Computable General Equilibrium Models for Policy Evaluation and Economic Consequence Analysis

Ian Sue Wing

Dept. of Earth & Environment, Boston University, 675 Commonwealth Ave., Boston MA 02215

isw@bu.edu

Edward J. Balistreri

Division of Economics and Business, Colorado School of Mines, 816 15th Street, Golden CO 80401

ebalistr@mines.edu

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ABSTRACT

This chapter reviews recent applications of computable general equilibrium (CGE) modeling in the analysis and evaluation of policies which affect interactions among multiple markets. At the core of this research is a particular approach to the data and structural representations of the economy, which we elaborate through the device of a canonical static multiregional model. We adapt and extend this template to shed light on the structural and methodological foundations of simulating dynamic economies, incorporating "bottom-up" representations of discrete production activities, and modeling contemporary theories of international trade with monopolistic competition and heterogeneous firms. These techniques are motivated by policy applications including trade liberalization, development, energy policy and greenhouse gas mitigation, the impacts of climate change and natural disasters, and economic integration and liberalization of trade in services.

1 INTRODUCTION

While economic research has historically been dominated by theoretical and econometric analyses, computational simulations have grown to satisfy the ever-expanding demand for the assessment of policies in a variety of settings. This third approach complements traditional economic research methods by marrying a rigorous theoretical structure in an empirically informed context. This chapter offers a review of computable general equilibrium (CGE) simulations, which have emerged as the workhorse of prospective characterization and quantification of the impacts of policies which are likely to affect interactions among multiple markets.

At its core, CGE modeling is a straightforward exercise of "theory with numbers", where the latter are dervied from input-output economic accounts and econometric estimates of key parameters. Advances in computing power and numerical methods have made it possible to specify and solve models with increasingly complex structural representations of the economy. These do far more than generate detailed information on the likely impacts of policies under consideration—their basis in theory enables researchers to pinpoint the economic processes that give rise to particular outcomes, and establish their sensitivity to various input parameters.

Our goal is to rigorously document key contemporary applications of CGE models to the assessment of the economic impacts of policies ranging from tax reforms to the mitigation and adaptation of global climate change. Throughout, we focus on the structural representation of the economy. In section 2 we begin by deriving the theoretical structure of a canonical static multi-regional simulation. This model is structurally simple but of arbitrary dimension, and is sufficiently general to admit the kinds of modifications necessary to address a wide variety of research questions and types of policies. We first demonstrate how our canonical model is general case of ubiquitous single region open-economy models with an

Armington structure, and show how the dynamics of capital accumulation may be introduced as a boundary condition of the economy (sections 2.2 and 2.3). In section 3 we illustrate the application of the canonical model in areas which are both popular and well-studied—international, development and public economics (section 3.1), emerging—energy economics and greenhouse gas emission abatement (section 3.2) and novel—climate change impacts and natural hazards (section 3.3). Section 4 moves beyond mere applications to document two prominent extensions to the canonical framework: the incorporation of discrete technology detail into representation of production in the sectors of the economy (with a focus on the electric power sector—section 4.1), and the representation of modern theories of trade based on heterogeneous firms and the implications for the effects of economic integration (sections 4.2 and 4.3). Section 5 concludes.

2 THE CANONCIAL MODEL

The economic principles underlying a standard closed-economy CGE model are well explained in pedagogic articles such as Sue Wing (2009, 2011). To conserve space we use these studies as the point of departure to derive the theoretical structure of a static open-economy multi-regional CGE model that will be the workhorse of the rest of this chapter, and, indeed, has emerged as the standard platform for international economic simulations since its introduction by Harrison et al. (1997a,b) and Rutherford (2005).

2.1 A Static Multiregional Armington Trade Simulation

The pivotal feature of our model is inter-regional trade in commodities, which follows the Armington (1969) constant elasticity of substitution (CES) specification. A region's demands of each commodity are satisfied by an "Armington" composite good, which supplied by aggregating together domestic and imported varieties of the commodity in question. The import supply composite is in turn a CES aggregation of quantities of the commodity produced in other regions, at prices which reflect the markup of transport margins over domestic production costs. These bilateral commodity movements induce derived demands for international freight transport services, whose supply is modeled as a CES aggregation of regions' transportation sector outputs at producer prices.

There are six institutions in the multiregional economy: within each region, households (I1), investment goods-producing firms (I2), commodity-producing firms (I3), domestic/import commodity aggregators (I4) and import agents (I5), and, globally, international commodity transporters (I6). As in Sue Wing (2009, 2011), households are modeled as a representative agent who derives utility from the consumption of commodities, and is endowed with internationally immobile factors of production which are rented to domestic goods-producing firms. In each region, commodity producers in a particular industry sector are modeled as a representative firm that combines inputs of primary factors and intermediate goods to generate a single domestic output.

The key departure from the familiar closed-economy model is that domestic output is sold to commodity aggregators or exported abroad at domestic prices. Regional aggregators of domestic and imported commodities are modeled as a representative firm that combines domestic and imported varieties of each commodity into an Armington composite good, which in turn is purchased by the industries and households in the region in question. The imported variety of each commodity is supplied by import agents which are modeled as a representative firm denominated over trade partners' exports. Finally, each region exports some of the output of each of its transportation sectors to international shippers, who are modeled as a global representative firm. Interregional movements of goods generate demands for international transportation services, with each unit of exports requiring the purchase of shipping services across various modes. Thus, the economy's institutions are linked by

Figure 1: Multiregional Accounting Framework

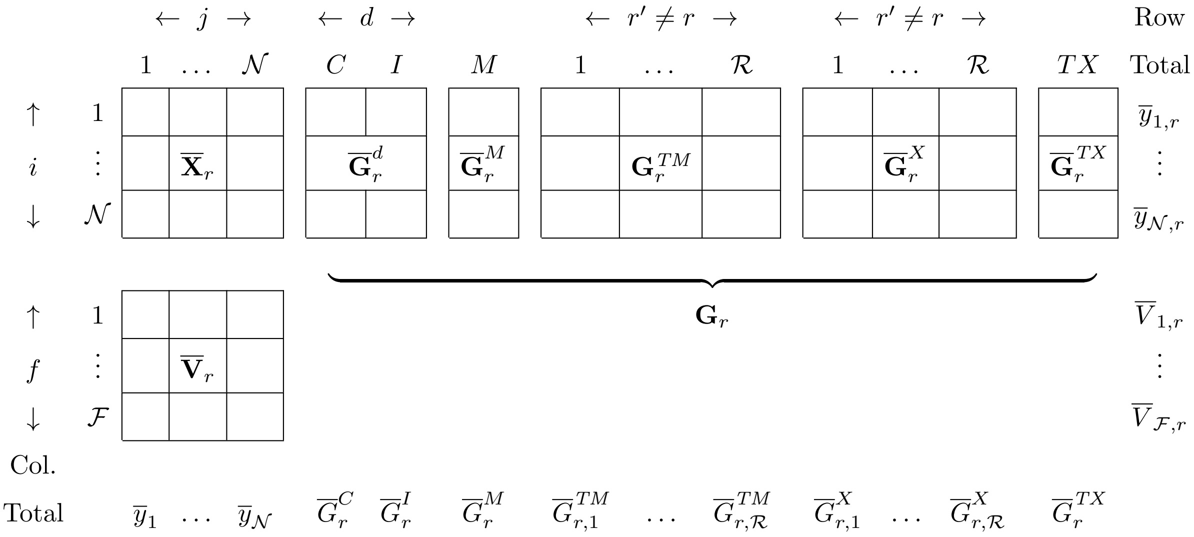
A. Sets

Regions	$r = \{1, \ldots, \mathcal{R}\}$
Commodities	$i = \{1, \ldots, \mathcal{N}\}$
Industries	$j = \{1, \ldots, \mathcal{N}\}$
Primary factors	$f = \{1, \ldots, \mathcal{F}\}$
Domestic demands	$d = \{$consumption (C), investment $(I)\}$
Transportation services	$s \subset i$

B. Arrays

Interindustry commodity flows	$\overline{\mathbf{X}}_r$
Primary factor inputs to sectors	$\overline{\mathbf{V}}_r$
Final commodity demands	$\overline{\mathbf{G}}_r$
Of which:	
Domestic final commodity uses	$\overline{\mathbf{G}}_r^d$
Aggregate commodity imports	$\overline{\mathbf{G}}_r^M$
International transport service demands	$\overline{\mathbf{G}}_r^{TM}$
Export supplies to other regions	$\overline{\mathbf{G}}_r^X$
International transport service supplies	$\overline{\mathbf{G}}_r^{TX}$

C. Benchmark Social Accounting Matrix



five markets: supply and demands for domestic goods (M1),the Armington domestic-import composite (M2), imported commodities (M3), international shipping services (M4), and primary factors (M5).

The values of transactions in these markets are recorded in the cells of interlinked regional input-output tables in the form of the simplified social accounting matrix (SAM) in Figure 1. This input-output structure is underlain by the price and quantity variables summarized in Table 1, in which markets correspond to the SAM's rows and institutions correspond to

Table 1: Summary of Variables in the Canonical Model

A. Institutions

		Output				Inputs			
		Price		Quantity		Price		Quantity	
(I1)	Households	$\mathscr{E}_r$	Unit expenditure index	u_r	Utility level	$p^A_{i,r}$	Armington goods price	$g^C_{i,r}$	Consumption demand for Armington good
(I2)	Investment goods producers	p^I_r	Investment price	G^I_r	Aggregate investment	$p^A_{i,r}$	”	$g^I_{i,r}$	Investment demand for Armington good
(I3)	Commodity producers	$p^D_{j,r}$	Domestic goods price	$y_{j,r}$	Domestic goods supply	$p^A_{i,r}$	”	$x_{i,j,r}$	Intermediate demand for Armington good
						$w_{f,r}$	Factor price	$v_{f,j,r}$	Factor demand
(I4)	Domestic/import goods aggregators	$p^A_{i,r}$	Armington goods price	$q^A_{i,r}$	Armington goods supply	$p^D_{i,r}$	Domestic goods price	$q^D_{i,r}$	Domestic goods supply
						$p^M_{i,r}$	Imported goods price	$q^M_{i,r}$	Imported goods supply
(I5)	Import agents	$p^M_{i,r}$	Imported goods price	$q^M_{i,r}$	Imported goods supply	$p^D_{i,r'}$	Domestic goods price in $r' \neq r$	$g^X_{i,r',r}$	r's imports from other regions r'
						p^T_s	Int'l shipping services price	$g^{TM}_{s,i,r',r}$	Int'l transport services
(I6)	International shippers	p^T_s	Int'l shipping services price	q^T_s	Int'l transport supply	$p^D_{s,r}$	r's domestic transport price	$g^{TX}_{s,r}$	Transport service exports from r

B. Markets

		Supply		Demands	
		Price	Quantity		
(M1)	Domestic goods	$p^D_{j,r}$	$y_{j,r}$	$q^D_{j,r}$	Domestic goods demanded by Armington aggregator
				$g^X_{j,r,r'}$	Commodity exports
				$g^{TX}_{s,r}$	International transport sales ($t \subset j$)
(M2)	Armington domestic-import composite	$p^A_{i,r}$	$q^A_{i,r}$	$x_{i,j,r}$	Intermediate demand for Armington good
				$g^C_{i,r}$	Consumption demand for Armington good
				$g^I_{i,r}$	Investment demand for Armington good
(M3)	Imported goods	$p^M_{i,r}$	$g^M_{i,r}$	$q^M_{i,r}$	Imported goods demanded by Armington aggregator
(M4)	International shipping services	p^T_s	q^T_s	$g^{TM}_{s,i,r,r'}$	Margins on exports from r to other regions s
(M5)	Primary factors	$w_{f,r}$	$V_{f,r}$	$v_{f,j,r}$	Goods producers' demands for factors

its columns. In line with CGE models' strength in analyzing the aggregate welfare impacts of price changes, we reserve special treatment for the households in each region, whose aggregate consumption we assume generates an economy-wide level of utility (u_r) at an aggregate "welfare price" given by the unit expenditure index ($\mathscr{E}_r$). The accounting identities corresponding to the SAM's column and row sums are the exhaustion of profit and supply-demand balance conditions in Figure 2. These make up the core of our CGE model.

Figure 2: The Canonical Model: Accounting Identities and Parameterization

A. Accounting identities based on the SAM

	Zero Profit Conditions (Institutions)		Supply-Demand Balance Conditions (Markets)
(I1)	$\mathscr{E}_r u_r \leq \sum_{i=1}^{\mathcal{N}} p^A_{i,r} g^C_{i,r}$	(M1)	$y_{j,r} \geq q^D_{j,r} + g^{TX}_{j,r} + \sum_{r' \neq r} g^X_{j,r,r'}$
(I2)	$p^I_r G^I_r \leq \sum_{i=1}^{\mathcal{N}} p^A_{i,r} g^I_{i,r}$	(M2)	$q^A_{i,r} \geq \sum_{j=1}^{\mathcal{N}} x_{i,j,r} + g^C_{i,r} + g^I_{i,r}$
(I3)	$p^D_{j,r} y_{j,r} \leq \sum_{i=1}^{\mathcal{N}} p^A_{i,r} x_{i,j,r} + w_{f,r} v_{f,j,r}$	(M3)	$g^M_{i,r} \geq q^M_{i,r} p^M_{i,r}$
(I4)	$p^A_{i,r} q^A_{i,r} \leq p^D_{i,r} q^D_{i,r} + p^M_{i,r} q^M_{i,r}$	(M4)	$q^T_s \geq \sum_{i=1}^{\mathcal{N}} \sum_{r=1}^{\mathcal{R}} \sum_{r'} g^{TM}_{s,i,r,r'} p^T_s$
(I5)	$p^M_{i,r} g^M_{i,r} \leq \sum_{r' \neq r} \left(p^D_{i,r'} g^X_{i,r',r} + \sum_{r'} p^T_s g^{TM}_{s,i,r',r} \right)$	(M5)	$V_{f,r} \geq \sum_{j=1}^{\mathcal{N}} v_{f,j,r}$
(I6)	$p^T_s q^T_s \leq \sum_{r=1}^{\mathcal{R}} p^D_{s,r} g^{TX}_{s,r}$		

B. Parameters

	Institutions	Substitution Elasticities	Technical Coefficients	
(I1)	Households	σ^C_r	$\alpha^C_{i,r}$	Armington good use: consumption
(I2)	Investment goods producers	σ^I_r	$\alpha^I_{i,r}$	Armington good use: investment
(I3)	Commodity producers	$\sigma^Y_{j,r}$	$\beta_{i,j,r}$	Intermediate Armington good use
			$\gamma_{f,j,r}$	Factor inputs
(I4)	Domestic/import commodity aggregators	$\sigma^{DM}_{i,r}$	$\zeta^D_{i,r}$	Domestic commodity output
			$\zeta^M_{i,r}$	Imported commodities
(I5)	Import agents	$\sigma^{MM}_{i,r}$	$\xi_{i,r',r}$	Exports to r from other regions s
			$\kappa_{t,i,r',r}$	International transport services
(I6)	International shippers	$\sigma^T_{r'}$	$\xi_{t,r}$	Transport service exports from r

To elaborate the model's algebraic structure we assume that institutional actors possess CES technology parameterized according to Figure 2.B, and behave in a manner consistent with consumer and producer optimization. This lets us derive the demand functions that are the fundamental bridge between the activity levels that reflect institutional behavior and the prices that establish market equilibrium:

(I1) *Representative agents* minimize the expenditure necessary to generate each unit of utility subject to the constraint of consumption technology by allocating unit quantities of each commodity consumed ($\widehat{g}^C_{i,r} = g^C_{i,r}/u_r$).

$$\min_{\widehat{g}^C_{i,r}} \left\{ \mathscr{E}_r = \sum_{i=1}^{\mathcal{N}} p^A_{i,r}\widehat{g}^C_{i,r} \middle| 1 = \left[\sum_{i=1}^{\mathcal{N}} \alpha^C_{i,r} \left(\widehat{g}^C_{i,r}\right)^{(\sigma^C_r-1)/\sigma^C_r} \right]^{\sigma^C_r/(\sigma^C_r-1)} \right\}.$$

The result is the unconditional demand for Armington goods inputs to consumption, $g^C_{i,r} = \left(\alpha^C_{i,r}\right)^{\sigma^C_r} \left(p^A_{i,r}\right)^{-\sigma^C_r} \mathscr{E}^{\sigma^C_r} u_r$.

(I2) *Investment goods producers* minimize the cost of generating a unit of output subject to the constraint of production technology by allocating unit quantities of commodity inputs ($\widehat{g}^I_{i,r} = g^I_{i,r}/G^I_r$).

$$\min_{\widehat{g}^I_{i,r}} \left\{ p^I_r = \sum_{i=1}^{\mathcal{N}} p^A_{i,r}\widehat{g}^I_{i,r} \middle| 1 = \left[\sum_{i=1}^{\mathcal{N}} \alpha^I_{i,r} \left(\widehat{g}^I_{i,r}\right)^{(\sigma^I_r-1)/\sigma^I_r} \right]^{\sigma^I_r/(\sigma^I_r-1)} \right\}.$$

The result is the unconditional demand for Armington goods inputs to investment, $g^I_{i,r} = \left(\alpha^I_{i,r}\right)^{\sigma^I_r} \left(p^A_{i,r}\right)^{-\sigma^I_r} \left(p^I_r\right)^{\sigma^I_r} G^I_r$.

(I3) *Commodity-producing industry sectors* minimize the cost of creating a unit of output subject to the constraint of production technology by allocating purchases of unit quantities of intermediate commodity inputs and primary factor inputs ($\widehat{x}_{i,j} = x_{i,j}/y_j$ and $\widehat{v}_{f,j} = v_{f,j}/y_j$).

$$\min_{\widehat{x}_{i,j,r},\widehat{v}_{f,j,r}} \Bigg\{ p^D_{j,r} = \sum_{i=1}^{\mathcal{N}} p^A_{i,r}\widehat{x}_{i,j,r} + \sum_{f=1}^{\mathcal{F}} w_{f,r}\widehat{v}_{f,j,r} \Bigg| \quad 1 = \left[\sum_{i=1}^{\mathcal{N}} \beta_{i,j,r}\widehat{x}_{i,j,r}^{(\sigma^Y_{j,r}-1)/\sigma^Y_{j,r}} + \sum_{f=1}^{\mathcal{F}} \gamma_{f,j,r}\widehat{v}_{f,j,r}^{(\sigma^Y_{j,r}-1)/\sigma^Y_{j,r}}\right]^{\sigma^Y_{j,r}/(\sigma^Y_{j,r}-1)} \Bigg\}.$$

The result is the unconditional demands for intermediate Armington commodity inputs and nonreproducible primary factor inputs, $x_{i,j,r} = \beta_{i,j,r}^{\sigma^Y_{j,r}} \left(p^A_{i,r}\right)^{-\sigma^Y_{j,r}} \left(p^D_{j,r}\right)^{\sigma^Y_{j,r}} y_{j,r}$ and $v_{f,j,r} = \gamma_{f,j,r}^{\sigma^Y_{j,r}} w_{f,r}^{-\sigma^Y_{j,r}} \left(p^D_{j,r}\right)^{\sigma^Y_{j,r}} y_{j,r}$.

