used as inputs for the stochastic simulation analysis.

Region	Normalized standard deviations of residuals: 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

Notes: Refer to Appendix C for region specification. Also, there was insufficient data for RoHIA and RoAFR with respect to production. Standard deviations are divided by mean production or GDP.

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.

Region	Observed price changes	GTAP results: Original parameters	New household & supply 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 price. 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).[10] Since the goal of this work is to validate the model for energy, and as indicated by usage shares, no energy source is more important than petroleum products, this sector will be the focal point of our analysis.[11]

[5] See Arndt (1996) and Pearson and Arndt (2000) for a detailed discussion the procedures used. Appendix B1 outlines its use here.
[6] Refer to Appendix B2 for a detailed discussion on the estimation of these models.
[7] For GE models the medium-run is typically specified as the time frame when capital and labor are perfectly mobile.
[8] Estimates for the time-series models are available upon request.
[9] Results are similar for petroleum products (gasoline), hence they are not presented.
[10] Refer to Hertel (1997) for a complete decomposition in the case of the GTAP model.
[11] 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.

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 (−0.27)	−0.17 (−0.11)	−0.18 (−0.18)	−1.03 (−0.56)
Canada	−0.72 (−0.37)	−0.13 (−0.12)	−0.57 (−0.57)	−1.42 (−1.05)
EU	−0.69 (−0.38)	−0.17 (−0.14)	−0.46 (−0.40)	−1.32 (−0.92)
Brazil	−0.77 (−0.38)	−0.07 (−0.07)	−0.30 (−0.30)	−1.13 (−0.74)
Japan	−0.82 (−0.33)	−0.14 (−0.04)	−0.06 (−0.06)	−1.03 (−0.43)
ChiHkg	−0.79 (−0.36)	−0.11 (−0.14)	−0.18 (−0.18)	−1.09 (−0.68)
India	−0.65 (−0.26)	−0.10 (−0.14)	−0.24 (−0.24)	−0.99 (−0.64)
LAEEX	−0.57 (−0.30)	−0.12 (−0.07)	−0.85 (−0.84)	−1.54 (−1.20)
RoLAC	−0.65 (−0.42)	−0.14 (−0.11)	−0.80 (−0.78)	−1.59 (−1.31)
EEFSUEX	−0.72 (−0.24)	−0.07 (−0.06)	−0.76 (−0.75)	−1.55 (−1.05)
RoE	−0.88 (−0.53)	−0.33 (−0.36)	−0.12 (−0.12)	−1.33 (−1.01)
MEASTNAEX	−0.45 (−0.14)	−0.08 (−0.01)	−1.15 (−1.12)	−1.67 (−1.28)
SSAEX	−0.88 (−0.67)	−0.33 (−0.38)	−0.44 (−0.44)	−1.65 (−1.49)
RoAFR	−0.55 (−0.18)	−0.08 (−0.04)	−0.57 (−0.56)	−1.20 (−0.78)
SASIAEEX	−0.69 (−0.40)	−0.23 (−0.28)	−0.46 (−0.46)	−1.37 (−1.14)
RoHIA	−0.99 (−0.61)	−0.10 (−0.04)	−0.47 (−0.47)	−1.56 (−1.12)
RoASIA	−0.64 (−0.36)	−0.14 (−0.15)	−0.84 (−0.82)	−1.62 (−1.33)
Oceania	−0.72 (−0.28)	−0.14 (−0.05)	−0.24 (−0.22)	−1.09 (−0.56)

* Agents' price elasticity of demand are divided by their respective share in total sales so that the sum of these share-weighted price elasticities gives the total, GE demand elasticity facing producers in a given region.

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 percentage change in aggregate quantity demanded is then each region's medium run 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 (−0.99 for India) and is more than −1.5 for seven of the eighteen regions under the original parameter settings. Notice that the elasticity is particularly high for the Middle East and North Africa (MEASTNAEX), which is largely due to the price responsiveness of export demand.[12] The trade elasticities driving these results were econometrically estimated on cross-section data 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' derived demands represent the dominant contributor to domestic quantity responses 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.

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 US which have produced a wide range of results.[13] The recent work by Bernard (2008) is utilized here. Estimates for other countries are drawn from Sterner et al. (1992): EU [−1.62, −0.37], Turkey (−0.61), Japan (−0.76); 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 demand for gasoline and finds they vary by household type, with the range spanning [0.29,0.94] for the US and [0.44,1.23] for Canada. Wohlgemuth (1997) reviewed the estimates of income elasticities of demand for OECD and non-OECD countries and points out that the literature 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 shows that the price elasticity of demand for gasoline is becoming more inelastic.