(I4) *Domestic/import commodity aggregators* minimize the cost of producing a unit of composite output of each commodity subject to the constraint of its CES aggregation technology by allocating purchases of unit quantities of domestic and imported varieties of the good ($\widehat{q}^D_{i,r} = q^D_{i,r}/q^A_{i,r}$ and $\widehat{g}^M_{i,r} = q^M_{i,r}/q^A_{i,r}$).

$$\min_{\widehat{q}^D_{i,r},\widehat{g}^M_{i,r}} \Bigg\{ p^A_{i,r} = p^D_{i,r}\widehat{q}^D_{i,r} + p^M_{i,r}\widehat{q}^M_{i,r} \Bigg| \quad 1 = \left[\zeta^D_{i,r}\left(\widehat{q}^D_{i,r}\right)^{(\sigma^{DM}_{i,r}-1)/\sigma^{DM}_{i,r}} + \zeta^M_{i,r}\left(\widehat{q}^M_{i,r}\right)^{(\sigma^{DM}_{i,r}-1)/\sigma^{DM}_{i,r}}\right]^{\sigma^{DM}_{i,r}/(\sigma^{DM}_{i,r}-1)} \Bigg\}.$$

The result is the unconditional demand for domestically-produced and imported varieties of each good, $q^D_{i,r} = \left(\zeta^D_{i,r}\right)^{\sigma^{DM}_{i,r}} \left(p^D_{i,r}\right)^{-\sigma^{DM}_{i,r}} \left(p^A_{i,r}\right)^{\sigma^{DM}_{i,r}} q^A_{i,r}$ and $q^M_{i,r} = \left(\zeta^M_{i,r}\right)^{\sigma^{DM}_{i,r}} \left(p^M_{i,r}\right)^{-\sigma^{DM}_{i,r}} \left(p^A_{i,r}\right)^{\sigma^{DM}_{i,r}} q^A_{i,r}$.

(I5) *Commodity importers* minimize the cost of producing a unit of composite import good subject to the constraint of aggregation technology by allocating purchases of unit commodity inputs over trade partners' exports and associated international transport services ($\widehat{g}^X_{i,r',r} = g^X_{i,r',r}/g^M_{i,r}$ and $\widehat{g}^{TM}_{s,i,r',r} = g^{TM}_{s,i,r',r}/g^M_{i,r}$). We simplify the problem by assuming that the export of a unit of commodity i requires fixed quantities of the t types of transport services ($\kappa_{s,i,r',r}$), which enables shipping costs to be specified as mode-specific markups over the producer prices of overseas goods.

$$\min_{\widehat{q}^M_{i,r}} \left\{ p^M_{i,r} = \sum_{r' \neq r} \left(p^D_{i,r'} \widehat{g}^X_{i,r',r} + \sum_{r'} p^T_s \widehat{g}^{TM}_{s,i,r',r} \right) \middle| \; \widehat{g}^{TM}_{s,i,r',r} = \kappa_{s,i,r',r} \widehat{g}^X_{i,r',r}, \right.$$
$$\left. 1 = \left[\sum_{r' \neq r} \xi_{i,r',r} \left(\widehat{g}^X_{i,r',r} \right)^{(\sigma^{MM}_{i,r} - 1)/\sigma^{MM}_{i,r}} \right]^{\sigma^{MM}_{i,r}/(\sigma^{MM}_{i,r} - 1)} \right\}.$$

The result is the unconditional demands for other regions' exports and for international transshipment services, $g^X_{i,r',r} = \xi^{\sigma^{MM}_{i,r}}_{i,r',r} \left(p^D_{i,r'} + \sum_s \kappa_{s,i,r',r} p^T_s \right)^{-\sigma^{MM}_{i,r}} \left(p^M_{i,r} \right)^{\sigma^{MM}_{i,r}} g^M_{i,r}$.

(I6) *International shippers* minimize the cost of producing a unit of transport service subject to the constraint of its aggregation technology by allocating purchases of regions' transportation sector outputs ($\widehat{g}^{TX}_{s,r} = g^{TX}_{s,r}/q^T_s$).

$$\min_{\widehat{g}^{TX}_{s,r}} \left\{ p^T_s = \sum_{r=1}^{\mathcal{R}} p^D_{s,r} \widehat{g}^{TX}_{s,r} \middle| 1 = \left[\sum_{r=1}^{\mathcal{R}} \chi_{s,r} \left(\widehat{g}^{TX}_{s,r} \right)^{(\sigma^T_{r'} - 1)/\sigma^T_{r'}} \right]^{\sigma^T_{r'}/(\sigma^T_{r'} - 1)} \right\}.$$

The result is the unconditional demand for transport services, $g^{TX}_{s,r} = \chi^{\sigma^T_s}_{s,r} \left(p^D_{s,r} \right)^{-\sigma^T_s} \left(p^T_s \right)^{\sigma^T_s} q^T_s$.

Substituting these results into the conditions for (I1)-(I6) and for (M1)-(M6) in Table 2 yields the zero profit conditions (1)-(6) and market clearance conditions (7)-(11) in Figure 2. These exhibit Karush-Kuhn-Tucker complementary slackness (indicated by "$\perp$") with the activity levels and prices, respectively, in Table 1. There are no markets in the conventional sense for either consumers' utility, or, in the present static framework, the investment good. The latter is treated simply as an exogenous demand (12). Regarding the former, u_r is the highest level of aggregate utility attainable given the values of aggregate household income ($\mathscr{I}_r$) and the unit expenditure index. This intuition is captured by the market clearance condition (13), with definition of the income level given by the income balance condition (14).

Together, (1)-(14) comprise a square system of $\mathcal{R}(5 + 7\mathcal{N} + \mathcal{F}) + 2\mathcal{T}$ nonlinear inequalities, $\boldsymbol{\Lambda}(\mathcal{B})$, in as many unknowns, $\mathcal{B} = \{u_r, G^I_r, y_{i,r}, q^A_{i,r}, g^M_{i,r}, q^T_s, p^D_{i,r}, p^A_{i,r}, p^M_{i,r}, p^T_s, w_{f,r}, p^I_r, \mathscr{E}_r, \mathscr{I}_r\}$,

Table 2: Equations of the CGE Model

$$\mathscr{E}_r \leq \left[\sum_{i=1}^{\mathcal{N}} \left(\alpha_{i,r}^{C}\right)^{\sigma_r^C} \left(p_{i,r}^{A}\right)^{1-\sigma_r^C}\right]^{1/(\sigma_r^C-1)} \qquad \perp \quad u_r \tag{1}$$

$$p_r^I \leq \left[\sum_{i=1}^{\mathcal{N}} \left(\alpha_{i,r}^{I}\right)^{\sigma_r^I} \left(p_{i,r}^{A}\right)^{1-\sigma_r^I}\right]^{1/(\sigma_r^I-1)} \qquad \perp \quad G_r^I \tag{2}$$

$$p_{j,r}^D \leq \left[\sum_{i=1}^{\mathcal{N}} \beta_{i,j,r}^{\sigma_{j,r}^Y} \left(p_{i,r}^{A}\right)^{1-\sigma_{j,r}^Y} + \sum_{f=1}^{\mathcal{F}} \gamma_{f,j,r}^{\sigma_{j,r}^Y} w_{f,r}^{1-\sigma_{j,r}^Y}\right]^{1/(1-\sigma_{j,r}^Y)} \qquad \perp \quad y_{j,r} \tag{3}$$

$$p_{i,r}^A \leq \left[\left(\zeta_{i,r}^{D}\right)^{\sigma_{i,r}^{DM}} \left(p_{i,r}^{D}\right)^{1-\sigma_{i,r}^{DM}} + \left(\zeta_{i,j,r}^{M}\right)^{\sigma_{i,r}^{DM}} \left(p_{i,r}^{M}\right)^{1-\sigma_{i,r}^{DM}}\right]^{1/(1-\sigma_{i,r}^{DM})} \qquad \perp \quad q_{i,r}^A \tag{4}$$

$$p_{i,r}^M \leq \left[\sum_{r'\neq r} \xi_{i,r',r}^{\sigma_{i,r}^{MM}} \left(p_{i,r'}^{D} + \sum_{r=1}^{\mathcal{R}} \kappa_{s,i,r',r} p_s^T\right)^{1-\sigma_{i,r}^{MM}}\right]^{1/(1-\sigma_{i,r}^{MM})} \qquad \perp \quad g_{i,r}^M \tag{5}$$

$$p_s^T \leq \left[\sum_{r=1}^{\mathcal{R}} \chi_{r,t}^{\sigma_s^T} \left(p_{s,r}^{D}\right)^{1-\sigma_s^T}\right] \qquad \perp \quad q_s^T \tag{6}$$

$$\begin{aligned} y_{i,r} \geq{} & \left(\zeta_{i,r}^{D}\right)^{\sigma_{i,r}^{DM}} \left(p_{i,r}^{D}\right)^{-\sigma_{i,r}^{DM}} \left(p_{i,r}^{A}\right)^{\sigma_{i,r}^{DM}} q_{i,r}^A \\ & + \sum_{r'\neq r} \xi_{i,r,r'}^{\sigma_{i,r'}^{MM}} \left(p_{i,r}^{D} + \sum_{r=1}^{\mathcal{R}} \kappa_{s,i,r,r'} p_s^T\right)^{-\sigma_{i,r'}^{MM}} \left(p_{i,r'}^{M}\right)^{\sigma_{i,r'}^{MM}} g_{i,r'}^M \end{aligned} \qquad \perp \quad p_{i,r}^D \tag{7}$$

$$\begin{aligned} q_{i,r}^A \geq{} & \left(\alpha_{i,r}^{C}\right)^{\sigma_r^C} \left(p_{i,r}^{A}\right)^{-\sigma_r^C} \mathscr{E}^{\sigma_r^C} u_r + \left(\alpha_{i,r}^{I}\right)^{\sigma_r^I} \left(p_{i,r}^{A}\right)^{-\sigma_r^I} \left(p_r^{I}\right)^{\sigma_r^I} G_r^I \\ & + \sum_{j=1}^{\mathcal{N}} \beta_{i,j,r}^{\sigma_{j,r}^Y} \left(p_{i,r}^{A}\right)^{-\sigma_{j,r}^Y} \left(p_{j,r}^{D}\right)^{\sigma_{j,r}^Y} y_{j,r} \end{aligned} \qquad \perp \quad p_{i,r}^A \tag{8}$$

$$g_{i,r}^M \geq \left(\zeta_{i,r}^{M}\right)^{\sigma_{i,r}^{DM}} \left(p_{i,r}^{M}\right)^{-\sigma_{i,r}^{DM}} \left(p_{i,r}^{A}\right)^{\sigma_{i,r}^{DM}} q_{i,r}^A \qquad \perp \quad p_{i,r}^M \tag{9}$$

$$q_s^T \geq \sum_{i=1}^{\mathcal{N}} \sum_{r=1}^{\mathcal{R}} \sum_{r'\neq r} \left[\xi_{i,r',r}^{\sigma_{i,r}^{MM}} \left(p_{i,r'}^{D} + \sum_{s} \kappa_{s,i,r',r} p_s^T\right)^{-\sigma_{i,r}^{MM}} \left(p_{i,r}^{M}\right)^{\sigma_{i,r}^{MM}} g_{i,r}^M\right] \qquad \perp \quad p_s^T \tag{10}$$

$$V_{f,r} \geq \sum_{j=1}^{\mathcal{N}} \gamma_{f,j,r}^{\sigma_{j,r}^Y} w_{f,r}^{-\sigma_{j,r}^Y} \left(p_{j,r}^{D}\right)^{\sigma_{j,r}^Y} y_{j,r} \qquad \perp \quad w_{f,r} \tag{11}$$

$$G_r^I \text{ given} \qquad \perp \quad p_r^I \tag{12}$$

$$u_r \geq \mathscr{I}_r / \mathscr{E}_r \qquad \perp \quad \mathscr{E}_r \tag{13}$$

$$\mathscr{I}_r = \sum_{f=1}^{\mathcal{F}} w_{f,r} V_{f,r} \qquad \perp \quad \mathscr{I}_r \tag{14}$$

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which constitutes the pseudo-excess-demand correspondence of our multiregional economy. Numerically calibrating the technical coefficients in Table on a micro-consistent benchmark multiregional input-output dataset yields our CGE model in a complementarity format:

$$\boldsymbol{\Lambda}(\mathcal{B}) \geq 0, \qquad \mathcal{B} \geq 0, \qquad \mathcal{B}'\boldsymbol{\Lambda}\left(\mathcal{B}\right) = \mathbf{0},$$

which can be solved as a mixed complementarity problem (MCP)—for details, see Sue Wing (2009). CGE models solve for relative prices, with the marginal utility of income being a convenient numeraire. A common practice is to designate one region (say $r^{\star}$) as the numeraire economy by fixing the value of its unit expenditure index, $\mathscr{E}_{r^{\star}} = 1$.

2.2 A Single-Region Open-Economy Armington Model

A noteworthy feature of this framework is that it encompasses the single-region open-economy Armington model as a special case. The latter is specified by omitting international transport (by dropping eqs. (6) and (10) and the corresponding variables $p_s^T = q_s^T = 0$) and collapsing bilateral exports and imports into aggregate values G^X and G^M, which are associated with the supply of and demand for an aggregate foreign exchange commodity (with price PFX). Producers in each industry allocate output between domestic and export markets according to a constant elasticity of transformation (CET) technology, while imported quantities of each commodity are a CET function of foreign exchange. The zero profit conditions implied by these assumptions are modifications of eqs. (3) and (5), shown below as (15) and (16). Applying Shephard's Lemma to derive the optimal unconditional supplies of domestic and imported varieties of each good yields the analogues of the market clearance conditions (7) and (9), shown below as eqs. (17) and (18). The model is closed through the specification of the current account, with commodity exports generating foreign exchange according to a CES technology (implying the zero profit condition (19)), and the price of foreign exchange exhibiting complementary slackness with the current account balance, CA_r. Eq. (20) illustrates the simplest case in which the latter is treated as exogenous, held fixed at the level prevailing in the benchmark calibration dataset.

$$\begin{aligned}
&\left[\left(\delta^D_{j,r}\right)^{\sigma^Y_{j,r}}\left(p^D_{j,r}\right)^{1-\sigma^Y_{j,r}} + \left(\delta^X_{j,r}\right)^{\sigma^Y_{j,r}}\left(p^X_{j,r}\right)^{1-\sigma^Y_{j,r}}\right]^{1/(1-\sigma^Y_{j,r})} \\
&\qquad \leq \left[\sum_{i=1}^{\mathcal{N}} \beta_{i,j,r}^{\sigma^Y_{j,r}}\left(p^A_{i,r}\right)^{1-\sigma^Y_{j,r}} + \sum_{f=1}^{\mathcal{F}} \gamma_{f,j,r}^{\sigma^Y_{j,r}} w_{f,r}^{1-\sigma^Y_{j,r}}\right]^{1/(1-\sigma^Y_{j,r})} \qquad \perp y_{i,r}
\end{aligned} \tag{15}$$

$$\left[\sum_{i=1}^{\mathcal{N}}\left(\mu^M_{i,r}\right)^{\sigma^M_r}\left(p^M_{i,r}\right)^{1-\sigma^M_r}\right]^{1/(1-\sigma^M_r)} \leq PFX_r \qquad \perp G^M_r \tag{16}$$

$$\begin{aligned}
&\left(\delta^D_{j,r}\right)^{\sigma^Y_{j,r}}\left(p^D_{j,r}\right)^{-\sigma^Y_{j,r}} \\
&\times\left[\left(\delta^D_{j,r}\right)^{\sigma^Y_{j,r}}\left(p^D_{j,r}\right)^{1-\sigma^Y_{j,r}} + \left(\delta^X_{j,r}\right)^{\sigma^Y_{j,r}}\left(p^X_{j,r}\right)^{1-\sigma^Y_{j,r}}\right]^{\sigma^Y_{j,r}/(1-\sigma^Y_{j,r})} y_{j,r} \\
&\qquad \geq \left(\zeta^D_{i,r}\right)^{\sigma^{DM}_{i,r}}\left(p^D_{i,r}\right)^{-\sigma^{DM}_{i,r}}\left(p^A_{i,r}\right)^{\sigma^{DM}_{i,r}} q^A_{i,r} \qquad \perp p^D_{i,r}
\end{aligned} \tag{17}$$

$$\begin{aligned}
&\left(\mu^M_{i,r}\right)^{\sigma^M_r}\left(p^M_{i,r}\right)^{-\sigma^M_r}\left[\sum_{i=1}^{\mathcal{N}}\left(\mu^M_{i,r}\right)^{\sigma^M_r}\left(p^M_{i,r}\right)^{1-\sigma^M_r}\right]^{\sigma^M_r/(1-\sigma^M_r)} G^M_r \\
&\qquad \geq \left(\zeta^M_{i,r}\right)^{\sigma^{DM}_{i,r}}\left(p^M_{i,r}\right)^{-\sigma^{DM}_{i,r}}\left(p^A_{i,r}\right)^{\sigma^{DM}_{i,r}} q^A_{i,r} \qquad \perp \quad p^M_{i,r}
\end{aligned} \tag{18}$$

$$PFX_r \leq \left[\sum_{i=1}^{\mathcal{N}}\left(\mu^X_{i,r}\right)^{\sigma^X_r}\left(p^X_{i,r}\right)^{1-\sigma^X_r}\right]^{1/(1-\sigma^X_r)} \qquad \perp G^X_r \tag{19}$$

$$G^X_r - G^M_r = CA_r \qquad \perp PFX_r \tag{20}$$

The single-region small open economy model is given by eqs. (1), (2), (15), (4), (16), (17), (8), (18) and (11)-(20), which comprise a square system of $8 + 5\mathcal{N} + \mathcal{F}$ nonlinear inequalities in as many unknowns, $\mathcal{B} = \{u, G^I, y_i, q^A_i, G^X_r, G^M_r, p^D_i, p^A_i, p^M_i, w_f, p^I, \mathscr{E}, \mathscr{I}, PFX\}$ for a given region r.

2.3 Introducing Dynamics

An important extension of these basic static frameworks is the introduction of a dynamic process that enables simulation of economies' time evolution. The simplest approach is to construct a "recursive dynamic" model in which factor accumulation is represented by semi-autonomous increase in the primary factor endowments in xx, and technological progress is represented by exogenous shifts in the technical coefficients of consumption and production. Letting $t = \{1, \ldots, T\}$ index time, the supply of labor is typically modeled as following an exogenous trend of population increase (say, $\Psi_{r,t}^{\text{Pop}}$) combined with an increasing index of labor productivity ($\Psi_{L,r,t}^{V} \geq 1$):

$$V_{L,r,t} = \Psi_{L,r,t}^{V} \Psi_{r,t}^{\text{Pop}} \overline{V}_{L,r} \tag{21}$$

Expansion of the supply of capital is semi-endogenous. Accumulation of regions' capital stocks ($KS_{r,t}$) is driven by investment and depreciation (at rate $\mathscr{D}$) according to the standard perpetual inventory formulation (22). Investment is determined myopically as a function of contemporaneous variables in each period's static MCP, with the simplest assumption being a constant household marginal propensity to save and invest out of aggregate income (MPS_r), in which case (12) is re-specified as eq. (23). Finally, exogenous rate of return (RK_r) are used to calculate capital endowments from the underlying stocks (22).

$$KS_{r,t+1} = G_{r,t}^{I} + (1 - \mathscr{D}) KS_{r,t} \tag{22}$$

$$G_r^I = MPS_r \ \mathscr{I}_r \qquad \perp \quad p_r^I \tag{23}$$

$$V_{K,r,t} = RK_r \ KS_{r,t} \tag{24}$$

These equations give rise to a multiregional and multisectoral Solow-Swan model, which, like its simpler theoretical counterpart, exhibits diminishing returns to accumulating factors which is compensated for by aggregate productivity growth. Exogenous technical progress can also be modeled by applying shift parameters that specify a decline in the values of the coefficients on inputs consumption—$\alpha_{i,r,t} = \Psi^{C}_{i,t}\overline{\alpha}_{i,r}$, and production—$\beta_{i,j,r,t} = \Psi^{YI}_{i,j,r,t}\overline{\beta}_{i,j,r}$ and $\gamma_{f,j,r,t} = \Psi^{YF}_{f,j,r,t}\overline{\gamma}_{f,j,r}$, with $\Psi^{C}_{i,t}, \Psi^{YI}_{i,j,r,t}, \Psi^{YF}_{f,j,r,t} \in (0, 1]$. Production in sector j experiences neutral technical progress when $\Psi^{YI}_{i,j,r,t} = \Psi^{YF}_{f,j,r,t} = \overline{\Psi}^{Y}_{j,r,t}$. A popular application of biased technical progress is energy-focused CGE models' way of capturing the historically-oberved non-price induced secular decline in the energy-GDP ratio. This is represented via "autonomous energy-efficiency improvement" (AEEI), an exogenously-specified decline in the coefficient on energy inputs ($e \subset i$) to production and consumption: $\Psi^{YI}_{e,j,r,t}, \Psi^{C}_{e,t} < 1$.