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 US. 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 (2009) 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 long-run elasticities.

Most of the original GTAP-E model specified parameters were closely aligned with Stern's view of the world, i.e. they were specified at unity. We investigate his assertion by undertaking a sequence of stochastic simulations. We first use only the new household demand and supply response parameters; however, we keep the original energy substitution parameters in this simulation analysis. 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 obtain less than half the observed price volatility (except for Oceania). We conclude that the firm's energy substitution possibilities are 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 (Cho et al., 2004; Jones, 1995; Ma et al., 2008; Renou-Maissant, 1999; Urga, 1999; and Urga and Walters, 2003) which exhibited the desired characteristics (e.g. relatively recent studies at a higher level of aggregation). These estimates are used to determine the targets for inter-fuel substitution. The resulting parameters used

[12] 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.

[13] 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.

Table 4
Literature price elasticities of demand considered for the new parameters. Note the countries in parentheses that represent the country specific study chosen for that region.

Region	Long-run household demand		Long-run household income	
USA	−0.20	Bernard (2008)	[0.29,1]	Nicol (2003)
Canada	[−0.83,−0.47]	Nicol (2003)	[0.44,1.30]	Nicol (2003)
EU	[−1.62,−0.37]	Sterner et al. (1992)	[0.71,2.03]	Sterner et al. (1992)
Brazil	−0.26	Wohlgemuth (1997)	[0.88,1.10]	Wohlgemuth (1997)
Japan	−0.76	Sterner et al. (1992)	0.77	Sterner et al. (1992)
China			[0.91,0.95]	Sterner et al. (1992)
India	−0.42	Ramanathan (1999)	[1.39,2.68]	Ramanathan (1999)
LAEEX (Mexico)	−0.21	Wohlgemuth (1997)	[0.99,1.72]	Wohlgemuth (1997)
RoLAC				
EEFSUEX				
RoE (Norway, Turkey)	[−0.90,−0.61]	Sterner et al. (1992)	[1.29,1.32]	Sterner et al. (1992)
MEASTNAEX (Kuwait)	−0.46	Eltony and Al-Mutairi (1995)	[0.32,0.99]	Wohlgemuth (1997)
SSAEX (Nigeria)	−0.53	Wohlgemuth (1997)	[1,1.28]	Wohlgemuth (1997)
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)

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.[14] 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 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.[15]

With the GTAP-E model recalibrated to these new elasticities of substitution in production, 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 the 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 medium run 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 US. The re-parameterized model produces volatility in US oil products price similar to historical estimates (5.84 in the model versus 6.13 historical, versus 1.47 using the 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.

8. Deterministic historical simulation of the model

Stochastic simulation of the global general equilibrium model has provided us with a useful vehicle for validating the global, general equilibrium model with respect to its performance in the energy markets. However, there is another way of checking the plausibility of the model's overall performance with respect to energy markets, and that is to undertake a full-blown, deterministic historical simulation in which all observable exogenous variables are simultaneously shocked. As noted in the introduction, historical simulations have been previously used to test whether CGE models capture essential features of national, regional or global economies (e.g., Kehoe et al., 1995; Fox, 2004; Dixon and Rimmer, 2009). In this case, we wish to ask a simple question: Given the strong rise in oil prices over the 2001–2006 period, accompanied by strong growth in the global demands, is the CGE model capable of predicting the correct direction of change in regional/global use of petroleum products?

Due to the unobserved nature of technical change — which a key driver of long run economic growth and structural change, as well as the lack of global data on policy changes over this period, our historical simulation is necessarily stylized. In particular, we shock only population, labor force (both skilled and unskilled), capital stock, investment, and technical progress. These growth rates are reported, by model region, in Table 5. Here, we see relatively rapid rates of capital accumulation in capital stock in China and India, leading to high rates of economic growth in those regions. In the EU, growth is much more sluggish, with lower rates of population, labor force growth, and capital accumulation.

This global economic growth generates an outward shift in the global demand for petroleum products, which, if prices had remained unchanged, would have boosted global consumption by 17%. Of course, prices did not remain unchanged; rather they rose by 154%, which brings in the question of the price elasticity of demand. From Fig. 1,[16] it is clear that if energy demand is price responsive, overall

[14] Koetse et al. (2008) also provide a meta-analysis for these estimates. Results from their work indicate that an elasticity of 0.25 would be reasonable, albeit at the lower end of their [0.18,0.52] cross-price elasticity range.

[15] 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.