The ease of implementation of the recursive-dynamic approach has led to its overwhelming popularity in applied modeling work, in spite of the limitations of ad-hoc savings-investment closure rules such as (23) which diverge sharply from the standard economic assumption of intertemporally optimizing firm and household behavior. The development and application of fully forward-looking CGE models has for this reason become an important area of research. Lau et al. (2002) derive a multisectoral Ramsey model in the complementarity format of equilibrium, using the consumption Euler equation and the intertemporal budget constraint of an intertemporal utility maximizing representative agent. The key features of their framework are a trajectory of aggregate consumption demand determined by exogenous long-run average rates of interest and discount, the intertemporal elasticity of substitution, and cumulative net income over the T periods of the simulation horizon, and an intertemporal zero-profit condition for capital stock accumulation dual to (22), which incorporates RK_r as a fully endogenous capital input price index. The resulting general equilibrium problem is specified and simultaneously solved for all t, which for large-T simulations can dramatically increase the dimension of the pseudo-excess demand correspondence and the associated complexity and computational cost. It is therefore unsurprising that single-region forward-looking CGE models[1] tend to be far more common than their multiregional counterparts.[2]

3 THE CANONICAL MODEL AT WORK

3.1 Traditional Applications: International, Development and Public Economics

CGE models have long been the analytical mainstay of assessments of trade liberalization and economic integration (Harrison et al., 1997a,b; Hertel, 1997). Such analysis has been facilitated by the compilation of integrated trade and input-output datasets such as the Global Trade Analysis Project (GTAP) database (Narayanan and Walmsley, 2008), which include a range of data on protection and distortions. Incorporating these data into the canonical model allows the analyst to construct an initial tariff-ridden status-quo equilibrium which can be used as benchmark from which to simulate the impacts of a wide variety of policy reforms.

Multilateral trade negotiations are perhaps the simplest illustrate (e.g., Hertel and Winters, 2006). These typically involve reductions in and inter-regional harmonization of two types of distortions, which may be conveniently introduced into the canonical model as ad-valorem taxes or subsidies. The first is export levies or subsidies that drive a wedge between the domestic and FOB prices of each good, and are represented using the parameter $\tau^X_{i,r} \gtrless 0$. The second is import tariffs that drive a wedge between CIF prices and landed costs, represented parametrically by $\tau^M_{i,r} > 0$. The benefits of this approach are simplicity, as well as the ability to capture the border effects of various kinds of non-tariff barriers to trade where empirical estimates of these measures' "ad valorem equivalents" are available (see, e.g., Fugazza and Maur, 2008). Modeling the "shocks" constituted by changes to such policy parameters follows a standard procedure which we will apply throughout this chapter: first, modify the zero profit conditions to represent the shcok as a price wedge, second, specify modifications implied by Hotelling's lemma to the supply and demand functions in the market clearance conditions, and third, reconcile the income balance condition with the net revenues or captured rents. Other extensions to the model structure might be warranted, depending on the interactions of interest. Adjusting the equations for import zero profit (5), domestic market clearance (7), and income balance (14) in Table 2, we obtain, respectively,

$$p_{i,r}^{M} \leq \left[\sum_{r' \neq r} \xi_{i,r',r}^{\sigma_{i,r}^{MM}} \left((1+\tau_{i,r}^{M})(1+\tau_{i,r'}^{X}) p_{i,r'}^{D} + \sum_{r=1}^{\mathcal{R}} \kappa_{s,i,r',r} p_{s}^{T} \right)^{1-\sigma_{i,r}^{MM}} \right]^{1/(1-\sigma_{i,r}^{MM})} \quad \perp \quad g_{i,r}^{M} \tag{25}$$

$$\begin{aligned} y_{i,r} \geq{} & \left(\zeta_{i,r}^{D}\right)^{\sigma_{i,r}^{DM}} \left(p_{i,r}^{D}\right)^{-\sigma_{i,r}^{DM}} \left(p_{i,r}^{A}\right)^{\sigma_{i,r}^{DM}} q_{i,r}^{A} + \sum_{r' \neq r} (1+\tau_{i,r}^{M})(1+\tau_{i,r'}^{X}) \xi_{i,r,r'}^{\sigma_{i,r'}^{MM}} \\ & \times \left((1+\tau_{i,r'}^{M})(1+\tau_{i,r}^{X}) p_{i,r}^{D} + \sum_{r=1}^{\mathcal{R}} \kappa_{s,i,r,r'} p_{s}^{T} \right)^{-\sigma_{i,r'}^{MM}} \left(p_{i,r'}^{M}\right)^{\sigma_{i,r'}^{MM}} g_{i,r'}^{M} \quad \perp \quad p_{i,r}^{D} \end{aligned} \tag{26}$$

$$\begin{aligned} \mathscr{I}_{r} ={} & \sum_{f=1}^{\mathcal{F}} w_{f,r} V_{f,r} + \sum_{i=1}^{\mathcal{N}} \tau_{i,r}^{X} p_{i,r}^{D} \sum_{r' \neq r} (1+\tau_{i,r'}^{M})(1+\tau_{i,r}^{X}) \xi_{i,r,r'}^{\sigma_{i,r'}^{MM}} \\ & \times \left((1+\tau_{i,r'}^{M})(1+\tau_{i,r}^{X}) p_{i,r}^{D} + \sum_{r=1}^{\mathcal{R}} \kappa_{s,i,r,r'} p_{s}^{T} \right)^{-\sigma_{i,r'}^{MM}} \left(p_{i,r'}^{M}\right)^{\sigma_{i,r'}^{MM}} g_{i,r'}^{M} \\ & + \sum_{i=1}^{\mathcal{N}} \tau_{i,r}^{M} \sum_{r' \neq r} p_{i,r'}^{D} (1+\tau_{i,r}^{M})(1+\tau_{i,r'}^{X}) \xi_{i,r',r}^{\sigma_{i,r}^{MM}} \\ & \times \left((1+\tau_{i,r}^{M})(1+\tau_{i,r'}^{X}) p_{i,r'}^{D} + \sum_{r=1}^{\mathcal{R}} \kappa_{s,i,r',r} p_{s}^{T} \right)^{-\sigma_{i,r}^{MM}} \left(p_{i,r}^{M}\right)^{\sigma_{i,r}^{MM}} g_{i,r}^{M} \quad \perp \quad \mathscr{I}_{r} \end{aligned} \tag{27}$$

The fact that $\boldsymbol{\tau}^{X}$ and $\boldsymbol{\tau}^{M}$ are pre-existing distortions means that it is necessary to recalibrate the model's technical coefficients to obtain a benchmark equilibrium. Trade policies are simulated by changing elements of these vectors from their benchmark values and computing new counterfactual equilibria that embody income and substitution effects in both the domestic economy, r, and its trade partners, r'. The resulting effects on welfare manifest themselves through the new tax revenue terms in the income balance equation. Hertel et al. (2007) demonstrate that the magnitude of these impacts strongly depends on the values of the elasticities governing substitution across regional varieties of each good, $\sigma_{i,r}^{MM}$.

The breadth and richness of analyses that can be undertaken simply by manipulating distortion parameters such as tax rates—or the endowments and productivity parameters the define boundary conditions of the economy, is truly remarkable and should not be underestimated.

International economics continues to be a mainstay of the CGE literature, with numerous articles over the past decade dedicated to assessing the consequences of various trade agreements and liberalization initiatives,[3] as well as a variety of multilateral price support schemes (Psaltopoulos et al., 2011), distortionary trade policies (Naud and Rossouw, 2008; Narayanan and Khorana, 2014), non-tariff barriers to trade (Fugazza and Maur, 2008; Winchester, 2009), and internal and external shocks (implemented in the model of section 2.2 by dropping eq. (18) and fixing the complementary variable $p^M_{i,r}$).[4] More analytically-oriented papers have investigated the manner in which the macroeconomic effects of shocks are modulated by imperfect competition (Konan and Assche, 2007), agents expectations (Boussard et al., 2006; Femenia and Gohin, 2011), and international mechanisms of price transmission (Siddig and Grethe, 2014). Still others studies advance the state of modeling, extending the canonical model beyond just trade into the realm of international macroeconomics by introducing foreign direct investment and its potential to generate domestic productivity spillovers (Lejour et al., 2008; Latorre et al., 2009; Deng et al., 2012), and financial assets and interregional financial flows (Maldonado et al., 2007; Lemelin et al., 2013; Yang et al., 2013). Following Markusen (2002) and Markusen et al. (2005), the typical approach taken by the latter crop of papers is to disaggregate capital input as a factor of production into domestic and foreign varieties, the second of which is internationally mobile and imperfectly substitutable for domestic capital.

A related development literature examines a broader range of outcomes in poor countries, for example the social, environmental and poverty impacts of trade policy and liberalization,[5] and the economic and social consequences of energy price shocks, energy market liberalization, and alternative energy promotion [6]. Similar studies investigate the macro-level developng country consequences of productivity improvements generated by foreign aid (Clausen and Schrenberg-Frosch, 2012), changes in the delivery of public services such as eduction and health (Debowicz and Golan, 2014; Roos and Giesecke, 2014) or domestic R&D and industrial policies to simulate economic growth (Breisinger et al., 2009; Bor et al., 2010; Ojha et al., 2013), and the growth consequences of worker protection and restrictions on international movements of labor (Ahmed and Peerlings, 2009; Moses and Letnes, 2004).

Yet another perspective on these issues is taken by the public economics literature, which investigates the economy-wide effects of energy and environmental tax changes (Karami et al., 2012; Markandya et al., 2013; Zhang et al., 2013), ageing-related and pension policies—through either a coupled CGE-microsimulation modeling framework (van Sonsbeek, 2010) or dynamic CGE models embodying overlapping generations of households,[7] actual and proposed tax reforms in developed and developing countries,[8] the welfare implications of decentralized public services provision (Iregui, 2005), and rising wage inequality within the OECD (Winchester and Greenaway, 2007).

Common to virtually all these studies is the economy-wide impact of a change in one or more distortions. This is customarily measured by the marginal cost of public funds (MCF): the effect on money-metric social welfare of raising an additional dollar of government revenue through changing a particular tax instrument (Dahlby, 2008). GCE models' strength is their ability to capture the influence that pre-existing market distortions may have on the MCF in real-world "second best" policy environments. Distortions interact, potentially offsetting or amplifying one another, with the result that imposing an additional distortion in an already tariff-ridden economy may not necessarily worsen welfare, while removing an existing distortion is not guaranteed to be welfare improving (see, e.g., Ballard and Fullerton, 1992; Fullerton and Rogers, 1993; Slemrod and Yitzhaki, 2001). CGE models can easily report the MCF for any given, or proposed instrument, as the ratio of the money-metric welfare cost to increased tax revenue. Ranking policy instruments based on their MCF gives a good indication of efficiency enhancing reforms. An instructive example is Auriol and Warlters' (2012) analysis of the MCF in 38 African countries quantifying the welfare effects of taxes on domestic production, labor and capital, in addition to imports and exports. Factor taxes deserve special attention because a tax on a factor that is in perfectly inelastic supply does not distort allocation, implying that the effects of distortionary factor taxes can only be represented by introducing price-responsive factor supplies, modifying the market clearance conditions (11). The most common way to address this is to endogenize the supply of labor through introducing labor-leisure choice or unemployment (for elaborations see, e.g., Sue Wing, 2011 and Balistreri, 2002).

3.2 Emerging Applications: Energy Policy and Climate Change Mitigation

Energy policies, as well as measures to mitigate the problem of climate change through reductions in economies' emissions of greenhouse gases (GHGs), are two areas that over the past decade has been at the forefront of CGE model development and application. Sticking with the types of parameterically-driven shocks discussed in section 3.1, the energy economics and policy literature has investigated economic consequences of changing taxes and subsidies on conventional energy,[9] the social and environmental dimensions of energy use and policy,[10] macroeconomic consequences of energy price shocks (He et al., 2010; Aydin and Acar, 2011; Guivarch et al., 2009), and energy use, efficiency and conservation: and how they influence, and are affected by, the rate and direction of innovation and economic growth.[11] Further technical/methodological studies evaluate the representation of energy technology and substitution possibilities in CGE models (Schumacher and Sands, 2007; Beckman et al., 2011; Lecca et al., 2011), and the consequences of, and mitigating effect of policy interventions on, depletion of domestic fossil fuel reserves in resource-dependent economies (Djiofack and

Omgba, 2011; Barkhordar and Saboohi, 2013; Bretschger and Smulders, 2011).

An important development in energy markets is the widespread expansion of policy initives promoting alternative and renewable energy supplies. This topic has been an area of particular growth in CGE assessments.[12] In most areas of the world such energy supplies are more costly to operate than conventional energy production activities. Consequently, they typically make up a small or non-existent fraction of the extant energy supply, and are unlikely to be represented in current input-output accounts on which CGE model calibrations are based. To assess the macroeconomic consequences of new energy technologies it is therefore necessary to introduce into the canonical model new, non-benchmark production activities whose technical coefficients are derived from engineering cost studies and other ancillary data sources, whose higher operating costs relative to conventional activities in the SAM render their operation inactive in the benchmark equilibrium, but which are capable of endogenously switching on and producing output in response to relative price changes or policy stimuli.

These so-called "backstop" technology options—indexed by b—are implemented by specifying additional production functions whose outputs are perfect substitutes for an existing source of energy supply (e.g., electricity, e'). Their associated cost functions embody a premium over benchmark prices, modeled by the markup factor $MKUP_{e',r} > 1$, which can be offset by an output subsidy $\tau^b_{e',r} < 0$:

$$\begin{aligned} p^D_{e',r} \leq \left(1 + \tau^b_{e',r}\right) MKUP^b_{e',r} \cdot & \left[\sum_{i=1}^{\mathcal{N}} \left(\beta^b_{i,e',r}\right)^{\sigma^Y_{e',r}} \left(p^A_{i,r}\right)^{1-\sigma^Y_{e',r}} \right. \\ & \left. + \sum_{f=1}^{\mathcal{F}} \left(\gamma^b_{f,e',r}\right)^{\sigma^Y_{e',r}} w_{f,r}^{1-\sigma^Y_{e',r}} + \left(\gamma^b_{FF,e',r}\right)^{\sigma^Y_{e',r}} \left(w^b_{FF,e',r}\right)^{1-\sigma^Y_{e',r}} \right]^{1/(1-\sigma^Y_{e',r})} \quad \perp \quad y^b_{e',r} \qquad (28) \end{aligned}$$

Note that once $\tau^b_{e',r} \leq 1/MKUP^b_{e',r} - 1$ the backstop becomes cost-competitive with conventional supply of e' and switches on, but an unpleasant side effect of perfect substitutability is “bang-bang” behavior where a small increase in the subsidy parameter induces a jump in the backstop’s output, which in the limit can result in the backstop capturing the entire market ($y^b_{e',r} \gg y_{e',r}$). To replace such unrealistic behavior with a smooth path of entry along which both backstop and conventional supplies coexist, a popular trick is to introduce into the backstop production function a small quantity of a technology-specific fixed factor (with price $w^b_{FF,e',r}$ and technical coefficient $\gamma^b_{FF,e',r}$) whose limited endowment constraints the output of the backstop, even at favorable relative prices. The impact is apparent from the fixed-factor market clearance condition:

$$V_{FF,e',r} \geq \left(\gamma^b_{FF,e',r}\right)^{\sigma^Y_{e',r}} \left(w^b_{FF,e',r}\right)^{-\sigma^Y_{e',r}} \left(p^D_{e',r}\right)^{\sigma^Y_{e',r}} y^b_{e',r} \qquad \perp\ w^b_{FF,e',r} \tag{29}$$

where, with the fixed-factor endowment (V_{FF}) held constant, the quantity of backstop output increases with the fixed-factor’s relative price, $\left(w^b_{FF}/p^D\right)^{\sigma^Y}$. Thus, once the elasticity of substitution between the fixed-factor and other inputs is sufficiently small, even a large increase in the backsop price results in only modest backstop activity. In dynamic models the exogenously specified trajectory of V_{FF} is an important device for tuning new technologies’ penetration to the modeler’s sense of plausibility, especially when the future character and magnitude of “market barriers”, unanticipated complementary investments or negative network externalities represented by the fixed-factor constraint are unknown.

A related topic that has seen the emergence of a voluminous literature is climate change mitigation through policies to limit anthropogenic emissions of greenhouse gases (GHGs). Carbon dioxide (CO_2), the chief GHG, is emitted to the atmosphere primarily from the combustion of fossil fuels. Policies to curtail fossil fuel use tend to limit the supply of energy, whose signature characteristics of being an input to virtually every economic activity and possessing few low-cost substitutes (especially in the short-run) with the upshot that GHG mitigation policies have substantial general equilibrium impacts (Hogan and Manne, 1977).

The simplest policy instrument to consider is an economy-wide GHG tax. For expositional clarity we partition the set of commodities and industries into the subset of energy goods/sectors associated with CO_2 emissions (indexed by e, as before) and the complementary subset of non-energy material goods/sectors, indexed by m. The stoichiometric linkage between CO_2 and the carbon content of the fuel being combusted implies a Leontief relationship between emissions and the quantity of use of each fossil fuel. This is represented using fixed emission factors ($\epsilon_{e,r}^{\mathrm{CO_2}}$) that transform a uniform tax on emissions (τ_r^{GHG}) into a vector of differentiated markups on the unit cost of the e Armington energy commodities, as shown in eq. (30).

This simple scheme cannot be extended to non-CO_2 GHGs, the majority of which emanate from a broad array of industrial processes and household activities but are not linked in any fixed way to inputs of particular energy or material commodities. Non-CO_2 GHGs targeted by the Kyoto Protocol are methane, nitrous oxide, hyrdro- and perfluorocarbons, and sulfur hexafluaoride, which we index by $o = \{1 \ldots \mathcal{O}\}$, and whose global warming impact in units of CO_2-equivalents are given by $\epsilon_o^{\mathrm{GHG}}$. In an important advance, Hyman et al. (2003) develop a methodology for modeling non-CO_2 GHG abatement by treating these emissions as (a) *inputs* to the activities of firms and households, which (b) substitute for a composite of all other commodity and factor inputs with CES technology. The upshot is that the impact of a tax on non-CO_2 GHGs is mediated through a CES demand function whose elasticity to the costs of pollution control can be tuned to reproduce marginal abatement cost curves derived from engineering or partial-equilibrium economic studies. The key tuning parameters are the technical coefficients on emissions ($\vartheta_{o,j,r}$) and the elasticity of substitution between emissions and other inputs ($\sigma_{o,j,r}^{\mathrm{GHG}}$). The latter indicates the relative attractiveness of industrial process changes as a margin of adjustment to GHG price or quantity restrictions. Eq. (31) highlights the implications for production costs at the margin, which increase by the product of the unit demand for emissions of each category of pollutant, $(\vartheta_{o,j,r})^{-\sigma^{\mathrm{GHG}}_{o,j,r}} \left(\tau^{\mathrm{GHG}}_r \epsilon^{\mathrm{GHG}}_o\right)^{-\sigma^{\mathrm{GHG}}_{o,j,r}} \left(p^D_{j,r}\right)^{\sigma^{\mathrm{GHG}}_{o,j,r}}$, and its effective price $(\tau^{\mathrm{GHG}}_r \epsilon^{\mathrm{GHG}}_o)$.

$$\begin{aligned} p^A_{i,r} \leq {} & \left[\left(\zeta^D_{i,r}\right)^{\sigma^{DM}_{i,r}} \left(p^D_{i,r}\right)^{1-\sigma^{DM}_{i,r}} + \left(\zeta^M_{i,j,r}\right)^{\sigma^{DM}_{i,r}} \left(p^M_{i,r}\right)^{1-\sigma^{DM}_{i,r}}\right]^{1/(1-\sigma^{DM}_{i,r})} \\ & + \begin{cases} \tau^{\mathrm{GHG}}_r \epsilon^{CO_2}_{e,r} & e \subset i \\ 0 & \text{otherwise} \end{cases} \qquad \perp \quad q^A_{i,r} \end{aligned} \tag{30}$$

$$\begin{aligned} p^D_{j,r} \leq {} & \left[\sum_{i=1}^{\mathcal{N}} \beta_{i,j,r}^{\sigma^Y_{j,r}} \left(p^A_{i,r}\right)^{1-\sigma^Y_{j,r}} + \sum_{f=1}^{\mathcal{F}} \gamma_{f,j,r}^{\sigma^Y_{j,r}} w_{f,r}^{1-\sigma^Y_{j,r}}\right]^{1/(1-\sigma^Y_{j,r})} \\ & + \sum_{o=1}^{\mathcal{O}} (\vartheta_{o,j,r})^{-\sigma^{\mathrm{GHG}}_{o,j,r}} \left(\tau^{\mathrm{GHG}}_r \epsilon^{\mathrm{GHG}}_o\right)^{1-\sigma^{\mathrm{GHG}}_{o,j,r}} \left(p^D_{j,r}\right)^{\sigma^{\mathrm{GHG}}_{o,j,r}} \qquad \perp \quad p^D_{j,r} \end{aligned} \tag{31}$$

$$\begin{aligned} \mathscr{I}_r = {} & \sum_{f=1}^{\mathcal{F}} w_{f,r} V_{f,r} + \sum_{e} \tau^{\mathrm{GHG}}_r \epsilon^{\mathrm{CO_2}}_{e,r} q^A_{e,r} \\ & + \sum_{j=1}^{\mathcal{N}} \sum_{o=1}^{\mathcal{O}} \left[(\vartheta_{o,j,r})^{-\sigma^{\mathrm{GHG}}_{o,j,r}} \left(\tau^{\mathrm{GHG}}_r \epsilon^{\mathrm{GHG}}_o\right)^{1-\sigma^{\mathrm{GHG}}_{o,j,r}} \left(p^D_{j,r}\right)^{\sigma^{\mathrm{GHG}}_{o,j,r}} y_{j,r}\right] \qquad \perp \quad \mathscr{I}_r \end{aligned} \tag{32}$$

A model of economy-wide GHG taxation is made up of eqs. (1), (2), (5)-(13), with eqs. (31) and (30) substituting for (3) and (4), τ^{GHG}_r specified as an exogenous parameter, and explicit accounting for recycling of the resulting tax revenue in the income balance condition (32), which replaces (14). In a domestic cap-and-trade system the tax is interpreted as the price of emission allowances and is endogenous, exhibiting complementary slackness with respect to the additional multigas emission limit (33). In the simplest case, rents generated under such a policy redound to households as payments to emission rights ($\mathscr{A}_r$), with which they are assumed to be endowed. The income balance condition (34) must then be substituted for (32).

$$\begin{aligned} & \sum_{e} \epsilon^{\mathrm{CO_2}}_{e,r} q^A_{e,r} \\ & + \sum_{j=1}^{\mathcal{N}} \sum_{o=1}^{\mathcal{O}} \left[(\vartheta_{o,j,r})^{-\sigma^{\mathrm{GHG}}_{o,j,r}} \left(\tau^{\mathrm{GHG}}_r \epsilon^{\mathrm{GHG}}_o\right)^{-\sigma^{\mathrm{GHG}}_{o,j,r}} \left(p^D_{j,r}\right)^{\sigma^{\mathrm{GHG}}_{o,j,r}} y_{j,r}\right] \leq \mathscr{A}_r \quad \perp \tau^{\mathrm{GHG}}_r \end{aligned} \tag{33}$$

$$\mathscr{I}_r = \sum_{f=1}^{\mathcal{F}} w_{f,r} V_{f,r} + \tau_r^{\mathrm{GHG}} \mathscr{A}_r \qquad \perp \quad \mathscr{I}_r \tag{34}$$

A multilateral emission trading scheme over the subset of abating regions, $\mathcal{R}^\dagger$, is easily implemented by dropping the region subscript on the allowance price ($\tau_r^{\mathrm{GHG}} = \tau^{\mathrm{GHG}}\ \forall r \in \mathcal{R}^\dagger$) and taking the sum of eq. (33) across regions to specify the aggregate emission limit (35). The latter, which is the sum of individual regional emission caps ($\overline{\mathscr{A}} = \sum_{r \in \mathcal{R}^\dagger} \mathscr{A}_r$), induces allocation of emissions across regions, sectors and gases to equalize the marginal costs of abatement. The income and/or welfare consequences for an individual region may be positive or negative depending on whether its residual emissions are below or above its cap, inducing net purchases or sales of allowances.

$$\begin{aligned} &\sum_{r \in \mathcal{R}^\dagger} \Bigg\{ \sum_e \epsilon_{e,r}^{\mathrm{CO_2}} q_{e,r}^A \\ &\quad + \sum_{j=1}^{\mathcal{N}} \sum_{o=1}^{\mathcal{O}} \left[\left(\vartheta_{o,j,r}\right)^{-\sigma_{o,j,r}^{\mathrm{GHG}}} \left(\tau^{\mathrm{GHG}} \epsilon_o^{\mathrm{GHG}}\right)^{-\sigma_{o,j,r}^{\mathrm{GHG}}} \left(p_{j,r}^D\right)^{\sigma_{o,j,r}^{\mathrm{GHG}}} y_{j,r} \right] - \overline{\mathscr{A}} \Bigg\} \leq 0 \quad \perp \tau^{\mathrm{GHG}} \qquad (35) \\ &\mathscr{I}_r = \sum_{f=1}^{\mathcal{F}} w_{f,r} V_{f,r} + \tau^{\mathrm{GHG}} \mathscr{A}_r - \sum_e \tau^{\mathrm{GHG}} \epsilon_{e,r}^{\mathrm{CO_2}} q_{e,r}^A \\ &\qquad - \sum_{j=1}^{\mathcal{N}} \sum_{o=1}^{\mathcal{O}} \left[\left(\vartheta_{o,j,r}\right)^{-\sigma_{o,j,r}^{\mathrm{GHG}}} \left(\tau^{\mathrm{GHG}} \epsilon_o^{\mathrm{GHG}}\right)^{1-\sigma_{o,j,r}^{\mathrm{GHG}}} \left(p_{j,r}^D\right)^{\sigma_{o,j,r}^{\mathrm{GHG}}} y_{j,r} \right] \qquad \perp \quad \mathscr{I}_r \qquad (36) \end{aligned}$$

Finally, slow progress in implementing binding regimes for climate mitigation—either an international system of emission targets or comprehensive economy-wide emission caps at the national level—has re-focused attention on assessing the consequences of piecemeal policy initiatives, particularly GHG abatement and allowance trading within sub-national regions and/or sectors nations. The major consequence is an inability to reallocate abatement across sources as a way of arbitraging differences in the marginal costs of emission reductions, which may be captured by differentiating emission limits and their complementary shadow prices among covered sectors (say j') and regions (say r'): $\mathscr{A}_{j',r'}$ and $\tau_{j',r'}^{\mathrm{GHG}}$. The key concern prompted by such rigidities is emission "leakage", which occurs when emission limits imposed on a subset of sources that interact in markets for output and polluting inputs actually stimulate unconstrained sources to emit more pollution. The extent of the consequent shift in emissions is captured by the leakage rate, defined as the negative of the ratio of the increase in unconstrained sources' emissions to constrained sources' abatement. Quantifying this rate and characterizing its precursors requires input-based accounting for emissions, as taxes or quotas apply not to the supply of energy commodities across the economy, but to their use by qualifying entities.

$$\begin{aligned}
&\sum_{e}\sum_{j'} \beta_{e,j',r'}^{\sigma^{Y}_{j',r'}} \left(p^{A}_{e,r'} + \tau^{\text{GHG}}_{j',r'} \epsilon^{CO_2}_{e,r'}\right)^{-\sigma^{Y}_{j',r'}} \left(p^{D}_{j',r'}\right)^{\sigma^{Y}_{j',r'}} y_{j',r'} \\
&\qquad + \sum_{j'}\sum_{o=1}^{\mathcal{O}} \left[\left(\vartheta_{o,j',r'}\right)^{-\sigma^{\text{GHG}}_{o,j',r'}} \left(\tau^{\text{GHG}}_{r} \epsilon^{\text{GHG}}_{o}\right)^{-\sigma^{\text{GHG}}_{o,j',r'}} \left(p^{D}_{j',r'}\right)^{\sigma^{\text{GHG}}_{o,j',r'}} y_{j',r'}\right] \leq \mathscr{A}_{j',r'} \quad \perp \tau^{\text{GHG}}_{j',r'} \qquad (37)
\end{aligned}$$

$$\begin{aligned}
p^{D}_{j',r'} \leq &\left[\sum_{e} \beta_{e,j',r'}^{\sigma^{Y}_{j',r'}} \left(p^{A}_{e,r'} + \tau^{\text{GHG}}_{j',r'} \epsilon^{CO_2}_{e,r'}\right)^{1-\sigma^{Y}_{j',r'}}\right. \\
&\qquad \left. + \sum_{m} \beta_{m,j',r'}^{\sigma^{Y}_{j',r'}} \left(p^{A}_{m,r'}\right)^{1-\sigma^{Y}_{j',r'}} + \sum_{f=1}^{\mathcal{F}} \gamma_{f,j,r}^{\sigma^{Y}_{j',r'}} w_{f,r}^{1-\sigma^{Y}_{j',r'}}\right]^{1/(1-\sigma^{Y}_{j',r'})} \\
&\qquad + \sum_{o=1}^{\mathcal{O}} \left(\vartheta_{o,j',r'}\right)^{-\sigma^{\text{GHG}}_{o,j',r'}} \left(\tau^{\text{GHG}}_{j',r'} \epsilon^{\text{GHG}}_{o}\right)^{1-\sigma^{\text{GHG}}_{o,j',r'}} \left(p^{D}_{j',r'}\right)^{\sigma^{\text{GHG}}_{o,j',r'}} \quad \perp p^{D}_{j',r'} \qquad (38)
\end{aligned}$$

$$\begin{aligned}
\mathscr{I}_r = &\sum_{f=1}^{\mathcal{F}} w_{f,r} V_{f,r} + \sum_{e}\sum_{j'} \tau^{\text{GHG}}_{j',r'} \mathscr{A}_{j',r'} \\
&\qquad + \sum_{j'}\sum_{o=1}^{\mathcal{O}} \left[\left(\vartheta_{o,j',r'}\right)^{-\sigma^{\text{GHG}}_{o,j',r'}} \left(\tau^{\text{GHG}}_{j',r'} \epsilon^{\text{GHG}}_{o}\right)^{1-\sigma^{\text{GHG}}_{o,j',r'}} \left(p^{D}_{j',r'}\right)^{\sigma^{\text{GHG}}_{o,j',r'}} y_{j',r'}\right] \quad \perp \mathscr{I}_r \qquad (39)
\end{aligned}$$

The foregoing models have principally been used to analyze the macroeconomic consequences of emission reduction policies at multiple scales—traditionally international,[13] but increasingly regional and national,[14] and even subnational (Zhang et al., 2013; Springmann et al., 2014) or sectoral (Rausch and Mowers, 2014). CGE models' key advantage is their ability to quantify complex interactions between climate policies and a panoply of other policy instruments and characteristics of the economy. While the universe of these elements is too broad to consider in detail, key issues include the distributional effects of climate policies on consumers, firms and regions,[15] mitigation in second best settings, fiscal policy interactions, and the double dividend,[16] alternative compliance strategies such as emission offsets and the Clean Development Mechanism,[17] interactions between mitigation and trade, emissions leakage, and the efficacy of countervailing border tariffs on GHGs embodied in traded goods,[18] the effects of structural change, innovation, technological progress and economic growth on GHG emissions and the costs of mitigation in various market settings,[19] energy market interactions,[20] and the role of discrete technology options on both the supply side (e.g., renewables and carbon-capture and storage) and the demand side (e.g., conventional and alternative-fuel transportation).[21]

3.3 New Horizons: Assessing the Impacts of Climate Change and Natural Hazards

Turning now to the flip-side of mitigation, the breadth and variety of pathways through which the climate influences economic activity are enormous (Dell et al., 2014), and improved understanding of these channels has spurred the growth of a large literature on the impacts of climate change. CGE models have the unique capability to represent in a comprehensive fashion the regional and sectoral scope of climatic consequences—if not their detail—and can easily accommodate region- and sector-specific damage functions from the impacts of climate change. However, this advantage comes at the cost of inability to capture intertemporal feedbacks. Following from the discussion in Section 2.3, despite recent progress in intertemporal CGE modeling, computational constraints often limit the resolution of these machines to a handful of regions and sectors and a short time-horizon. Thus, as summarized in Table 3, a common feature of the CGE models in this are of application is that they are either static

Table 3: CGE Studies of Climate Change: Impacts and Adaptation

Studies	**Regions**	**Sectoral Focus**	**Models Employed**
Deke et al. (2001)	Global (11 regions)	Agriculture, Sea-level rise	DART (Klepper et al., 2003)
Darwin (1999)	Global (8 regions)	Agriculture Sea level rise	FARM (Darwin et al., 1995)
Darwin et al. (2001)			
Jorgenson et al. (2004)	U.S. (1 region)	Agriculture, Forestry Water, Energy, Air quality, Heat stress, Coastal protection	IGEM (Jorgenson and Wilcoxen, 1993)
Bosello et al. (2006) Bosello and Zhang (2006) Bosello et al. (2007) Bosello et al. (2007)	Global (8 regions)	Health Agriculture Energy demand Sea level rise	GTAP-EF (Roson, 2003)
Berrittella et al. (2006), Bigano et al. (2008)	Global (8 regions)	Tourism, Sea level rise	Couples HTM (Hamilton et al., 2005) with GTAP-EF
Eboli et al. (2010)	Global (14 regions)	Agriculture, Tourism, Health, Energy demand, Sea level rise	ICES
Bosello et al. (2010a)			Couples AD-WITCH (Bosello et al., 2010b) with ICES
Ciscar et al. (2011)	Europe (5 regions)	Agriculture, Sea-level rise, Flooding, Tourism	GEM-E3 (Capros et al., 1997)

simulations of a future time period (e.g., Roson, 2003; Bosello and Zhang, 2006; Bosello et al., 2007) or recursive dynamic simulations driven by contemporaneously-determined investment (e.g., Deke et al., 2001; Eboli et al., 2010; Ciscar et al., 2011), with 2050 being the typical simulation horizon. Consequently, they tend to simulate the welfare effects of passive market adjustments to climate shocks, or, at best, "reactive" contemporaneous averting expenditures in sectors and regions, but not proactive investments in adaptation.

Table 3 indicates that, apart from a few studies (Jorgenson et al., 2004; Eboli et al., 2010; Ciscar et al., 2011; Bosello et al., 2012), CGE analyses tend to investigate the broad multi-market effects of one or two impact endpoints at a time. The latter are derived by forcing global climate models with various scenarios of GHG emissions to calculate changes in climate variables at the regional scale, generating response surfaces of temperature, precipitation or sea-level rise that are then run through natural science or engineering-based impact models to generate a vector of impact endpoints of particular kinds. These “impact factors” are a region × sector array of exogenous shocks which are inputs to the model’s counterfactual simulations.

Shocks fall into three basic categories. First, they affect the supply of climatically exposed primary factors such as land (Deke et al., 2001; Darwin et al., 2001), which we denote $IF^{\text{Fact.}}_{f,r} \in (0,1)$, and scale the factor endowments in the model. The factor market clearance and income balance conditions (11) and (14) are then:

$$IF^{\text{Fact.}}_{f,r} V_{f,r} \geq \sum_{j=1}^{\mathcal{N}} \gamma^{\sigma^Y_{j,r}}_{f,j,r} w^{-\sigma^Y_{j,r}}_{f,r} \left(p^D_{j,r}\right)^{\sigma^Y_{j,r}} y_{j,r} \qquad \perp \quad w_{f,r} \tag{40}$$

$$\mathscr{I}_r = \sum_{f=1}^{\mathcal{F}} w_{f,r} IF^{\text{Fact.}}_{f,r} V_{f,r} \qquad \perp \quad \mathscr{I}_r \tag{41}$$

Second, impact factors affect sectors’ transformation efficiency (see, e.g., Jorgenson et al., 2004), thereby acting as productivity shift parameters in the unit cost function, where adverse impacts drive up both the marginal cost of production and reduce affected sectors’ demands for inputs according to the scaling factor $IF^{\text{Prod.}}_{f,r} \in (0,1)$. As a consequence, the zero profit and market clearance conditions (3) and (8) become:

$$p^D_{j,r} \leq \left(IF^{\text{Prod.}}_{j,r}\right)^{-1} \left[\sum_{i=1}^{\mathcal{N}} \beta^{\sigma^Y_{j,r}}_{i,j,r} \left(p^A_{i,r}\right)^{1-\sigma^Y_{j,r}} + \sum_{f=1}^{\mathcal{F}} \gamma^{\sigma^Y_{j,r}}_{f,j,r} w^{1-\sigma^Y_{j,r}}_{f,r}\right]^{1/(1-\sigma^Y_{j,r})} \qquad \perp \quad y_{i,r} \tag{42}$$

$$\begin{aligned} q^A_{i,r} \geq{} & \left(\alpha^C_{i,r}\right)^{\sigma^C_r} \left(p^A_{i,r}\right)^{-\sigma^C_r} \mathscr{E}^{\sigma^C_r} u_r + \left(\alpha^I_{i,r}\right)^{\sigma^I_r} \left(p^A_{i,r}\right)^{-\sigma^I_r} \left(p^I_r\right)^{\sigma^I_r} G^I_r \\ & + \sum_{j=1}^{\mathcal{N}} \left(IF^{\text{Prod.}}_{j,r}\right)^{\sigma^Y_{j,r}-1} \beta^{\sigma^Y_{j,r}}_{i,j,r} \left(p^A_{i,r}\right)^{-\sigma^Y_{j,r}} \left(p^D_{j,r}\right)^{\sigma^Y_{j,r}} y_{j,r} \qquad \perp \quad p^A_{i,r} \end{aligned} \tag{43}$$

Third, impact factors affect the efficiency of inputs to firms’ production and households’ consumption activities. Perhaps the clearest example of this is the impact of increased temperatures on the demands for heating and cooling services, and in turn electric power. Such warranted increases in the consumption of climate-related inputs can be treated as a biased technological retrogression which increases the coefficient on the relevant commodities (say, i') in the model's cost and expenditure functions: $IF^{\text{Input}}_{i',j,r} > 1$ and $IF^{\text{Input}}_{\neg i',j,r} = 1$. Here, zero profit in consumption (1) and eqs. (3) and (8) become:

$$\mathscr{E}_r \le \left[\sum_{i=1}^{\mathcal{N}} \left(\alpha^C_{i,r}\right)^{\sigma^C_r} \left(p^A_{i,r} / IF^{\text{Input}}_{i,\text{Hhold.},r}\right)^{1-\sigma^C_r} \right]^{1/(\sigma^C_r - 1)} \quad \perp \quad u_r \tag{44}$$

$$p^D_{j,r} \le \left[\sum_{i=1}^{\mathcal{N}} \beta^{\sigma^Y_{j,r}}_{i,j,r} \left(p^A_{i,r} / IF^{\text{Input}}_{j,r}\right)^{1-\sigma^Y_{j,r}} + \sum_{f=1}^{\mathcal{F}} \gamma^{\sigma^Y_{j,r}}_{f,j,r} w^{1-\sigma^Y_{j,r}}_{f,r} \right]^{1/(1-\sigma^Y_{j,r})} \quad \perp \quad y_{i,r} \tag{45}$$

$$\begin{aligned} q^A_{i,r} \ge {} & \left(\alpha^C_{i,r}\right)^{\sigma^C_r} \left(p^A_{i,r} / IF^{\text{Input}}_{i,\text{Hhold.},r}\right)^{-\sigma^C_r} \mathscr{E}^{\sigma^C_r} u_r + \left(\alpha^I_{i,r}\right)^{\sigma^I_r} \left(p^A_{i,r}\right)^{-\sigma^I_r} \left(p^I_r\right)^{\sigma^I_r} G^I_r \\ & + \sum_{j=1}^{\mathcal{N}} \beta^{\sigma^Y_{j,r}}_{i,j,r} \left(p^A_{i,r} / IF^{\text{Input}}_{i,\text{Hhold.},r}\right)^{-\sigma^Y_{j,r}} \left(p^D_{j,r}\right)^{\sigma^Y_{j,r}} y_{j,r} \quad \perp \quad p^A_{i,r} \end{aligned} \tag{46}$$

In each instance, intersectoral and interregional adjustments in response to impacts, and the consequences for sectoral output, interregional trade and regional welfare, can be computed.