[16] Specifically, Fig. 1 represents an outward shift in demand (due to an increase in population and other effects) and the increase in petroleum products prices (represented as a movement up the demand schedule). In Fig. 1, demand is elastic, such that the effects of the demand shift and the price increase reduce quantity demanded. In Fig. 1b, demand is inelastic, and the same shift in demand and increase in price leads to an increase in quantity demanded.

Table 5
Demand and supply drivers, 2001–2006 percentage changes.
Source: U.S. census bureau (population); GTAP-D baseline (labor, capital, investment, and GDP); and model results (technological change).

Region	Determinants of economic growth: Population % Change	Labor supply % change: Unskilled	Labor supply % change: Skilled	Capital % Change	Investment % Change	TFP % Change	Real GDP % Change
USA	4.4	6.3	6.0	24.6	17.0	1.1	17.0
CAN	4.1	7.7	7.4	20.2	14.6	0.8	14.6
EU27	0.5	1.4	2.4	14.9	10.1	0.8	10.0
BRAZIL	6.1	1.0	20.6	16.5	13.9	0.9	13.9
JAPAN	0.2	0.7	−2.2	15.5	11.1	1.4	11.1
CHIHKG	3.4	4.4	19.2	64.5	46.3	2.8	45.5
INDIA	7.5	9.5	29.5	36.6	34.8	2.7	34.8
LAEEX	7.2	6.5	27.0	14.4	12.5	0.2	12.5
RoLAC	8.3	9.1	30.3	24.2	17.0	0.0	17.0
EEFSUEX	−0.9	2.2	5.5	14.8	30.9	3.6	29.8
RoE	6.3	5.5	19.0	11.4	16.3	1.8	17.3
MEASTNAEX	9.8	13.4	24.2	22.4	22.5	1.8	21.3
SSAEX	11.4	14.4	20.2	22.6	23.4	1.8	20.7
RoAFR	4.9	8.9	11.9	8.6	17.4	1.5	16.9
SASIAEEX	6.6	12.1	33.3	27.5	25.8	1.2	25.2
RoHIA	2.8	−3.8	16.4	29.2	26.3	2.2	26.1
RoASIA	9.2	11.1	25.6	22.5	27.4	2.0	28.0
Oceania	6.4	8.0	6.5	22.2	18.5	0.0	18.5

consumption would be expected to decline in the face of the increase in the price of petroleum products over the period. Yet this was not the case. As shown in the first column of Table 6, observed, global consumption rose by about 10%. This suggests a much more inelastic, five year demand schedule, as portrayed in the bottom panel of Fig. 1.

Before turning to the results, we note that this historical period coincides with a worldwide boom in biofuel production — led by the US and the EU, as well as Brazil. Hertel et al. (2010) use a modified GTAP model to analyze this growth in biofuels. They find that, in the US this growth was fueled by a ban on competing fuel additives (MTBE), as well as higher oil prices. In the EU, this was fueled by a rise in subsidies, and less so by the rise in fuel prices. When combined, with the growth in sugarcane-based ethanol in Brazil, those authors show that this biofuel boom had a significant impact on global oil demand and prices. For this reason, we need to also take these factors into account in our historical analysis, and we adopt the 2001–2006 shocks from their study.

Columns 2–4 in Table 6 report the model predictions for regional consumption of petroleum products, using alternative specifications of the GTAP-E model. Column 2 reports the predictions with the original GTAP-E parameters. Rather than rising by the observed 10%, global consumption of petroleum actually falls by nearly 20% under this model specification. This is another clear indication that energy demand is far too elastic in the GTAP-E model.

Modifying the consumer demand elasticities moderates the decline in consumption somewhat (column 3), but it still falls by nearly 17% globally. We might expect a larger impact (recall that there were substantial changes to household demand for oil products, i.e. gasoline); however, firms' responsiveness is the most important piece of oil products demand (recall Table 3).[17]

The final column in Table 6 shows the prediction using the revised model parameters. Now, rather than falling, global petroleum product consumption rises as expected, although this rise is still short of the observed change. This, more modest, rise in oil products use predicted by the model is due to the fact that we have not shocked other energy prices directly. With rising oil prices, owners of other energy substitutes (e.g., coal) were also able to raise their prices over this period. As a consequence, the model over-predicts the extent of inter-fuel substitution during this historical period, thereby under-estimated the growth in petroleum product demand.