The magnitude of damage to the economy due to climate change estimated by CGE studies varies according to the scenario of warming or other climate forcing used to drive impact endpoints, the sectoral and regional resolution of both the resulting shocks and the models used to simulate their economic effects, and the latter's substitution possibilities. Table 4 gives a sense of the relevant variation across six studies that focus on the economic consequences of different endpoints circa 2050. The magnitude of economic consequences is generally small, rarely exceeding one tenth of one percent of GDP. Effects also vary in sign, with some regions benefiting from increased output while others sustaining losses. While there does not appear to be obvious systematic variation in the sign of effects, either across different endpoints or among regions, uncovering relevant patterns is complicated by a host of confounding factors. The studies use different climate change scenarios, and for each impact category economic shocks are constructed from distinct sets of empirical and modeling studies, each with its own regional and sectoral coverage, using different procedures. The influence that such critical details have on model results difficult to discern because the unavoidable omission of modeling details necessitated by journal articles terse exposition. In particular, the precise steps, judgment and assumptions involved in constructing region-by-sector arrays of economic shocks out of inevitably patchy empirical evidence tends to be reported only in a summary fashion. Strengthening the empirical basis for such input data, and documenting in more detail the analytical procedures to generate $IF^{\text{Fact.}}_{f,j,r}$, $IF^{\text{Prod.}}_{j,r}$ and $IF^{\text{Input}}_{i',j,r}$, will go a long way toward improving the replicability of studies in this literature. Indeed, this area of research is rich with opportunities for interdisciplinary collaboration among modelers, empirical economists, natural scientists and engineers.

Recent large-scale studies define the state of the art in this regard. In the PESETA study of climate impacts on Europe in the year 2050 (Ciscar et al., 2009, 2011, 2012), estimates of physical impacts were constructed by propagating a consistent set of climate warming scenarios through different process simulations in four impact categories: agriculture (Iglesias et al., 2012), flooding (Feyen et al., 2012), sea-level rise (Bosello et al., 2012), and tourism (Amelung and Moreno, 2012). These “bottom-up” results were then incorporated into the GEM-E3 model using a variety of techniques to map the endpoints to the types of effects on economic sectors (Ciscar et al., 2012). Estimated changes in crop yields were implemented as neutral productivity retrogressions in the agriculture sector. Flood damages were translated into additional unproductive expenditures by households, secular reductions in the output of the agriculture sector, and reductions in the outputs of and capital inputs to industrial and commercial sectors. Changes in visitor occupancy were combined with “per bed-night” expenditure data to estimate changes in tourist spending by country, and in turn expressed as secular changes in exports of GEM-E3’s market services sector. Costs of migration induced by land lost to sea-level rise are incurred by households as additional expenditures, while related coastal flooding is assumed to equiproportionally reduce sectors endowments of capital. (The direct macroeconomic effects of reduced land endowments were not considered.)

In Bosello et al. (2012), estimates of the global distribution of physical impacts in six cate-

Table 4: Costs of Climate Change impacts to year 2050: Selected CGE Modeling Studies

Forcing Scenario and Input Data	**Impact Endpoints, Economic Shocks and Damage Costs**
Agriculture (Bosello and Zhang, 2006)	
0.93°C global mean temperature rise; temperature-agricultural output relationship calculated by FUND	Endpoints considered: temperature, CO_2 fertilization effects on agricultural productivity Shocks: land productivity in crop sectors Change in GDP from baseline: 0.006-0.07% increases in rest of Annex 1 regions, 0.01-0.025% loss in USA and energy exporting countries, -0.13% loss in the rest of the world
Energy Demand (Bosello et al., 2007)	
0.93°C global mean temperature rise; temperature-energy demand elasticities from De Cian et al. (2013)	Endpoints considered: temperature effects on demand for 4 energy commodities Shocks: productivity of intermediate and final energy uses Change in GDP from baseline: 0.04-0.29% loss in remaining Annex I (developed) regions, 0.004-0.03% increase in Japan, China/India and the rest of the world, 0.3% loss in energy exporting countries. Results for perfect competition only.
Health (Bosello et al., 2006)	
1°C global mean temperature rise; temperature-disease and disease-cost relationships extrapolated from numerous empirical and modeling studies	Endpoints considered: malaria, schistosomiasis, dengue fever, cardiovascular disease, respiratory ailments, diarrheal disease Shocks: labour productivity, increased household expenditures on public and private health care, reduced expenditures on other commodities Direct costs/benefits (% of GDP): 9% in US and Europe, 11% in Japan and the remainder of the Annex 1, 14% in Eastern Europe and Russia, benefits of 1% in energy exporters and 3% in the rest of the world Change in GDP from baseline: 0.04-0.08% increase in Annex 1 regions, 0.07-0.1% loss in energy exporting countries and the rest of the world
Sea level rise/Tourism (Bigano et al., 2008)	
Uniform global 25cm sea level rise; land loss calculated by FUND	Endpoints considered: land loss, change in tourism arrivals as a function of land loss Shocks: reduction in land endowment Direct costs (% of GDP): $<$ 0.005% loss in most regions, 0.05% in North Africa, 0.1-0.16% South- and South-East Asia and 0.24% in Sub-Saharan Africa. Costs are due to land loss only. Change in GDP from baseline: $<$ 0.0075% loss in most regions, 0.06% in South Asia and 0.1% in South-East Asia
Ecosystem services (Bosello et al., 2011)	
1.2°C/3.1°C temperature rise, with and without impacts on ecosystems	Endpoints considered: timber and agricultural production, forest/cropland/grassland carbon sequestration Shocks: reduced land productivity, reduced carbon sequestration resulting in increased temperature change impacts on 5 endpoints in Eboli et al. (2010) Change in GDP (3.1°C, 2001-2050 NPV @ 3%): \$22-\$32Bn additional loss in E. and Mediterranean Europe, \$5Bn reduction in loss in N. Europe
Water Resources (Calzadilla et al., 2010)	
Scenarios of rainfed and irrigated crop production, irrigation efficiency based on Rosegrant et al. (2008)	Endpoints considered: crop production Shocks: supply/productivity of irrigation services Change in Welfare: losses in 5 regions range from \$60M in Sub-Saharan Africa to \$442M in Australia/New Zealand, gains in 11 regions range from \$180M in the rest of the world to \$3Bn in Japan/Korea

gories in the year 2050 were derived from the results of different process simulations forced by a 1.9°C global mean temperature increase. Endpoints were expressed as shocks within the ICES model. Regional impacts on energy and tourism were treated as shocks to household demand. Changes in final demand for oil, gas, and electricity (based on results from a bottom-up energy system simulation— Mima et al., 2011) were expressed as biased productivity shifts in the aggregate unit expenditure function. A two-track strategy was adopted to simulate changes in tourism flows (arrival changes from an econometrically-calibrated simulation of tourist flows— Bigano et al., 2007), with non-price climate-driven substitution effects captured through secular productivity biases which scale regional households demands for market services (the ICES commodity which includes recreation), and the corresponding income effects imposed as direct changes in regional expenditure. Regional impacts on agriculture and forestry, health, and the effects of river floods and sea-level rise, were treated as supply-side shocks. Changes in agricultural yields (generated by a crop simulation— Iglesias et al., 2011) and forest net primary productivity (simulated by a global vegetation model— Bondeau et al., 2007; Tietjen et al., 2009) were represented as exogenous changes in the productivity of the land endowment in the agriculture sector and the natural resource endowment in the timber sector, respectively. The impact of higher temperatures on employment performance was modeled by reducing aggregate labour productivity (based on heat and humidity effects estimated by Kjellstrom et al., 2009). Losses of land and buildings due to sea-level rise (whose costs were derived from a hydrological simulation— Van Der Knijff et al., 2010) were expressed as secular reductions in regional endowments of land and capital, which are assumed to decline by the same fraction. Damages from river flooding span multiple sectors and are therefore imposed using different methods: reduction of the endowment of arable land in agriculture and equiproportional reduction in the productivity of capital inputs to other industry sectors, as well as reductions in labour productivity (equivalent to a one-week average annual loss of working days per year in each region) for affected populations.

An important aspect of climate impacts assessment that is ripe for investigation is the application of CGE models to evaluate the effects of specific adaptation investments. Work in this area is currently limited by a lack of information about the relevant technology options, and pervasive uncertainty about the magnitude, timing, and regional and sectoral incidence of various types of impacts. The difficult but essential work of characterizing adaptation technologies that are the analogues of those in section 3.2 will render similar analyses for reactive adaptation straightforward. Moreover, Bosello et al.'s (2010a) methodological advance of coupling a CGE model with an optimal growth simulation of intertemporal feedbacks on the accumulation of stock adaptation capacity (Bosello et al., 2010b) paves the way to model *proactive* investment in adaptation.

Similar issues arise in CGE analyses of the macroeconomic costs of natural and man-made hazards (Rose, 2005; Rose et al., 2004; Rose and Guha, 2004; Rose and Liao, 2005; Rose et al., 2009; Dixon et al., 2010). The key distinction that must be made is between the three types of impact factors. The parameter $IF^{\text{Fact.}}_{i,j,r}$ captures components of damage that cause direct destruction of the capital stock (e.g., earthquakes, floods or terrorist bombings) or reduction in the labor supply (e.g., morbidity/mortality or evacuation of populations from the disaster zone). Second, $IF^{\text{Prod.}}_{j,r}$ captures impacts that reduce sectors' productivity while leaving factor endowments intact, such as utility lifeline outages (Rose and Liao, 2005) or pandemic disease outbreaks where workers in many sectors shelter at home as a precaution (Dixon et al., 2010). Third, $IF^{\text{Input}}_{i',j,r}$ can be used to model input-using biases of technical change in the post-disaster recovery phase, e.g., increased demand for construction services.

The fact that these input parameters must often be derived from engineering loss estimation simulations such as the US Federal Emergency Management Agency's HAZUS software raises additional methodological issues. Principal among these are the need to specify reductions in the aggregate endowment of capital input that are consistent with capital stock losses across a range of sectors, and to reconcile them with exogenous estimates of industry output losses for the purpose of isolating non-capital related shocks to productivity. The broader concern, which applies equally to climate impacts, is the extent to which the methods used to derive the input shocks inadvertently incorporate the kinds of economic adjustments that CGE model is tasked with simulating—leading to potential double-counting of both losses and the mitigating effects of substitution. These questions are the subject of ongoing research.

4 EXTENSIONS TO THE STANDARD MODEL

4.1 Production Technology: Substitution Possibilities, Bottom-Up vs. Top-Down

In the vast majority of CGE models firms' technology is specified using hierarchical or nested CES production functions, whose properties of monotonicity and global regularity facilitate the computation of equilibrium (Perroni and Rutherford, 1993, 1998), while providing the flexibility to capture complex patterns of substitution among capital, labor, and intermediate inputs of energy and materials. A key consequence of this modeling choice is that numerical calibration of the resulting model to a SAM becomes a severely under-determined problem, with the number of model parameters greatly exceeding the degrees of freedom in the underlying benchmark calibration dataset.

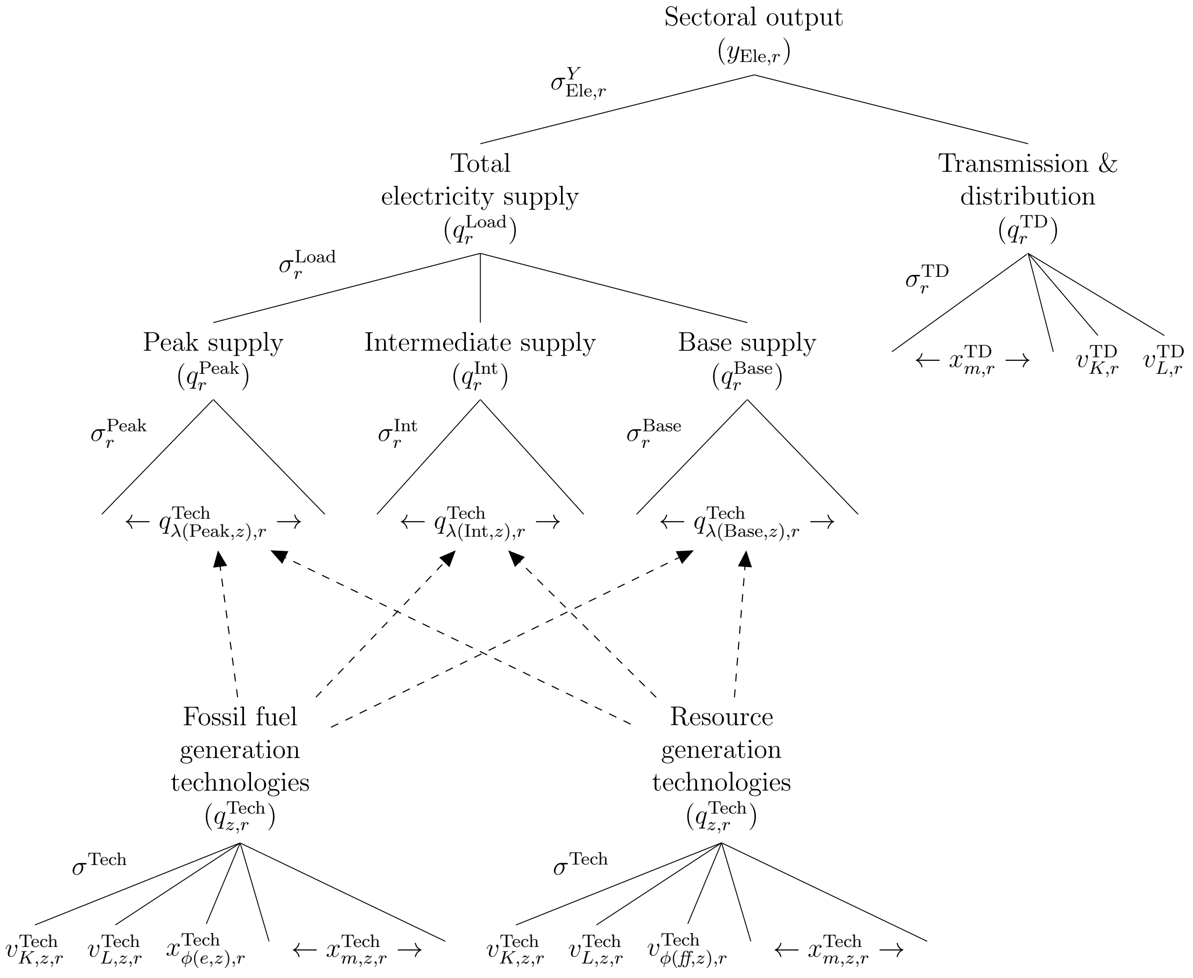
It is common for both the nested structure of production and the corresponding elasticity of substitution parameters to be be selected on the basis of judgment and assumptions, a practice which has long been criticized by mainstream empirical economists (e.g., Jorgenson, 1984). While econometric calibration of CGE models' technology has traditionally been restricted to flexible functional forms such as the Translog (McKitrick, 1998; McKibbin and Wilcoxen, 1998; Fisher-Vanden and Sue Wing, 2008; Fisher-Vanden and Ho, 2010; Jin and

Jorgenson, 2010), there has been recent interest in estimating nested CES functions (van der Werf, 2008; Okagawa and Ban, 2008). Progress in this area continues to be hampered by lack of data, owing to the particular difficulty of compiling time-sequences of input-output datasets with consistent price and quantity series. In an attempt to circumvent this problem, various approaches have been developed for calibrating elasticity parameters to reproduce empirically estimated input price elasticities (e.g., Arndt et al., 2002; Adkins et al., 2003; Gohin, 2005), but these have yet to be widely adopted by the CGE modeling community.

A parallel development is the trend toward modifying CGE models' specification of production to incorporate discrete "bottom-up" technology options. This has been especially popular in climate change mitigation research, where it enables CGE models to capture the effects of GHG abatement measures on the competition between conventional and alternative energy technologies, and to simulate the general equilibrium incidence of policies to promote "green" energy supply or conversion options such as renewable electricity or hybrid electric vehicles. The incorporation of bottom-up detail in CGE models marries the detail of primal partial equilibrium activity analysis simulations with general equilibrium feedbacks of price and substitution adjustments across the full range of consuming sectors in the economy. This hybrid modeling approach has been used in energy technology assessments relating to transportation (Schafer and Jacoby, 2005) and fuel supply (Chen et al., 2011), its most popular are of application is prospective analyses of electric power production, an example of which we provide below.

Methods for incorporating discrete technology detail and substitution in CGE models break down into two principal classes, namely the "decomposition" approach of Böhringer and Rutherford (2008, 2009) and Lanz and Rausch (2011) and the "integrated" approach of Böhringer (1998). The first method simulates a top-down CGE model in tandem with a bottom-up energy technology model iterating back and forth to convergence.[22] Briefly, the representative agent in the top-down model is "endowed" with quantities of energy supplied

Figure 3: A Bottom-Up/Top-Down Model of Electric Power Production



by the various active technology options, which it uses to compute both the prices of the inputs to and outputs of the energy supply sectors, and the levels of aggregate demand for energy commodities. These results are passed as inputs to the bottom-up model to compute the aggregate cost-minimizing mix of energy supply, conversion or demand activities, whose outputs are used to update the top-down model's endowments at the subsequent iteration. The second approach embeds activity-analysis representations of bottom-up technology options directly into a top-down model's sectoral cost functions, numerically calibrating discrete activities' inputs and outputs to be jointly consistent with ancillary statistics and the social accounts. The key requirement is a consistent macro-level representation of sub-sectoral technology options and their competition in both input and output markets, which is precisely where the nested CES model of production proves useful.

To illustrate what the integrated approach involves, we consider a simplified version of the top-down/bottom-up model of electricity production in Sue Wing (2006, 2008). Figure 3 shows the production structure, which divides the sector into five activities. Delivered electricity (A1) is a CES function of transmission and distribution (A2) and aggregate electricity supply (A3). Transmission and distribution is a CES function of labor, capital, intermediate non-fuel inputs, while aggregate electricity supply is a CES aggregation of three load segments $\ell = \{\text{peak, intermediate, base}\}$. Each load segment (A4) is a CES aggregation of subsets of the z generation outputs, defined by the mapping from load to technology $\lambda(\ell, z)$. Lastly, individual technologies (A5) produce electricity from labor, capital, non-energy materials and either fossil fuels ($e \subset i$) or "fixed-factor" energy resources ($\mathit{ff} \subset f$) in the case of nuclear, hydro or renewable power. The latter are defined by the fuel-to-technology mappings $\phi(e, z)$ and $\phi(\mathit{ff}, z)$.

Several aspects of this formulation merit discussion. First, substitutability between transmission and the total quantity of electricity generated by the sector captures the fact that transmission investments' reductions in congestion and line losses can maintain the level of delivered power with less physical energy, at least over a small range, suggesting the substitution elasticity value $\sigma^Y_{\text{Ele},r} \ll 1$. Second, while disaggregation of electricity supply—rather than demand—into load segments may seem counterintuitive, it is a conscious choice driven by the exigencies of data availability and model tractability. Demand-side specification of load segments necessitates row disaggregation of the SAM into separate accounts for individual users' demands for peak, intermediate and base power. The necessary information is simply not available, which motivates the present structure that is designed to keep delivered electric power as a homogeneous commodity while differentiating generation by different technologies. This device is meant to capture the fact that only subsets of the universe of

Table 5: Summary of Variables in the Bottom-Up/Top-Down Model of Electric Power Production

A. Activities

		Output				Inputs			
		Price		Quantity		Price		Quantity	
(A1)	Sectoral output	$p^{D}_{\mathrm{Ele},r}$	Domestic delivered electricity price	$y_{\mathrm{Ele},r}$	Domestic delivered electricity supply	p^{TD}_{r}	Transmission & distribution	q^{TD}_{r}	Transmission & distribution
						p^{Load}_{r}	Aggregate generation price	q^{Load}_{r}	Aggregate generation
(A2)	Transmission & distribution	p^{TD}_{r}	Transmission price	q^{TD}_{r}	Transmission supply	$p^{A}_{m,r}$	Armington material goods price	$x^{\mathrm{TD}}_{m,r}$	Armington material goods demand
						$w_{L,r}$	Wage	$v^{\mathrm{TD}}_{L,r}$	Labor demand
						$w_{K,r}$	Capital rental rate	$v^{\mathrm{TD}}_{K,r}$	Capital demand
(A3)	Total electricity supply	p^{Load}_{r}	Electricity price	q^{Load}_{r}	Electricity supply	$p^{\mathrm{Load}}_{\ell,r}$	Electricity price by load segment	q^{ℓ}_{r}	Electricity supply by load segment
(A4)	Load segments	$p^{\mathrm{Load}}_{\ell,r}$	Electricity price by load segment	q^{ℓ}_{r}	Electricity supply by load segment	$p^{\mathrm{Tech}}_{\lambda(\ell,z),r}$	Generation price	$q^{\mathrm{Tech}}_{\lambda(\ell,z),r}$	Generation supply
(A5)	Generation	$p^{\mathrm{Tech}}_{z,r}$	Generation price	$q^{\mathrm{Tech}}_{z,r}$	Generation supply	$p^{A}_{e,r}$	Armington fossil fuel price	$x^{\mathrm{Tech}}_{\phi(e,z),r}$	Armington fossil fuel demand
						$p^{A}_{m,r}$	Armington material goods price	$x^{\mathrm{Tech}}_{m,z,r}$	Armington material goods demand
						$w_{L,r}$	Wage	$v^{\mathrm{Tech}}_{L,z,r}$	Labor demand
						$w_{K,r}$	Capital rental rate	$v^{\mathrm{Tech}}_{K,z,r}$	Capital demand
						$w_{ff,r}$	Fixed factor price	$v^{\mathrm{Tech}}_{\phi(ff,z),r}$	Fixed factor demand

B. Subsectoral allocations

		Supply		Demands	
		Price	Quantity		
(S1)	Transmission & distribution	p^{TD}_{r}	q^{TD}_{r}	q^{TD}_{r}	Demand for transmission services
(S2)	Aggregate electricity supply	p^{Load}_{r}	q^{Load}_{r}	q^{Load}_{r}	Demand for aggregate electric energy
(S3)	Load segments	p^{ℓ}_{r}	q^{ℓ}_{r}	q^{ℓ}_{r}	Demand for energy aggregated by load segment
(S4)	Generation technologies	$p^{\mathrm{Tech}}_{z,r}$	$q^{\mathrm{Tech}}_{z,r}$	$q^{\mathrm{Tech}}_{\lambda(z,\ell),r}$	Load segment demands for generation technology outputs
(S5)	Factors	$w_{K,r}$	$v_{K,\mathrm{Ele},r}$	$v^{\mathrm{Tech}}_{K,r}, v^{\mathrm{TD}}_{K,r}$	Capital demand by technologies and transmission
		$w_{L,r}$	$v_{L,\mathrm{Ele},r}$	$v^{\mathrm{Tech}}_{L,r}, v^{\mathrm{TD}}_{L,r}$	Labor demand by technologies and transmission
		$w_{ff,r}$	$v_{ff,\mathrm{Ele},r}$	$v^{\mathrm{Tech}}_{ff,r}$	Fixed factor energy resource demand by technologies
(S6)	Armington domestic-import composite	$p^{A}_{i,r}$	$x_{i,\mathrm{Ele},r}$	$x^{\mathrm{Tech}}_{e,z,r}$	Generation technology demands for Armington fossil fuel inputs
				$x^{\mathrm{Tech}}_{m,r}, x^{\mathrm{TD}}_{m,r}$	Generation and transmission demand for Armington non-energy material inputs

generation technologies compete against one another to serve particular electricity market segments. Thus, specifying relatively easy substitution among generators but not between load segments ($\sigma_r^{\text{Load}} \ll 1 < \sigma_r^{\ell}$) enables coal and nuclear electricity (say) to be highly fungible within base load, but unable to substitute for peak natural gas or wind generation. Third, from an energy modeling standpoint, the CES aggregation technology's nonlinearity has the disadvantage of preventing generation in energetic units from summing up to the kilowatt hours of delivered electricity. But it is well known that modeling discrete activities' outputs as near-perfect substitutes can lead to "bang-bang" behavior wherein small differences in technologies' marginal costs induce large swings in their market shares. The present formulation's strength is that it enables generation technologies with widely differing marginal costs to coexist, and the resulting market shares to respond smoothly to policy shocks such as the GHG tax in section 3.2.

The supply-demand correspondences for the outputs of the transmission, aggregate electricity supply, load class and generation technology activities are indicated by subsectoral allocations (S1)-(S4) in Table 5. These are trivial—all of the action is in the allocation of factors (capital, labor and non-fossil energy resources) as well as fuel and non-fuel intermediate Armington goods among transmission and the different technologies, (S5)-(S6). The resulting input-output structure is underlain by the price and quantity variables in Table 5, organized according to the exhaustion of profit and supply-demand balance identities in Figure 4. Table 6 provides the algebraic elaboration of these identities, in which (A1)-(A5) are given by the zero profit conditions (48)-(51) and (S1)-(S6) are given by the market clearance conditions (52)-(57).

Calibration is the major challenge to computational implementation of this model. Recall that the present scheme requires a column disaggregation of the SAM in Figure 1.C that allocates inputs to the electricity sector among the various activities. The typical method relies on two pieces of exogenous information, namely, statistics on the benchmark quan-

Figure 4: Bottom-Up/Top-Down Representation of Electric Power Production: Accounting Identities and Parameterization

A. Accounting identities

	Zero Profit Conditions (Activities)		Supply-Demand Balance Conditions (Subsectoral allocations)
(A1)	$p^{D}_{\text{Ele},r} y_{\text{Ele},r} \le p^{\text{Load}}_{r} q^{\text{Load}}_{r} + p^{\text{TD}}_{r} q^{\text{TD}}_{r}$		
(A2)	$p^{\text{TD}}_{r} q^{\text{TD}}_{r} \le w_{K,r} v^{\text{TD}}_{K,z,r} + w_{L,r} v^{\text{TD}}_{L,z,r} + \sum_{\phi(m,z)} p^{A}_{m,r} x^{\text{Tech}}_{m,z,r}$		(S1) − (S4) are trivial
(A3)	$p^{\text{Load}}_{r} q^{\text{Load}}_{r} \le \sum_{\ell} p^{\text{Load}}_{\ell,r} q^{\ell}_{r}$	(S5)	$v_{f,\text{Ele},r} \ge v^{\text{TD}}_{f,z,r} + \sum_{z} v^{\text{Tech}}_{f,z,r}$
(A4)	$p^{\text{Load}}_{\ell,r} q^{\ell}_{r} \le \sum_{\lambda(\ell,z),r} p^{\text{Tech}}_{z,r} q^{\text{Tech}}_{z,r}$	(S6)	$x_{i,\text{Ele},r} \ge \begin{cases} \sum_{\phi(e,z)} x^{\text{Tech}}_{e,z,r} & \text{Fossil fuels} \\ x^{\text{TD}}_{m,r} + \sum_{z} x^{\text{Tech}}_{m,z,r} & \text{Materials} \end{cases}$
(A5)	$p^{\text{Tech}}_{z,r} q^{\text{Tech}}_{z,r} \le w_{K,r} v^{\text{Tech}}_{K,z,r} + w_{L,r} v^{\text{Tech}}_{L,z,r} + \begin{cases} \sum_{\phi(e,z)} p^{A}_{e,r} x^{\text{Tech}}_{e,z,r} & \text{Fossil fuel} \\ \sum_{\phi(\mathit{ff},z)} w_{\mathit{ff},r} v^{\text{Tech}}_{\mathit{ff},z,r} & \text{Non-fossil} \end{cases}$		

B. Parameters

	Institutions	Substitution Elasticities	Technical Coefficients	
(A1)	Delivered electric power	$\sigma^{Y}_{\text{Ele},r}$	$\varpi_{\text{Load},r}$	Total electricity supply
			$\varpi_{\text{TD},r}$	Transmission
(A2)	Transmission & distribution	σ^{TD}_{r}	$\beta^{\text{TD}}_{m,r}$,	Intermediate Armington good use
			$\gamma^{\text{TD}}_{K,r}$, $\gamma^{\text{TD}}_{L,r}$	Capital and labor inputs
(A3)	Total electricity supply	σ^{Load}_{r}	$\nu_{\ell,r}$	Load segments
(A4)	Load segments	σ^{ℓ}_{r}	$\eta_{z,\ell,r}$	Technologies' outputs
(A5)	Technologies	σ^{Tech}	$\theta^{K}_{z,r}, \theta^{L}_{z,r}$	Capital and labor
			$\theta^{M}_{m,z,r}$	Materials
			$\theta^{F}_{e,z,r}, \theta^{F}_{\mathit{ff},z,r}$	Fossil and fixed-factor energy

Table 6: Algebraic Representation of Bottom-Up Technologies in Electric Power Production

$$p^D_{\mathrm{Ele},r} \leq \left[\left(\varpi_{\mathrm{Gen},r}\right)^{\sigma^Y_{\mathrm{Ele},r}} \left(p^{\mathrm{Load}}_r\right)^{1-\sigma^Y_{\mathrm{Ele},r}} + \left(\varpi_{\mathrm{TD},r}\right)^{\sigma^Y_{\mathrm{Ele},r}} \left(p^{\mathrm{TD}}_r\right)^{1-\sigma^Y_{\mathrm{Ele},r}} \right]^{1/(1-\sigma^Y_{\mathrm{Ele},r})} \quad \perp \quad y_{\mathrm{Ele},r} \tag{47}$$

$$p^{\mathrm{Load}}_r \leq \left[\sum_{\ell} \left(\nu_{\ell,r}\right)^{\sigma^{\mathrm{Load}}_r} \left(p^{\mathrm{Load}}_{\ell,r}\right)^{1-\sigma^{\mathrm{Load}}_r} \right]^{1/(1-\sigma^{\mathrm{Load}}_r)} \quad \perp \quad q^{\mathrm{Load}}_r \tag{48}$$

$$p^{\mathrm{TD}}_r \leq \left[\sum_{m} \left(\beta^{\mathrm{TD}}_{i,r}\right)^{\sigma^{\mathrm{TD}}_r} \left(p^A_{m,r}\right)^{1-\sigma^{\mathrm{TD}}_r} + \left(\gamma^{\mathrm{TD}}_{K,r}\right)^{\sigma^{\mathrm{TD}}_r} w^{1-\sigma^{\mathrm{TD}}_r}_{K,r} + \left(\gamma^{\mathrm{TD}}_{L,r}\right)^{\sigma^{\mathrm{TD}}_r} w^{1-\sigma^{\mathrm{TD}}_r}_{L,r} \right]^{1/(1-\sigma^{\mathrm{TD}}_r)} \quad \perp \quad q^{\mathrm{TD}}_r \tag{49}$$

$$p^{\mathrm{Load}}_{\ell,r} \leq \left[\sum_{\lambda(z,\ell)} \left(\eta_{z,\ell,r}\right)^{\sigma^{\mathrm{Load}}_{\ell,r}} \left(p^{\mathrm{Tech}}_{z,r}\right)^{1-\sigma^{\mathrm{Load}}_{\ell,r}} \right]^{1/(1-\sigma^{\mathrm{Load}}_{\ell,r})} \quad \perp \quad q^{\ell}_r \tag{50}$$

$$p^{\mathrm{Tech}}_{z,r} \leq \left[\begin{array}{c} \left(\theta^K_{z,r}\right)^{\sigma^{\mathrm{Tech}}} w^{1-\sigma^{\mathrm{Tech}}}_{K,r} + \left(\theta^L_{z,r}\right)^{\sigma^{\mathrm{Tech}}} w^{1-\sigma^{\mathrm{Tech}}}_{L,r} \\ + \left(\theta^M_{m,z,r}\right)^{\sigma^{\mathrm{Tech}}} \left(p^A_{m,r}\right)^{1-\sigma^{\mathrm{Tech}}} \end{array} + \begin{cases} \left(\theta^F_{\phi(e,z),r}\right)^{\sigma^{\mathrm{Tech}}} \left(p^A_{e,r}\right)^{1-\sigma^{\mathrm{Tech}}} & \text{Fossil} \\ \left(\theta^F_{\phi(ff,z),r}\right)^{\sigma^{\mathrm{Tech}}} w^{1-\sigma^{\mathrm{Tech}}}_{ff,r} & \text{Non-fossil} \end{cases} \right]^{1/(1-\sigma^{\mathrm{Tech}})} \quad \perp \quad q^{\mathrm{Tech}}_{z,r} \tag{51}$$

$$q^{\mathrm{Load}}_r \geq \left(\varpi_{\mathrm{Gen},r}\right)^{\sigma^Y_{\mathrm{Ele},r}} \left(p^{\mathrm{Load}}_r\right)^{-\sigma^Y_{\mathrm{Ele},r}} \left(p^D_{\mathrm{Ele},r}\right)^{\sigma^Y_{\mathrm{Ele},r}} y_{\mathrm{Ele},r} \quad \perp \quad p^{\mathrm{Load}}_r \tag{52}$$

$$q^{\mathrm{TD}}_r \geq \left(\varpi_{\mathrm{TD},r}\right)^{\sigma^Y_{\mathrm{Ele},r}} \left(p^{\mathrm{TD}}_r\right)^{-\sigma^Y_{\mathrm{Ele},r}} \left(p^D_{\mathrm{Ele},r}\right)^{\sigma^Y_{\mathrm{Ele},r}} y_{\mathrm{Ele},r} \quad \perp \quad p^{\mathrm{TD}}_r \tag{53}$$

$$q^{\ell}_r \geq \left(\nu_{\ell,r}\right)^{\sigma^{\mathrm{Load}}_r} \left(p^{\mathrm{Load}}_{\ell,r}\right)^{-\sigma^{\mathrm{Load}}_r} \left(p^{\mathrm{Load}}_r\right)^{\sigma^{\mathrm{Load}}_r} q^{\mathrm{Load}}_r \quad \perp \quad p^{\mathrm{Load}}_{\ell,r} \tag{54}$$

$$q^{\mathrm{Tech}}_{z,r} \geq \left(\eta_{\lambda(z,\ell),r}\right)^{\sigma^{\mathrm{Load}}_{\ell,r}} \left(p^{\mathrm{Tech}}_{z,r}\right)^{-\sigma^{\mathrm{Load}}_r} \left(p^{\mathrm{Load}}_{\ell,r}\right)^{\sigma^{\mathrm{Load}}_{\ell,r}} q^{\ell}_r \quad \perp \quad p^{\mathrm{Tech}}_{z,r} \tag{55}$$

$$\begin{aligned} V_{f,r} \geq & \sum_{j \neq \mathrm{Ele}}^{\mathcal{N}} \gamma^{\sigma^Y_{j,r}}_{f,j,r} w^{-\sigma^Y_{j,r}}_{f,r} \left(p^D_{j,r}\right)^{\sigma^Y_{j,r}} y_{j,r} \\ & + \begin{cases} \gamma^{\sigma^{\mathrm{TD}}_r}_{K,r} w^{-\sigma^{\mathrm{TD}}_r}_{K,r} \left(p^{\mathrm{TD}}_r\right)^{\sigma^{\mathrm{TD}}_r} q^{\mathrm{TD}}_r + \sum_z \left(\theta^K_{z,r}\right)^{\sigma^{\mathrm{Tech}}} w^{-\sigma^{\mathrm{Tech}}}_{K,r} \left(p^{\mathrm{Tech}}_{z,r}\right)^{\sigma^{\mathrm{Tech}}} q^{\mathrm{Tech}}_{z,r} & K \in f \\ \gamma^{\sigma^{\mathrm{TD}}_r}_{L,r} w^{-\sigma^{\mathrm{TD}}_r}_{L,r} \left(p^{\mathrm{TD}}_r\right)^{\sigma^{\mathrm{TD}}_r} q^{\mathrm{TD}}_r + \sum_z \left(\theta^L_{z,r}\right)^{\sigma^{\mathrm{Tech}}} w^{-\sigma^{\mathrm{Tech}}}_{L,r} \left(p^{\mathrm{Tech}}_{z,r}\right)^{\sigma^{\mathrm{Tech}}} q^{\mathrm{Tech}}_{z,r} & L \in f \\ \sum_{\phi(ff,z)} \left(\theta^F_{ff,z,r}\right)^{\sigma^{\mathrm{Tech}}} w^{-\sigma^{\mathrm{Tech}}}_{ff,r} \left(p^{\mathrm{Tech}}_{z,r}\right)^{\sigma^{\mathrm{Tech}}} q^{\mathrm{Tech}}_{z,r} & ff \subset f \end{cases} \end{aligned} \quad \perp \quad w_{f,r} \tag{56}$$

$$\begin{aligned} q^A_{i,r} \geq & \left(\alpha^C_{i,r}\right)^{\sigma^C_r} \left(p^A_{i,r}\right)^{-\sigma^C_r} \mathscr{E}^{\sigma^C_r} u_r + \left(\alpha^I_{i,r}\right)^{\sigma^I_r} \left(p^A_{i,r}\right)^{-\sigma^I_r} \left(p^I_r\right)^{\sigma^I_r} G^I_r + \sum_{j \neq \mathrm{Ele}}^{\mathcal{N}} \beta^{\sigma^Y_{j,r}}_{i,j,r} \left(p^A_{i,r}\right)^{-\sigma^Y_{j,r}} \left(p^D_{j,r}\right)^{\sigma^Y_{j,r}} y_{j,r} \\ & + \begin{cases} \sum_{\phi(e,z)} \left(\theta^F_{e,z,r}\right)^{\sigma^{\mathrm{Tech}}} \left(p^A_{e,r}\right)^{-\sigma^{\mathrm{Tech}}} \left(p^{\mathrm{Tech}}_{z,r}\right)^{\sigma^{\mathrm{Tech}}} q^{\mathrm{Tech}}_{z,r} & e \subset i \\ \beta^{\sigma^{\mathrm{TD}}_r}_{m,r} \left(p^A_{m,r}\right)^{-\sigma^{\mathrm{TD}}_r} \left(p^{\mathrm{TD}}_r\right)^{\sigma^{\mathrm{TD}}_r} q^{\mathrm{TD}}_r + \sum_z \left(\theta^M_{m,z,r}\right)^{\sigma^{\mathrm{Tech}}} \left(p^A_{m,r}\right)^{-\sigma^{\mathrm{Tech}}} \left(p^{\mathrm{Tech}}_{z,r}\right)^{\sigma^{\mathrm{Tech}}} q^{\mathrm{Tech}}_{z,r} & m \subset i \end{cases} \end{aligned} \quad \perp \quad p^A_{i,r} \tag{57}$$