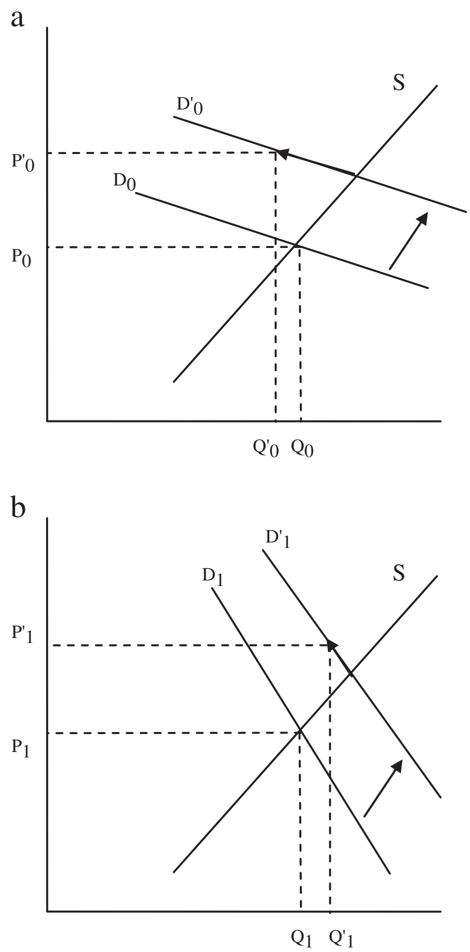

Fig. 1. a. outward shift in petroleum demand in the face of elastic demand results in a decline in the quantity consumed. b. outward shift in petroleum demand in the face of inelastic demand results in a rise in the quantity consumed.

[17] Household demand for oil products does in fact decline by much less with the new demand parameters (e.g., for the U.S. household demand declined by 13.5% with the old parameters, but only −3.1% with the new demand parameters).

Table 6
Percentage change in oil products output by historical outcome and model parameter specification.
Source: energy information agency statistics on oil products consumption, and model results.

Region	Historical outcome	Model predictions: Original parameters	Demand only	New parameters
USA	5.29	−21.85	−18.35	2.48
CAN	9.05	−18.56	−17.90	1.50
EU27	1.82	−23.32	−21.88	−5.68
BRAZIL	3.67	−20.24	−19.62	−0.20
JAPAN	−3.96	−13.35	−10.33	6.14
CHIHKG	47.69	3.24	3.34	28.72
INDIA	23.22	−15.02	−16.12	6.64
ROW	13.47	−20.55	−19.59	−0.16
Total	9.98	−18.41	−16.81	2.60

Given these limitations, as well as the stylized nature of this historical simulation (TFP does not vary by sector, no treatment of petroleum stocks, etc.), the discrepancy between the GTAP estimated results and the historical outcome is hardly surprising. But it is reassuring that the revised model gets the broad changes right. Combining this, with the evidence from our stochastic simulations, we conclude that the revised model offers a valid medium term representation of global petroleum markets.

9. Discussion

CGE models have garnered much use recently; however, with few exceptions, these models have not been validated against historical data. This paper performs such a validation exercise using the publicly available, widely used/adapted GTAP-E model of energy. A careful investigation into the ability of this model to replicate historical price volatility, given medium run (five year moving average) stochastic shocks to supply and demand in the world petroleum market, reveals that the model is incapable of producing historically observed volatility. Further investigation suggests that the elasticities of substitution between petroleum and other fuels are also 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 observed regional petroleum price distributions. We recommend using these revised parameter specifications in future analyses using the GTAP-E model.[18] To further evaluate the implications of the improved parameter specification we examine the ability of the GTAP-E model to replicate fundamental changes in the global petroleum products market over the 2001–2006 period. This was a period of rapidly increasing demand, and sharply rising prices. However, despite a rise in global average petroleum prices of 154% over this period, petroleum consumption also rose by 10%. The original GTAP-E model is incapable of reconciling these facts, due its elastic demand for petroleum. However, the modified model delivers a much more satisfying prediction for global petroleum products usage. In short, validation of CGE models is essential if they are to be more useful and influential in future debates over economic policies.

The CGE model used here is suitable for a medium-run time-frame; it does not attempt to come to grips with dynamic adjustment processes or long run responses in the presence of endogenous capital accumulation. In order to accurately capture these aspects of the economy's response to an energy price shocks, a dynamic model is needed. An example of the kind of model that might be well-suited to such analysis is offered by Babiker et al. (2009a,b) who explore the implications of capital vintaging as well as forward-looking behavior in the context of climate policy analysis.

[18] And as one reviewer pointed out, CGE modelers should be diligent in ensuring that their model specifications (e.g., parameters) are adequate to consider the time-frame their model is meant to capture.

Appendix A. Supplementary data

Supplementary data to this article can be found online at doi:10.1016/j.eneco.2011.01.005.

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