Table 7: The Bottom-Up/Top-Down Calibration Problem

$$\min_{\substack{\overline{x}^{\text{Tech}}_{i,z,r},\overline{x}^{\text{TD}}_{m,z,r},\\ \overline{v}^{\text{Tech}}_{f,z,r},\overline{x}^{\text{TD}}_{f,z,r}}} \sum_{z} \left(\overline{q}^{\text{Tech}}_{z,r} - \Upsilon^{\text{Gen}}_{z,r}\right)^2 + \sum_{z} \sum_{f=K,L} \left(\overline{v}^{\text{Tech}}_{f,z,r}/\overline{q}^{\text{Tech}}_{z,r} - \Upsilon^{\text{Tech}}_{f,z,r}\right)^2 + \sum_{z} \sum_{m} \left(\overline{v}^{\text{Tech}}_{m,z,r}/\overline{q}^{\text{Tech}}_{z,r} - \Upsilon^{\text{Tech}}_{m,z,r}\right)^2$$

$$+ \sum_{z} \sum_{\phi(e,z)} \left(\overline{x}^{\text{Tech}}_{e,z,r}/\overline{q}^{\text{Tech}}_{z,r} - \Upsilon^{\text{Tech}}_{e,z,r}\right)^2 + \sum_{z} \sum_{\phi(\mathit{ff},z)} \left(\overline{v}^{\text{Tech}}_{ff,z,r}/\overline{q}^{\text{Tech}}_{z,r} - \Upsilon^{\text{Tech}}_{ff,z,r}\right)^2 \quad \text{s.t.}$$

$$\text{(A1')} \quad \overline{y}_{\text{Ele},r} = \overline{q}^{\text{Load}}_{r} + \overline{q}^{\text{TD}}_{r}$$

$$\text{(A2')} \quad \overline{q}^{\text{TD}}_{r} = \overline{v}^{\text{TD}}_{K,z,r} + \overline{v}^{\text{TD}}_{L,z,r} + \sum_{\phi(m,z)} \overline{x}^{\text{Tech}}_{m,z,r}$$

$$\text{(A3')} \quad \overline{q}^{\text{Load}}_{r} = \sum_{\ell} \overline{q}^{\ell}_{r}$$

$$\text{(A4')} \quad \overline{q}^{\ell}_{r} = \sum_{\lambda(\ell,z),r} \overline{q}^{\text{Tech}}_{z,r}$$

$$\text{(A5')} \quad \overline{q}^{\text{Tech}}_{z,r} = \overline{v}^{\text{Tech}}_{K,z,r} + \overline{v}^{\text{Tech}}_{L,z,r} + \begin{cases} \displaystyle\sum_{\phi(e,z)} \overline{x}^{\text{Tech}}_{e,z,r} & \text{Fossil fuel} \\ \displaystyle\sum_{\phi(\mathit{ff},z)} \overline{v}^{\text{Tech}}_{\mathit{ff},z,r} & \text{Non-fossil} \end{cases}$$

$$\text{(S5')} \quad \overline{v}_{f,\text{Ele},r} = \overline{v}^{\text{TD}}_{f,z,r} + \sum_{z} \overline{v}^{\text{Tech}}_{f,z,r}$$

$$\text{(S6')} \quad \overline{x}_{i,\text{Ele},r} = \begin{cases} \displaystyle\sum_{\phi(e,z)} \overline{x}^{\text{Tech}}_{e,z,r} & \text{Fossil fuels} \\ \overline{x}^{\text{TD}}_{m,r} & \text{Materials} \end{cases}$$

tities of electricity generated by the different technologies ($\Upsilon^{\text{Gen}}_{z,r}$), and descriptions of the contributions of inputs of factors and Armington intermediate energy and material goods to the unit cost of generation ($\Upsilon^{\text{Tech}}_{f,z,r}$ and $\Upsilon^{\text{Tech}}_{i,z,r}$, respectively). The calibration problem is therefore to find benchmark input vectors whose elements satisfy the identities in Figure 4.A but yield a vector of technology outputs and input proportions that do not diverge "too far" from the exogenous data. The least squares fitting procedure in Table 7 operationalizes this idea, recasting (A1)-(A5) and (S5)-(S6) as equality constraints posed in terms of the SAM's benchmark quantities (indicated by a bar over a variable) with all prices set to unity. It is customary to focus on generation while allowing the inputs to—and the ultimate size of—the transmission and distribution activity to be determined as residuals to this nonlinear program.

Finally, even this systematized procedure involves a fair amount of judgment and assumptions. For example, the dearth of data on fixed-factor resource inputs in input-output accounts requires the values of $\overline{v}^{\text{Tech}}_{\mathit{ff},z,r}$ to be assumed as fractions of the electric power sector's benchmark payments to capital, and engineering data on technology characteristics often lump labor and materials together into operations and maintenance (O&M) expenditures, necessitating ad-hoc disaggregation.

4.2 Heterogeneous Firms and Endogenous Productivity Dynamics

In this section we describe the radical extension of the canonical model to incorporate contemporary theories of trade, focusing on the nexus of monopolistic competition, heterogeneous firms and endogenous productivity. The Armington trade model's assumption of perfectly competitive producers ignores the existence of monopolistic competition in a range of manufacturing and service industries. In these sectors, each firm produces a unique variety of good and faces a differentiated cost of production made up of a fixed cost and a variable cost that depends on the firm's productivity. An important limitation of the canonical model is its failure to account for the fact that openness to trade induces competitive selection of firms and reallocation of resources from unproductive to productive producers, generating *export variety* gains from trade (Feenstra, 2010) which can substantially exceed the gains-from-trade predictions of standard CGE simulations (see Balistreri et al., 2010). By contrast, the heterogeneous-firm framework is more consistent with several stylized facts (Balistreri et al., 2011): persistent intra-industry trade-related differences in firm productivities (Bartelsman and Doms, 2000), the comparative scarcity and relatively high productivity of exporting firms (Bernard and Jensen, 1999), and the association between higher average productivity, openness (Trefler, 2004) and lower trade costs (Bernard et al., 2006).

Our heterogeneous-firm CGE simulation follows the theoretical structure developed by Melitz (2003). We consider a single industry $h \in j$ as the heterogeneous-firm sector. A h-producing firm in region r deciding whether to sell to region r' balances the expected revenue from entering that bilateral export market, (r, r'), against the expected cost. On entry, the firm's costs are sunk and its productivity is fixed according to a draw from a probability distribution. Which firms are able to sell profitably in (r, r') is jointly determined by five factors: their productivity levels ($\varphi_{h,r,r'}$), the costs of bilateral trade ($\mathscr{C}_{h,r,r'}$), the fixed operating and sunk costs associated with market entry ($\mathscr{F}^O_{h,r,r'}$ and $\mathscr{F}^S_{h,r}$), and the level of demand. An individual firm takes these as given, and maximizes profit by selecting which bilateral markets to supply. If fixed costs are higher in foreign markets relative to the domestic market, the firm will export only if its productivity is relatively high; symmetrically, if its productivity is sufficiently low it will sell its product only to the domestic market, or exit entirely. While there are no fixed costs of *production*, the model's crucial feature is fixed costs of *trade* which give rise to scale economies at the sectoral level, so that the average cost of export supply declines with increasing export volume.

On the importer's side, both the aggregate demand for the relevant composite commodity and the associated price level are identical to the canonical model ($q^A_{h,r'}$ and $p^A_{h,r'}$). The key differences are that the composite is a Dixit-Stiglitz CES aggregation of a continuum of varieties of good h, with each variety produced by a firm that may reside at home or abroad. Letting $\omega_{h,r,r'} \in \Omega_{h,r}$ index the varieties exported from r to r', and $p^H_{h,r,r'}[\omega_{h,r,r'}]$ denote each variety's firm-specific price, the importer's composite price index is

$$p^A_{h,r'} = \left[\sum_r \int_{\Omega_{h,r,r'}} \left(p^H_{h,r,r'}[\omega_{h,r,r'}] \right)^{1-\sigma^H_h} d\omega_{h,r,r'} \right]^{1/(1-\sigma^H_h)} .$$

where σ^H_h is the elasticity of substitution between varieties. Computational implementation of this expression assumes a representative monopolistic firm in (r, r') who sets an average price for its specific variety, $\widetilde{p}^H_{h,r,r'}$. Given a mass of $n_{h,r,r'}$ such firms, the formula for the composite price reduces to eq. (59), which replaces (4) as the zero-profit condition for composite good production. By Shephard's lemma, the demand for imports of varieties from firms located in r is given by the corresponding market clearance condition (60). The crucial feature is the scale effect associated with the increases in the number of available varieties, $n_{h,r,r'}$, which implies the need to keep track of the number of firms.

Faced with this demand curve for its unique variety, each h-producer maximizes profit by setting marginal cost equal to marginal revenue. To specify the profit maximization problem of the representative firm we exploit the large-group monopolistic competition assumption that the behavior of an individual firm has no impact on the composite price. Further, we assume that sunk, fixed, and variable costs are all incurred at the marginal opportunity cost of domestic output, which for exporters in r is simply $p^D_{h,r}$. Under these conditions, a monopolistic firm with productivity $\varphi_{h,r,r'}$ has unit production cost $p^D_{h,r}/\varphi_{h,r,r'}$ and maximizes profit via the markup pricing rule:

$$\mathscr{C}_{h,r,r'} p^D_{h,r}/\varphi_{h,r,r'} \geq (1 - 1/\sigma^H_h) p^H_{h,r,r'}, \tag{58}$$

where $\mathscr{C}_{h,r,r'}$ is a Samuelsonian iceberg trade cost which we treat as a market-specific calibration parameter.[23] The key to operationalizing this condition is expressing the average price ($\widetilde{p}^H_{h,r,r'}$) in terms of the average productivity level ($\widetilde{\varphi}_{h,r,r'}$) by identifying the marginal firm that earns zero profits, and then relating the marginal firm to the average firm through the distribution of producer productivities. Melitz (2003) developed a method for doing this, which we follow below.

An individual firm's productivity is assumed to be determined by a random draw from a Pareto distribution with density $\pi[\varphi] = a\underline{\varphi}^a \varphi^{-1-a}$ and cumulative probability $\Pi[\varphi] = 1 - \underline{\varphi}^a \varphi^{-a}$, where a is the shape parameter and $\underline{\varphi}$ is a lower productivity bound. The centerpiece of the model is that every bilateral link is associated with a productivity level $\varphi^\star_{h,r,r'}$ at which optimal markup pricing yields zero profit, such that a firm that draws $\varphi^\star_{h,r,r'}$ is the marginal firm. Firms drawing $\varphi_{h,r,r'} > \varphi^\star_{h,r,r'}$ earn positive profits and supply market (r, r'). Thus, with a mass $N_{h,r}$ of h-producing firms in region r, the share of producers that enter this market is $1 - \Pi[\varphi^\star_{h,r,r'}] = n_{h,r,r'}/N_{h,r}$. This property may be exploited by

Table 8: Equations of the Heterogeneous Firms Sector (h)

$$\begin{aligned}
p^A_{h,r'} &\leq \left[\sum_r n_{h,r,r'}(\widetilde{p}^H_{h,r,r'})^{1-\sigma^H_h}\right]^{1/(1-\sigma^H_h)} && \perp \quad q^A_{h,r'}, && (59)\\
\widetilde{q}^H_{h,r,r'} &\geq n_{h,r,r'}\left(\widetilde{p}^H_{h,r,r'}\right)^{-\sigma^H_h}\left(p^A_{h,r'}\right)^{\sigma^H_h} q^A_{h,r'} && \perp \quad \widetilde{p}^H_{r,r'}. && (60)\\
\widetilde{\varphi}_{h,r,r'} &= \underline{\varphi}^{-1}\widetilde{a}_h^{1/(1-\sigma^H_h)}(n_{h,r,r'}/N_{h,r})^{-1/a} && \perp \quad \widetilde{\varphi}_{h,r,r'} && (61)\\
\widetilde{p}^H_{h,r,r'} &\leq \frac{\sigma^H_h}{\sigma^H_h-1}\widetilde{\varphi}_{h,r,r'}\mathscr{C}_{h,r,r'}p^D_{h,r} && \perp \quad \widetilde{q}^H_{h,r,r'} && (62)\\
p^D_{h,r}\mathscr{F}^O_{h,r,r'} &= \widetilde{p}^H_{h,r,r'}\widetilde{q}^H_{h,r,r'}\widetilde{a}_h/\sigma^H_h && \perp \quad n_{h,r,r'} && (63)\\
\Delta p^D_{h,r}\mathscr{F}^S_{h,r} &= \frac{\sigma^H_h-1}{a_h\sigma^H_h N_{h,r}}\sum_{r'}\widetilde{p}^H_{h,r,r'}\widetilde{q}^H_{h,r,r'}n_{h,r,r'} && \perp \quad N_{h,r} && (64)\\
y_{i,r} &\geq \begin{cases} \Delta\mathscr{F}^S_{h,r}N_{h,r} + \displaystyle\sum_{r'\neq r} n_{h,r,r'}\mathscr{F}^O_{h,r,r'} & \\ \quad +\underline{\varphi}^{-1}\widetilde{a}_h^{1/(1-\sigma^H_h)}\displaystyle\sum_{r'\neq r} n_{h,r,r'}\mathscr{C}_{h,r,r'}\left(\frac{n_{h,r,r'}}{N_{h,r}}\right)^{-1/a}\widetilde{q}^H_{h,r,r'} & h \in i \\ \left(\zeta^D_{i,r}\right)^{\sigma^{DM}_{i,r}}\left(p^D_{i,r}\right)^{-\sigma^{DM}_{i,r}}\left(p^A_{i,r}\right)^{\sigma^{DM}_{i,r}} q^A_{i,r} & \\ \quad +\sum_{r'\neq r}\xi_{i,r,r'}^{\sigma^{MM}_{i,r'}}\left(p^D_{i,r}\right)^{-\sigma^{MM}_{i,r'}}\left(p^M_{i,r'}\right)^{\sigma^{MM}_{i,r'}} g^M_{i,r'} & \text{otherwise} \end{cases} && \perp \quad p^D_{i,r} && (65)
\end{aligned}$$

integrating over the density function to obtain the CES-weighted average productivity level:

$$\begin{aligned}
\widetilde{\varphi}_{h,r,r'} = \left[\frac{1}{1-\Pi[\varphi^\star_{h,r,r'}]}\int_{\varphi^\star_{h,r,r'}}^{\infty}\varphi^{\sigma^H_h-1}\pi[\varphi]d\varphi\right]^{1/(\sigma^H_h-1)} &= \widetilde{a}_h^{1/(1-\sigma^H_h)}\varphi^\star_{h,r,r'}\\
= \widetilde{a}_h^{1/(1-\sigma^H_h)}\Pi^{-1}[1-n_{h,r,r'}/N_{h,r}] &= \underline{\varphi}^{-1}\widetilde{a}_h^{1/(1-\sigma^H_h)}(n_{h,r,r'}/N_{h,r})^{-1/a}
\end{aligned}$$

where $\widetilde{a}_h = (a+1-\sigma^H_h)/a$ is a parameter. The above expression can be substituted into (58) to yield the representative monopolistic firm's zero-profit condition (62).

To find the level of productivity we must pin down the number of firms in (r, r'). The latter is defined implicitly by the free-entry condition for the marginal firm, which breaks even with an operating profit that just covers its fixed operating cost of entering the market. By the Marshallian large group assumption, profit is the ratio of a firm's revenue to the elasticity of substitution among varieties, while the fixed cost can be expressed as the opportunity cost, $p^D_{h,r}\mathscr{F}^O_{h,r,r'}$. Eqs. (58) and (60) can be combined to express revenue as $p^H_{h,r,r'}q^H_{h,r,r'} = n_{h,r,r'}\left(p^H_{h,r,r'}\right)^{1-\sigma^H_h}\left(p^A_{h,r'}\right)^{\sigma^H_h} q^A_{h,r'} \propto \varphi^{\sigma^H_h-1}_{h,r,r'}$, so that the ratio of average to marginal revenue is related to the ratio of the average and marginal productivity by: $\left(\widetilde{\varphi}_{h,r,r'}/\varphi^{\star}_{h,r,r'}\right)^{\sigma^H_h-1} = \widetilde{a}^{-1}$. This simplification enables the free-entry condition to be recast in terms of the representative firm's average variables as the zero-profit condition (63).

Similar logic applies to the total mass of region-r firms, which is defined implicitly by a free-entry condition that balances a firm's sunk cost against expected profits over its lifetime. Assuming that each firm has a flow probability of disappearance, Δ, steady-state equilibrium requires an average of $\Delta N_{h,r}$ firms to be replaced each period at an aggregate nominal opportunity cost of $\Delta p^D_{h,r}\mathscr{F}^S_{h,r}N_{h,r}$. Thus, ignoring discounting or risk aversion, the representative firm's profit must be large enough to cover an average loss of $\Delta p^D_{h,r}\mathscr{F}^S_{h,r}$. On the other side of the balance sheet, expected aggregate profit is simply the operating profit in each market $(\widetilde{p}^H_{h,r,r'}\widetilde{q}^H_{h,r,r'}/\sigma^H_h - p^D_{h,r}\mathscr{F}^O_{h,r,r'})$ weighted by the probability of operating in that market $(n_{h,r,r'}/N_{h,r})$. Using (63) to substitute out fixed operating costs, the free-entry condition equating average sunk costs with average aggregate profit is given by the zero-profit condition (64). With this condition the heterogeneous-firm trade equilibrium is fully specified. The final requirement for integrating the heterogeneous-firm sector into the framework of the canonical model is an elaboration of the h-sector's supply-demand balance for the domestic commodity. The market clearance condition associated with $p^D_{h,r}$ tracks the disposition of domestic output into the various sunk, fixed, and variable costs as in (65).

Operationalizing this model requires us to reconcile our heterogeneous firms algebraic framework with standard trade flow accounts such as Figure 1. To do so we need three pieces of exogenous data: the elasticity of substitution between varieties (σ_h), the Pareto distribution parameters (a and $\underline{\varphi}$), and an approximation of bilateral fixed operating costs $(\mathscr{F}^O_{h,r,r'})$.[24] The calibration proceeds in five steps.

1. *Average firm revenue:* Plugging estimates of the fixed cost and the substitution elasticity into the zero-cutoff-profit condition (63), along with a typical choice of units ($p^D_{h,r} = 1 \ \forall h, r$) pins down the revenue of the average firm operating in each bilateral market ($\widetilde{p}^H_{h,r,r'}\widetilde{q}^H_{h,r,r'}$).

2. *The number of firms:* The fact the total value of trade is the product of the number of firms and average revenue means that the trade account in the SAM can be divided by result of step 1 to give the benchmark value of $n_{h,r,r'}$. Plugging this quantity into eq. (64) enables us to derive the total mass of firms, $N_{h,r}$. The key is to treat the flow of sunk cost payments ($\Delta\mathscr{F}^S_{h,r}$) as a free composite parameter whose value is chosen to scales the measure of the total number of firms relative to those operating on each bilateral link. In performing this procedure it is necessary to ensure that $n_{h,r,r'}/N_{h,r} < 1$ for the largest market supplied by r (typically the domestic market, $r = r'$).

3. *Average firm productivity:* Substituting the shares of firms on each bilateral link from step 2 into eq. (61) facilitates direct calculation of the average productivity level, $\widetilde{\varphi}_{h,r,r'}$.

4. *Average firm price and output:* Multiplying both sides of (60) by the firm-level average price ($\widetilde{p}_{h,r,r'}$) expresses average revenue from step 1 in terms of the average firm-level price and the composite price and quantity. By choosing composite units such that $p^A_{h,r'} = 1$ (which allows us to interpret $q_{h,r'}$ as region r' gross consumption observed in the trade accounts) we can solve for $\widetilde{p}_{h,r,r'}$, and, in turn, $\widetilde{q}_{h,r,r'}$.

5. *Iceberg trade costs:* Unobserved trade costs ($\mathscr{C}_{h,r,r'}$) can be recovered from the markup pricing rule (62).

4.3 The Heterogeneous-Firm CGE Model in Action: Liberalizing Trade in Services

We illustrate how the results of the heterogeneous-firms specification can differ from those of our canonical model by considering the liberalization of services trade in poor countries. The model in section 4.2 is calibrated on a stylized aggregation of the GTAP version 7 database which divides the world into three regions (OECD, middle-income and low-income countries) whose industries are grouped into three broad sectors (manufacturing, services and a rest-of-economy aggregate). We use the heterogeneous-firms structure to model the manufacturing and services sectors. For our exogenous parameters we use $\sigma_h = 3.8$ taken from Bernard et al. (2003), and $a = 4.582$, $\underline{\varphi} = 0.2$ and a vector of values $\mathscr{F}^O_{h,r,r'}$, taken from Balistreri et al. (2011). To capture the importance of business services, we model production using Balistreri et al.'s (2009) nested CES structure in every sector, where value added and intermediate purchases of services are combined with an elasticity of substitution of 1.25 to form a composite input commodity.

From a practical modeling standpoint the non-convexity generated by positive feedback from expansion of exports to productivity improvement to decline in the average cost of exporting can easily render the solution to a CGE model infeasible in the absence of countervailing economic forces that limit the general equilibrium response to increasing returns. To achieve the requisite degree of attenuation we introduce countervailing diminishing returns in the production of h-goods by using a specific-factor input formulation for the heterogeneous-firms sectors. This device puts a brake on output expansion by limiting the composite good's supply, which with fully reversible production would be near-perfectly elastic. Our approach is to allocate a portion of firm revenues toward payments to a sector-specific primary "fixed factor" resource. The fixed factor's benchmark cost share, as well as the elasticities of substitution between it and other components of the composite input, are numerically calibrated to

Table 9: Liberalization of Trade in Services: A Stylized CGE Assessment

	Full Unilateral Reform[a]	Regulatory Reform Only[b]	Unilateral Tariff Reduction[c]	OECD Free Trade Area[d]	OECD Trade Reform[e]
A. Welfare impacts under different specifications of trade (% Equivalent Variation)					
Armington	–	–	-0.50	0.01	–
Heterogeneous-firms	6.90	7.86	-1.01	0.34	6.09
B. Productivity impacts (% change in $\sum_s \widetilde{\varphi}_{r,r'} N_{r,r'}$)					
Services					
OECD	-0.02	-0.03	0.01	-0.00	-0.01
Middle income	-0.03	-0.08	0.06	-0.01	-0.07
Low income	29.12	28.83	0.20	0.39	6.95
Manufacturing					
OECD	0.01	0.05	-0.04	-0.19	-0.62
Middle income	-0.07	-0.09	0.02	-0.02	-0.25
Low income	-1.74	2.19	-4.14	-0.75	17.02
C. Variety impacts (% change in Feenstra's Ratio)					
Services					
OECD	0.03	0.02	0.01	0.01	0.08
Middle income	0.06	0.03	0.04	-0.02	-0.07
Low income	10.33	10.52	-0.19	0.04	2.41
Manufacturing					
OECD	0.01	0.00	0.01	0.01	0.33
Middle income	0.04	-0.01	0.05	-0.02	-0.08
Low income	0.98	0.97	-0.03	0.17	7.45

[a] Low income countries unilaterally reduce tariffs on imports of manufactures and services by 50% and reduce fixed costs on service firms operating within their borders by 25%.
[b] Services firms in low income countries see their fixed costs reduced by 25%.
[c] Low income countries unilaterally reduce tariffs on imports of manufactures and services by 50%.
[d] Free trade agreement with OECD that reduces bilateral tariffs by 50%.
[e] Free trade agreement with OECD that reduces bilateral tariffs by 50% and reduces bilateral fixed costs by 50%.

be consistent with the central values in Balistreri et al. (2009), and imply a composite-input supply elasticity of four.

We investigate the impacts of the low-income region liberalizing tariff and non-tariff barriers to trade in services. We model the latter based on Balistreri et al.'s (2009) estimates for Kenya, where barriers in ad valorem terms range from 0-57% with a median value of 13%, which we use as an estimate of the available savings from regulatory reforms. The service sector is calibrated so that fixed costs account for about 26% of revenues, which suggests that a 25% reduction in these costs is roughly equivalent to a 50% reduction in regulatory barriers. We simulate five liberalization scenarios, three which are a mix of reductions in low-income countries' import tariffs on services and manufactures and fixed costs for service-sector firms, and two which simulate bilateral trade integration with the OECD. Table 9 gives details of the scenarios, along with key model results. The first thing to note is the relative welfare impact of the regulatory reform scenarios in panel A. Unilateral regulatory reform that reduces the fixed costs of services firms in the low-income region generates a welfare gain of 7.9%. In contrast, given optimal tariff considerations, unilateral tariff reductions lead to losses of 1% under the heterogeneous-firms structure and 0.5% under the Armington structure. Considering bilateral policies between low-income countries and the OECD, combining 50% tariff reductions with 50% reductions in bilateral fixed trade costs results in an 18 fold increase in welfare gains (from 0.4% to 6%). Moreover, even in the tariff-only bilateral scenario the heterogeneous firm model generates far larger gains than its Armington counterpart (0.01% versus 0.39%). The heterogeneous-firm representation of trade therefore has fundamentally important implications for measuring policy reforms. Panels B and C of Table 9 highlight two key sources of differential economic impact: productivity shifts associated with changes in the selection of firms into export markets on the supply side, and changes in variety associated with the .

Unilateral regulatory reforms generate sizable productivity and variety gains for low-income countries. We report the gains associated with new varieties of the services good, calculated according to Feenstra's (2010) expenditure-share based method (see Balistreri and Rutherford (2012) for details). Directly interpreting the change in $n_{h,r,r'}$ as an indicator of the underlying change in varieties can be misleading because liberalization may induce the replacement of high-price low-quantity domestic varieties with foreign varieties. Indeed, while the net number of varieties has been shown to decline with trade costs (Baldwin and Forslid, 2010; Feenstra, 2010), this does not by itself indicate a gain or loss as each variety has a different price.

We close this section by emphasizing that our simulations rely on a set of parameters not commonly used by CGE models. In particular, the values of shape parameter on the distribution of firm productivities and the bilateral fixed costs of trade are drawn from the structural estimation procedures developed in Balistreri et al. (2011). It has traditionally been the case that these sorts of parameters are estimated using econometric models that are divorced from broader theory of general equilibrium or its particular algebraic elaboration in the numerical simulation to be parameterized. By contrast, structural estimation techniques bring econometric and numerical simulation modeling together in a consistent fashion by imposing theory-based restrictions on the values of estimated parameters. An important example is Anderson and van Wincoop's (2003) widely cited study, whose welfare impacts have been shown to be inconsistent with its estimation procedure unless the latter is properly constrained by restrictions based on the conditions of general equilibrium (Balistreri and Hillberry, 2008, 2007).

Structural estimation of the parameters of our heterogeneous-firm model proceeds by isolating the complementarity conditions that characterize the trade equilibrium and imposing these as a set of constraints on econometric estimation. Following Balistreri et al. (2011), consider a vector-valued function that specifies the equilibrium in bilateral trade markets conditional on the observed benchmark demand for the regional domestic-import composites, $q^A_{h,r}$, and the domestic supply of the traded good, $y_{h,r}$. The system of equations may be stacked to generate the vector-valued function $\Xi(\mathscr{V}, \mathbf{\Gamma}) = \mathbf{0}$ which implicitly maps the vector of parameters, $\mathbf{\Gamma}$, to the vector of endogenous variables, $\mathscr{V}$. The key parameters to be estimated are the Pareto shape coefficient and the bilateral fixed costs of trade, $a, \mathscr{F}^O_{h,r,r'} \in \widehat{\mathbf{\Gamma}}$, while the endogenous variable that we are interested in reproducing is the value of bilateral trade, $\widetilde{q}^H_{h,r,r'} \widetilde{p}^H_{h,r,r'} n_{h,r,r'} \in \widehat{\mathscr{V}}$. Using $\overline{\mathscr{V}}$ to denote the corresponding vector of observations of the variables, we can find the best estimates of the parameters by solving the nonlinear program:

$$\min_{\widehat{\mathbf{\Gamma}},\widehat{\mathscr{V}}} \left\{ \left(\widehat{\mathscr{V}} - \overline{\mathscr{V}} \right)^2 \middle| \, \Xi(\widehat{\mathscr{V}}, \widehat{\mathbf{\Gamma}}, \mathbf{\Gamma}^\star) = \mathbf{0}, \mathbf{\Gamma}^\star = \mathscr{K} \right\}$$

where $\mathbf{\Gamma}^\star$ are a set of assumed parameters and $\mathscr{K}$ is a vector of constants.

This methodology has an appealing general applicability, but in practice it is severely constrained by the degrees of freedom offered by the data, which permit only a limited number of structural parameters to be estimated. For example, in their central case, Balistreri et al. (2011) only estimate the Pareto shape parameter and fixed trade costs. Furthermore, the structure of bilateral fixed costs is such that only each region's vectors of aggregate inward and outward costs can be estimated, not the full bilateral matrix. Notwithstanding these shortcomings, the need to link CGE models' structural representations of the economy to underlying empirically-determined parameters will likely mean that structural estimation will continue to be an area of active research in the foreseeable future.

5 CONCLUSIONS

This chapter documents contemporary Computable General Equilibrium (CGE) approaches to policy evaluation. The algebraic formulation of a canonical multiregion model of world trade and production is presented. This standard class of models is widely employed in the study of economic integration and climate policy. The standard model is extended to consider specific advances in CGE research. First, the incorporation of detailed process-level production technologies are shown using bottom-up techniques. These techniques enhance models that consider energy systems. It is especially popular in climate change mitigation research, where it allows CGE models to credibly represent the impacts of policy on fuel and alternative energy use.

In the context of trade policy the canonical model is extended using a trade structure that is currently favored by many trade theorists. The model consider services and manufacturing firms providing differentiated products and engaged in monopolistic competition. Critical to this new theory is the selection of firms with different productivities (heterogeneous firms) into different national markets. This extension illustrates important margins for the gains from trade, that are not apparent in the standard model. In particular, there are variety effects as the number and composition of available goods and services change with policy. In addition, firm heterogeneity indicates that resource reallocation within an industry toward more productive firms can boost overall productivity.

The model formulations presented offer an illustrative guide and documentation of contemporary CGE applications. While technically advanced, these models offer the same advantages for policy evaluation that have been the hallmark of CGE models over the past three decades. The rigorous theoretic structure allows for an investigation of the drivers behind specific outcomes, and the sensitivity of specific outcomes to alternative assumptions. Examples presented here are useful for practitioners interested in advanced and alternative techniques and as a guide to understanding the model interactions present in many contemporary analyses.

Notes

[1] Jorgenson and Wilcoxen (1993); Bye (2000); Bovenberg and Goulder (2001); Balistreri (2002); Diao et al. (2005); Bovenberg et al. (2005); Dellink (2005); Otto et al. (2007); Otto and Reilly (2008); Otto et al. (2008).

[2] (Bernstein et al., 1999; Diao et al., 2003; Babiker et al., 2009; Ross et al., 2009; Tuladhar et al., 2009).

[3] Jean et al. (2014); Aydin and Acar (2010); Missaglia and Valensisi (2014); Engelbert et al. (2014); Braymen (2011); Kawai and Zhai (2009); Lee et al. (2009); Chao et al. (2006); Lee et al. (2004); Georges et al. (2013); Bout et al. (2012); Gouel et al. (2011); Winchester (2009); Ghosh and Rao (2010); Brockmeier

and Pelikan (2008); Ariyasajjakorn et al. (2009); Ghosh and Rao (2005); Francois et al. (2005); Lee and van der Mensbrugghe (2004); Flaig et al. (2013); Perali et al. (2012); Kitwiwattanachai et al. (2010); Bajo-Rubio and Gmez-Plana (2005).

[4] lvarez Martinez and Polo (2012); von Arnim (2009).

[5] Kleinwechter and Grethe (2012); Naranpanawa et al. (2011); Pauw and Thurlow (2011); Gumilang et al. (2011); Mabugu and Chitiga (2009); Acharya and Cohen (2008); Abbott et al. (2009); O'Ryan et al. (2005); Mirza et al. (2014); Hertel and Zhai (2006); Chan et al. (2005); Naude and Coetzee (2004).

[6] Solaymani and Kari (2013); Naranpanawa and Bandara (2012); AlShehabi (2012); Dartanto (2013); Arndt et al. (2011); Scaramucci et al. (2006).

[7] Aglietta et al. (2007); Creedy and Guest (2008); Fougre et al. (2007); Rausch and Rutherford (2010); Lisenkova et al. (2013); Wright (2013).

[8] Radulescu and Stimmelmayr (2010); Toh and Lin (2005); Field and Wongwatanasin (2007); Giesecke and Nhi (2010); Boeters (2013); Mabugu et al. (2013).

[9] Al Shehabi (2013); Bjertnaes (2011); He et al. (2014); Jiang and Lin (2014); Sancho (2010); Liu and Li (2011); Akkemik and Oguz (2011); Lin and Jiang (2011); Vandyck and Regemorter (2014); Solaymani and Kari (2014); He et al. (2011).

[10] Santos et al. (2013); Allan et al. (2008); Hanley et al. (2009); Bjertaes and Fhn (2008); Shi et al. (2009); O'Neill et al. (2012).

[11] Allan et al. (2007); Anson and Turner (2009); Turner and Hanley (2011); Martinsen (2011); Lu et al. (2010); Otto et al. (2007); Parrado and Cian (2014); Dimitropoulos (2007); Lecca et al. (2014); Turner (2009).

[12] Timilsina et al. (2011, 2013); Bae and Cho (2010); Proenca and Aubyn (2013); Cansino et al. (2013, 2014); Hoefnagels et al. (2013); Boehringer et al. (2013); Arndt et al. (2012); Gunatilake et al. (2014); Wianwiwat and Asafu-Adjaye (2013); Doumax et al. (2014); Ge et al. (2014); Trink et al. (2010); Kretschmer and Peterson (2010).

[13] Kallbekken and Westskog (2005); Klepper and Peterson (2005); Nijkamp et al. (2005); Bohringer and

Welsch (2004); Bohringer and Helm (2008); Kallbekken and Rive (2007); Calvin et al. (2009); Magne et al. (2014).

[14] Klepper and Peterson (2006); Bohringer et al. (2007); Kasahara et al. (2007); Telli et al. (2008); Thepkhun et al. (2013); Hermeling et al. (2013); Orlov and Grethe (2012); Hubler et al. (2014); Lu et al. (2010); Lim (2011); Liang et al. (2007); Loisel (2009); Wang et al. (2009); Dai et al. (2011); Hubler (2011); Meng et al. (2013).

[15] Bovenberg et al. (2005, 2008); Rose and Oladosu (2002); van Heerden et al. (2006); Oladosu and Rose (2007); Ojha (2009).

[16] Bor and Huang (2010); Fraser and Waschik (2013); Allan et al. (2014); Boeters (2014); Dissou and Siddiqui (2014).

[17] McCarl and Sands (2007); Glomsrod et al. (2011); Michetti and Rosa (2012); Bohringer et al. (2014).

[18] Babiker (2005); Babiker and Rutherford (2005); Ghosh et al. (2012); Bao et al. (2013); Branger and Quirion (2014); Hubler (2012); Alexeeva-Talebi et al. (2012); Bohringer et al. (2012); Weitzel et al. (2012); Lanzi et al. (2012); Boeters and Bollen (2012); Caron (2012); Turner et al. (2012); Kuik and Hofkes (2010); Bruvoll and Faehn (2006); Jakob et al. (2013); Egger and Nigai (2014).

[19] Viguier et al. (2006); Otto et al. (2007); Fisher-Vanden and Ho (2007); Fisher-Vanden and Sue Wing (2008); Peretto (2008); Mahmood and Marpaung (2014); Sue Wing and Eckaus (2007); Jin (2012); Qi et al. (2014); Bretschger et al. (2011); Heggedal and Jacobsen (2011).

[20] Hagem et al. (2006); Maisonnave et al. (2012); Daenzer et al. (2014).

[21] Schafer and Jacoby (2005); McFarland et al. (2004); Jacoby et al. (2006); Berg (2007); Qi et al. (2014); Okagawa et al. (2012); van den Broek et al. (2011); Karplus et al. (2013b,a); Kretschmer et al. (2009); Glomsrod and Taoyuan (2005); Timilsina et al. (2011); Timilsina and Mevel (2013); Sands et al. (2014).

[22] Examples of the latter are MARKAL (Schafer and Jacoby, 2005), and economic dispatch or capacity expansion models of the electric power sector (Lanz and Rausch, 2011).

[23] Theoretical models make the simplifying assumption that variable trade and transport costs are incurred

as a loss of product as the product moves through space—iceberg melt. This is generally inappropriate in CGE models, which must be consistent with transport services payments and government revenues from tariffs and other trade distortions recorded in their calibration dataset. We introduce $\mathscr{C}_{h,r,r'}$, however, because it serves as an important unobserved-trade-cost parameter that facilitates a calibration of the model under symmetric demand across all varieties. Like the coefficients $\xi_{i,r}$ and $\kappa_{t,i,r',r}$ in the canonical model, the values of $\mathscr{C}_{h,r,r'}$ are fixed such that the model replicates the trade equilibrium in the benchmark. See Balistreri and Rutherford (2012) for in-depth discussion of the equivalence between calibrating the heterogeneous firms model using idiosyncratic demand biases versus unobserved trade costs.

[24] Numerical results are typically not sensitive to the scale and distribution of benchmark fixed costs because only the value of the elasticity parameter determines the markup over marginal cost. Assumptions about fixed operating costs simply scale our measure of the number of firms: the larger the assumed values of $\mathscr{F}^{O}_{h,r,r'}$, the larger the implied per-firm revenue, and, with a given value of trade, the smaller the calibrated initial number of firms.

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